Gondwana Research 22 (2012) 341–352

Contents lists available at SciVerse ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

Magnetic fabric of Late Jurassic arc plutons and kinematics of terrane accretion in the Blue Mountains, northeastern Oregon

Jiří Žák [a,*], Kryštof Verner [b,c], Kenneth Johnson [d], Joshua J. Schwartz [e]

[a] Institute of Geology and Paleontology, Faculty of Science, Charles University, Albertov 6, Prague, 12843, Czech Republic
[b] Czech Geological Survey, Klárov 3, Prague, 11821, Czech Republic
[c] Institute of Petrology and Structural Geology, Faculty of Science, Charles University, Albertov 6, Prague, 12843, Czech Republic
[d] Department of Natural Sciences, University of Houston-Downtown, 1 Main Street, Houston, TX 77002, USA
[e] Department of Geological Sciences, California State University Northridge, 18111 Nordhoff Street, Northridge, CA, USA

ARTICLE INFO

Article history:
Received 12 May 2011
Received in revised form 28 July 2011
Accepted 19 September 2011
Available online 17 October 2011

Handling Editor: J.G. Meert

Keywords:
Anisotropy of magnetic susceptibility (AMS)
Baker terrane
Blue Mountains Province
North American craton
terrane accretion

ABSTRACT

The Blue Mountains Province of northeastern Oregon, western Idaho, and southeastern Washington (USA) consists of the amalgamated Wallowa distal island arc, Baker mélange-bearing accretionary wedge–forearc, and Olds Ferry fringing island arc terranes. Anisotropy of magnetic susceptibility (AMS) and particularly the orientation of magnetic lineations in Middle to Late Jurassic diorite–tonalite–granodiorite plutons intruding the Baker terrane indicate a change in tectonic regime from flattening with principal stretching at a high angle to the local orientation of the terrane boundaries at around 160 Ma to constriction with boundary-subparallel subhorizontal stretching at ca. 146 Ma. The former magnetic fabric is compatible with magnetic lineations recording strain related to top-to-the-southwest back-thrusting onto the Olds Ferry arc. In contrast, the ~146 Ma boundary-parallel stretching may record strain partitioning whereby a part of the Baker terrane was extruded laterally parallel to terrane boundaries after the terrane collision. After restoration for the clockwise post-mid-Cretaceous terrane rotation, the ~160 Ma restored principal stretching directions are compatible with the overall left-oblique subduction and convergence of the Wallowa distal and Olds Ferry fringing arc terranes. Magnetic fabric data from the plutons thus support the interpretation that the early displacement of the Blue Mountains Superterrane, and perhaps also its possible correlative Intermontane Superterrane of the Canadian Cordillera, was southward along the truncated North American continental margin during the late Middle Jurassic.

1. Introduction

The North American Cordillera is a 'classic' region where the terrane concept has been developed mainly in the late 1970s and 1980s (e.g., Irwin, 1972; Coney et al., 1980; see Dickinson, 2004, 2008 and Piercey and Colpron, 2009 for reviews). The recognition of numerous fragments of oceanic lithosphere, subduction–accretionary complexes, and island arcs that have been tectonically accreted to and dispersed along the western margin of the North American craton during Mesozoic time was a landmark in understanding the evolution of active continental margins and accretionary orogens. For decades, vigorous research has centered mainly on terranes in the Sierra Foothills, Klamath Mountains, and British Columbia (Fig. 1a; Snoke and Barnes, 2006). One of the regions that has long escaped attention, but is now seeing renewed scientific interest, is the Blue Mountains Province (BMP) of northeastern Oregon, southeastern Washington, and western Idaho (Fig. 1b). The BMP is composed of several terranes that may be correlated with both the Sierra Nevada–Klamath terranes to the southwest and with the Canadian Intermontane superterrane to the northwest (Fig. 1a). The BMP thus represents an important piece of the terrane 'puzzle' along the western margin of the North American Craton.

Despite a large body of stratigraphic, geochronologic, and geochemical data that has recently been accumulated on the Mesozoic tectonic evolution of the BMP (see Vallier and Brooks, 1995; Dorsey and LaMaskin, 2007, 2008; LaMaskin et al., 2008, 2009, 2011; and Schwartz et al., 2010, 2011a, 2011b, for detailed overviews), many issues including terrane correlations, kinematics, and timing of terrane accretion in the BMP still remain unclear and are open to debate. In this paper, we examine magnetic fabrics determined using the anisotropy of magnetic susceptibility method (AMS) in several Middle to Late Jurassic upper-crustal plutons that were emplaced over a time-span of ~15 M.y. prior to, during and after the amalgamation of oceanic arc terranes in the BMP. Below, we first briefly describe the large-scale architecture of the Blue Mountains terranes and geologic setting of the examined plutons. We then describe in detail magnetic fabrics in each pluton and, finally, we use the magnetic fabric analysis to reconstruct regional kinematics prior to, during and after terrane

* Corresponding author. Tel.: +420 221951475; fax: +420 221951452.
E-mail address: jirizak@natur.cuni.cz (J. Žák).

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doi:10.1016/j.gr.2011.09.013

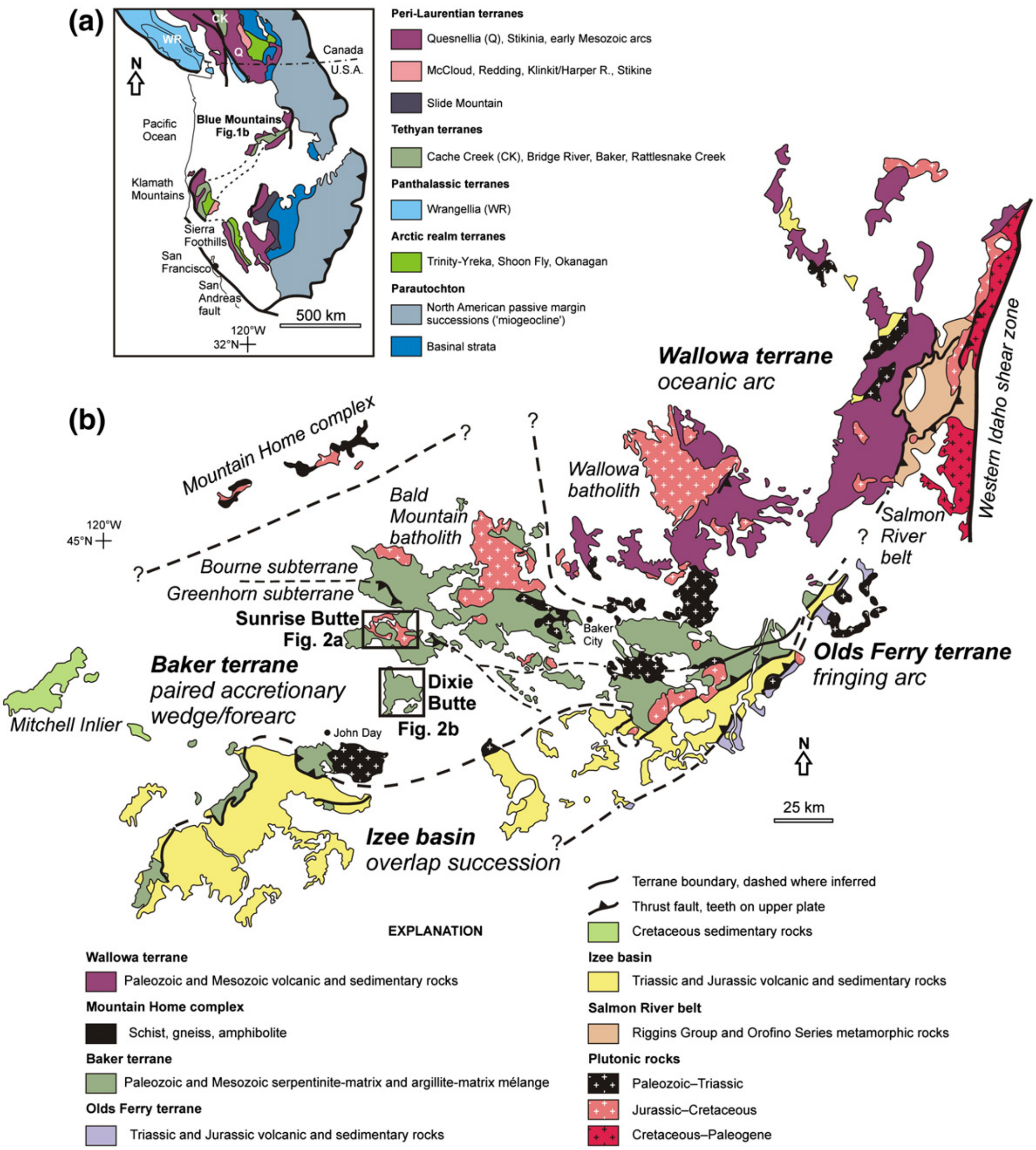

Fig. 1. (a) Greatly simplified map of the southern Cordilleran terranes showing geologic position and possible correlation of the Blue Mountains Province with the neigboring terrane assemblages. Redrafted from Piercey and Colpron (2009). (b) Simplified geologic map showing terranes and their boundaries in the Blue Mountains Province. Redrafted from Schwartz et al. (2011 a).

accretion in order to refine a recent model for the tectonic development of terranes in the BMP.

2. Large-scale terrane architecture in the Blue Mountains Province

The Blue Mountains Province is a large erosional inlier that exposes the uplifted late Paleozoic to Mesozoic variably metamorphosed basement rocks from beneath Tertiary and Quaternary deposits and Columbia River flood basalts. The basement comprises four principal lithotectonic or lithostratigraphic units (Fig. 1b; e.g., Dickinson, 1979; Avé Lallemant et al., 1985; Dorsey and LaMaskin, 2007, 2008; Schwartz et al., 2010, 2011a; LaMaskin et al., 2011):

1. The outboard Wallowa terrane is an oceanic island-arc assemblage consisting of Permian (~264 to ~225 Ma; Walker, 1995) and Triassic volcanic and volcaniclastic rocks. The island-arc volcanic complex is overlain unconformably by Triassic to Lower Jurassic limestone and clastic sedimentary successions (Stanley et al., 2008), and these rocks are in turn unconformably overlain by a Middle to Upper Jurassic flysch-like succession (the Coon Hollow Formation; LaMaskin et al., 2008).
2. The less extensively exposed, inboard Olds Ferry terrane is also an island-arc complex that consists of Middle Triassic to Lower Jurassic weakly metamorphosed volcanic and volcaniclastic rocks of chiefly andesitic composition (Brooks and Vallier, 1978; LaMaskin, 2008).
3. Between the two island-arc assemblages is the Baker terrane (Fig. 1b), a subduction–accretionary wedge–forearc complex that contains extensively disrupted fragments of ocean floor and island-arc igneous and sedimentary rocks ranging in age from Middle Devonian to Early Jurassic (Nestell, 1983; Nestell et al., 1995; Nestell and Nestell, 1998; Nestell and Orchard, 2000). The Baker terrane consists of at least two subterranes (Ferns and

Brooks, 1995). The northerly Bourne subterrane is made up of chert–argillite chaotic mélange (the Elkhorn Ridge Argillite) containing limestone blocks of Middle Devonian to Late Triassic age and chert blocks with radiolaria indicating Permian to Early Jurassic age (Blome et al., 1986; Schwartz et al., 2011a). The Greenhorn subterrane is dominated by serpentinite-matrix mélange containing blocks of metaigneous and metavolcaniclastic rocks, chert–argillite breccia, and moderate- to high-pressure metamorphic rocks. The serpentinite-matrix mélange is overlain unconformably by a Permian to Triassic clastic metasedimentary succession (the Badger Creek unit) dominated by sandstone and argillite with minor conglomerate, chert, and limestone.

Ferns and Brooks (1995) interpreted the Bourne and Greenhorn subterranes as an accretionary wedge and forearc, respectively, and suggested that during terrane convergence the Greenhorn subterrane was thrust over the Bourne subterrane which, in turn, was thrust over the Wallowa arc. The latter is well documented along the northern Wallowa terrane/Bourne subterrane boundary which is a broad, imbricated south-dipping reverse-fault zone containing slabs of the Wallowa arc-related rocks tectonically incorporated into the Bourne mélange (Schwartz et al., 2010).

4. The Izee unit comprises Triassic and Jurassic sedimentary successions that can be divided into two megasequences (Dorsey and LaMaskin, 2007). Megasequence 1 is an Upper Triassic to Lower Jurassic succession of marine argillite, turbidites, chert–clast sandstones and conglomerates, and chaotic deposits. The Early to early-Late Jurassic megasequence 2 comprises marine, chiefly turbidite deposits that overlie unconformably the megasequence 1. The Izee basin was earlier interpreted as a separate forearc basin terrane (Dickinson, 1979) but recently was reinterpreted as a regional overlap succession that rests unconformably upon the Baker and Olds Ferry terranes (Dorsey and LaMaskin, 2007).

In regional map view, terrane boundaries are curved in detail but generally trend ~E–W (in the west) and then continuously switch to ~NNE–SSW trend (in the east). This eastern termination corresponds to the Salmon River suture zone along which the Baker and Olds Ferry terranes taper eastward and are separated from the western margin of the North American craton (Fig. 1b; Gray and Oldow, 2005). Prograde garnet growth in this region is well constrained at ~128 Ma and is interpreted to reflect thrusting of the previously amalgamated terranes over the western North American margin (Getty et al., 1993). The ~E–W trend of the Blue Mountains terranes is also oriented at a high angle to the generally ~NNW–SSE trend of the Sierra–Klamath and Canadian Cordillera terranes (Fig. 1a) as a result of significant clockwise vertical-axis rotation (see Housen and Dorsey, 2005 for details). A paleomagnetic study of Wilson and Cox (1980) inferred rotation by 60° ± 29° on the basis of samples from plutonic and contact metamorphic rocks of the Wallowa batholith and Baker terrane. Similarly, Hillhouse et al. (1982) estimated rotation by 66° ± 21° from remagnetized Upper Triassic volcanogenic rocks of the Wallowa terrane. Cretaceous sedimentary rocks of the Ochoco basin, Mitchell Inlier, that passed a paleomagnetic fold test indicate the amount of rotation of 37° ± 7°, which was resolved into 21° from the mid-Cretaceous to early/middle Eocene and an additional 16° after Eocene (Housen and Dorsey, 2005; see also Grommé et al., 1986). It follows from the above that the paleomagnetic data from igneous and metamorphic rocks lack paleohorizontal control and thus involve an unknown amount of tilt of the sampled units and that large rotations are consistently derived from older rocks in the BMP, thus all of the above estimates may be correct.

3. Geologic setting and field relationships of the Late Jurassic plutons in the Greenhorn subterrane

The terranes in the BMP were intruded by a number of plutons and batholiths that define three distinct phases of plutonism at ~154–162 Ma, ~141–148 Ma, and ~111–125 Ma (Fig. 1b; see LaMaskin et al., 2009, and Schwartz et al., 2011b for details). Plutons in the Greenhorn subterrane, which are the focus of this paper, are assigned to the first two phases. The earliest ~154–162 Ma plutons are magnesian, calcic to calc-alkalic, and metaluminous and are characterized by low Sr/Y (Schwartz et al., 2011b). These plutons were emplaced during regional shortening recorded in the Baker terrane and bracketed between ~159 and ~154 Ma (D_2 of Avé Lallemant, 1995; Schwartz et al., 2010, 2011a). In contrast, the younger ~145–148 Ma plutons exhibit high Sr/Y and have more restricted compositions (Schwartz et al., 2011b), reflecting a change in the character of magmatism ~6 M.y. after the regional shortening. Schwartz et al. (2011b) recently interpreted the low Sr/Y plutons as formed from partial melting of shallow-level (<<40 km) depleted mantle or island-arc crust, whereas the high Sr/Y plutons were derived from a garnet-bearing source at depths > 35–40 km.

3.1. The Sunrise Butte composite pluton

The Sunrise Butte pluton is located southwest of the Bourne/Greenhorn subterrane boundary (Fig. 1b). The pluton intrudes the siliciclastic sedimentary rocks of the Badger Creek unit which overlies or is in faulted contact against several bodies of serpentinite (Fig. 2a). The southwestern pluton margin is intrusive and discordant where the contact truncates lithologic boundaries and faults in the host rock (Fig. 2a). The contact is generally steep or dips moderately outward (Ferns et al., 1984) and strikes ~NW–SE but in detail has an irregular, curvilinear outline in plan view (Fig. 2a). To the northwest, the pluton is in intrusive contact against a large body of peridotite and also encloses a ~4 × 2 km irregular block of the serpentinite and metasedimentary rocks (Fig. 2a). The pluton is extensively overlain by Miocene basalt lava flows; thus its subsurface geometry is unknown.

The Sunrise Butte pluton is composite and, from the northeast to the southwest, consists of three principal intrusive units that differ in composition, radiometric ages, and geochemical signature (Fig. 2a; Johnson et al., 2007; Johnson and Schwartz, unpublished data). The Desolation Creek unit (low Sr/Y), dated at 160.2 ± 2.1 Ma, is the northwesternmost rim of the pluton and comprises hornblende–biotite granodiorite, tonalite, and quartz diorite. The central Sunrise Butte and its equivalent Deadwood Creek units (both have high Sr/Y) make up much of the exposed part of the pluton and are largely composed of hornblende–biotite granodiorite to tonalite, dated at 146.7 ± 2.3 Ma. Part of the southwestern margin of the pluton is delineated by the Onion Gulch unit of two-pyroxene diorites and quartz diorites (low Sr/Y; 147.9 ± 1.8 Ma; Johnson and Schwartz, unpublished data).

The plutonic rocks of the Sunrise Butte composite pluton exhibit generally little macroscopic and microscopic evidence of solid state deformation with the exception of a few localities in the Desolation Creek and along the southern margin of the Onion Gulch units. Hence, the magnetic fabrics discussed later are mostly interpreted in terms of hypersolidus strains (magmatic to submagmatic; Paterson et al., 1998).

3.2. Dixie Butte plutons

To the south of Sunrise Butte, a number of small (<3 km^2) plutons intrude a large Middle Jurassic metavolcanic complex of the Dixie Butte Meta-andesite (Fig. 2b). The volcanic complex consists of a lower sequence of tuffaceous sedimentary rocks and volcaniclastic breccias and an upper sequence of lava flows, volcaniclastic breccias and sills, all of predominantly basaltic andesite to andesite composition (LaMaskin et al., 2009; Schwartz et al., 2011b). The plutons can be grouped into two distinct suites. A mafic suite comprises the Dixie Summit (low Sr/Y; U–Pb zircon age 162 ± 2.9 Ma; Schwartz

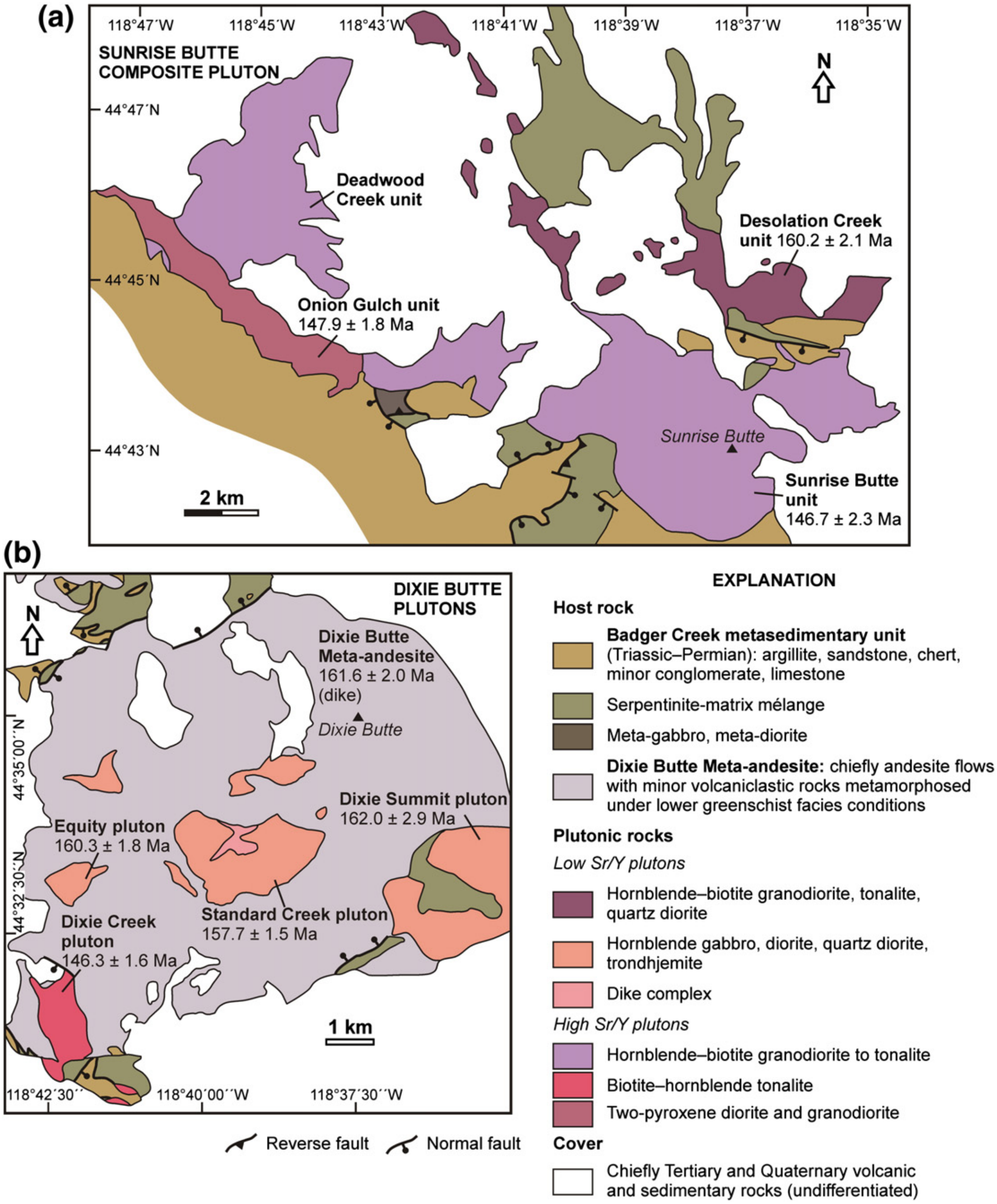

Fig. 2. Geologic map of the Sunrise Butte and Dixie Butte plutons and their host rocks, extensively overlain by Tertiary volcanic and sedimentary successions.

et al., 2011b) and the Equity (low Sr/Y; U–Pb zircon age 160.3 ± 1.8 Ma; Schwartz et al., 2011b) plutons, which are sheeted intrusions in the east-central and west-central part of the Dixie Butte area, respectively (Fig. 2b). These rocks range in composition from gabbro to quartz diorite (frequently altered at greenschist facies conditions) and are comagmatic with the metavolcanic complex (Schwartz et al., 2011b). A younger granodiorite suite is represented by the Standard Creek pluton (low Sr/Y; U–Pb zircon age 157.7 ± 1.5 Ma; Schwartz et al., 2011b) in the central part of the Dixie Butte area (Fig. 2b). The pluton is presumably a steep-sided stock with an irregular, weakly E–W elongated outline in plan view (~3 × 2 km; Fig. 2b) and is composed of biotite–hornblende granodiorite (also commonly altered). The youngest intrusion is the Dixie Creek pluton (high Sr/Y; U–Pb zircon age 146.3 ± 1.6 Ma; Schwartz et al., 2011b) in the southwestern part of the Dixie Butte area (Fig. 2b). In plan view, the pluton has a roughly rectangular, ~NNW–SSE elongated shape (~2 × 1 km) and intrudes the meta-andesite and serpentinite faulted against the Badger Creek metasedimentary unit at its southern margin (Fig. 2b). The dominant rock type is biotite–hornblende tonalite much less affected by the greenschist-facies alteration than the older plutons and lacking a solid-state overprint (Schwartz et al., 2011b).

4. Anisotropy of magnetic susceptibility (AMS) of the Sunrise Butte and Dixie Butte plutons

The AMS method (see Hrouda, 1982; Jackson and Tauxe, 1991; Tarling and Hrouda, 1993; Bouchez, 1997; Borradaile and Henry, 1997; and Borradaile and Jackson, 2004, 2010 for detailed overviews) was used in this contribution to analyze pluton fabrics at 49 stations. The AMS can be visualized as an ellipsoid (its maximum principal direction K_1 is denoted as magnetic lineation and its minimum direction K_3 is the pole to magnetic foliation) and can be further characterized by a number of parameters (Tarling and Hrouda, 1993, p. 18–19). We use the mean magnetic susceptibility (k_m)

which reflects the type and volume fraction of magnetic minerals in the rock, degree of anisotropy (P) which reflects the eccentricity of the AMS ellipsoid and may thus relate to the intensity of the preferred orientation of the magnetic minerals, and shape parameter (T) which indicates the symmetry of the AMS ellipsoid ($-1<T<0$ prolate, $T\sim0$ triaxial, $1>T>0$ oblate AMS ellipsoid). The AMS methodology and data from the examined plutons are provided in detail in the Supplementary content to this article and presented in a concise form in Figs. 3–6.

4.1. Magnetic fabric of the Sunrise Butte plutons

4.1.1. Desolation Creek unit

As inferred from the AMS, the ~160 Ma Desolation Creek unit exhibits an unusually complex internal structure over a small outcrop area (Fig. 3). In most cases, the principal susceptibilities are strongly clustered about their respective mean directions at individual stations; however, a detailed analysis and statistical evaluation of the AMS directional data suggest that at least four distinct orientations of magnetic fabric can be recognized in this intrusive unit.

1. At station JZ19 only ~60 m from the pluton margin (Fig. 3a), magnetic foliations tend to strike ~ENE–WSW and dip steeply to the ~NNW (Fig. 3a). Magnetic foliations are thus subparallel to the nearby ~E–W-trending pluton/host rock contact and also to the ~E–W cleavage (D_2) that has been reported from the Badger Creek unit by Avé Lallemant (1995). Magnetic lineations scatter along the k_1–k_2 plane from nearly down-dip to plunging shallowly to the ~ENE. Nevertheless, the k_1 axes tend to cluster about the mean orientation of 51°/36° (Fig. 3a).
2. At two stations, magnetic foliations strike ~NE–SW and dip steeply to moderately to the ~SE (station JZ6) or ~NW (station JZ8) being associated with magnetic lineations plunging moderately to the ~E (slightly oblique to the mean foliation plane dip) or plunging gently to the ~SW, respectively (Fig. 3a). The latter is the most intriguing case as both magnetic foliations and lineations are almost perpendicular to the nearby intrusive contact.
3. At stations JZ5 and JZ44 in the central part of the exposure, magnetic foliations strike ~N–S to ~NNW–SSE and dip gently to moderately to the ~E (Fig. 3a), being associated with down-dip (subhorizontal) ~E-trending or dip-oblique ~NE-trending lineations (Fig. 3a).
4. At stations JZ25 and JZ27, magnetic foliations tend to strike ~NW–SE and dip gently to moderately to the ~NE while the magnetic lineations define either a down-dip or subhorizontal mean orientation (Fig. 3a). Similar orientations were also measured in the northwestern exposures of the Desolation Creek unit where magnetic foliations dip moderately to steeply to the ~NE and lineations are dip-oblique, plunging moderately to the ~E (stations JZ35, JZ45; Fig. 3a). Here, however, fabric relations to the intrusive contacts cannot be established as the pluton is extensively concealed beneath Tertiary lava flows.

A further analysis of the data also reveals a significant difference in the AMS parameters between the southeastern and northwestern exposures of the Desolation Creek unit. The eastern exposures are characterized by low mean susceptibility on the order of 10^{-4} SI (the AMS is largely controlled by paramagnetic minerals; Bouchez, 1997) and a low degree of anisotropy; the P parameter varies from 1.005 to 1.052 corresponding to 0.5–5% anisotropy (Fig. 3b). The T parameter scatters widely from −0.581 to 0.900, but most specimens (74%) yield an oblate shape of the AMS ellipsoid (Fig. 3b, c). In contrast, the mean susceptibilities in the northwestern exposures are on the order of 10^{-2} SI (Fig. 3b, c) suggesting that a ferromagnetic *s.l.* fraction dominates the AMS signal (Bouchez, 1997). Furthermore, the degree of anisotropy is noticeably elevated, ranging from 1.063 to 1.266 (6–27% anisotropy), and the T parameter is more variable (−0.557 to 0.797) with the data almost symmetrically distributed about the

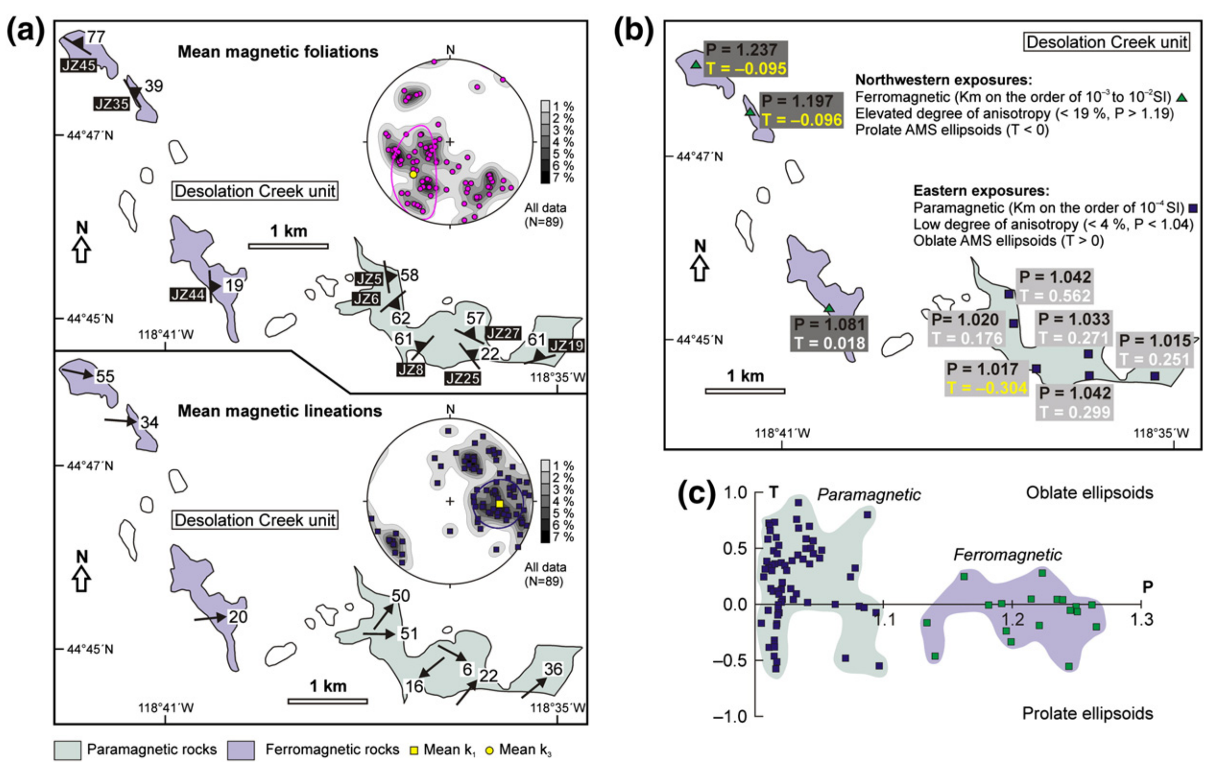

Fig. 3. (a) Maps of the Desolation Creek unit showing mean magnetic foliations and lineations at each station. Inset synoptic stereonets (equal area, lower hemisphere projection) portray the minimum and maximum principal susceptibilities of all specimens and respective mean directions with 95% confidence ellipses. (b) Map of the Desolation Creek unit showing average degree of anisotropy (P) and shape parameter (T) at each station. (c) Magnetic susceptibility P–T plot of all analyzed specimens from the Desolation Creek unit.

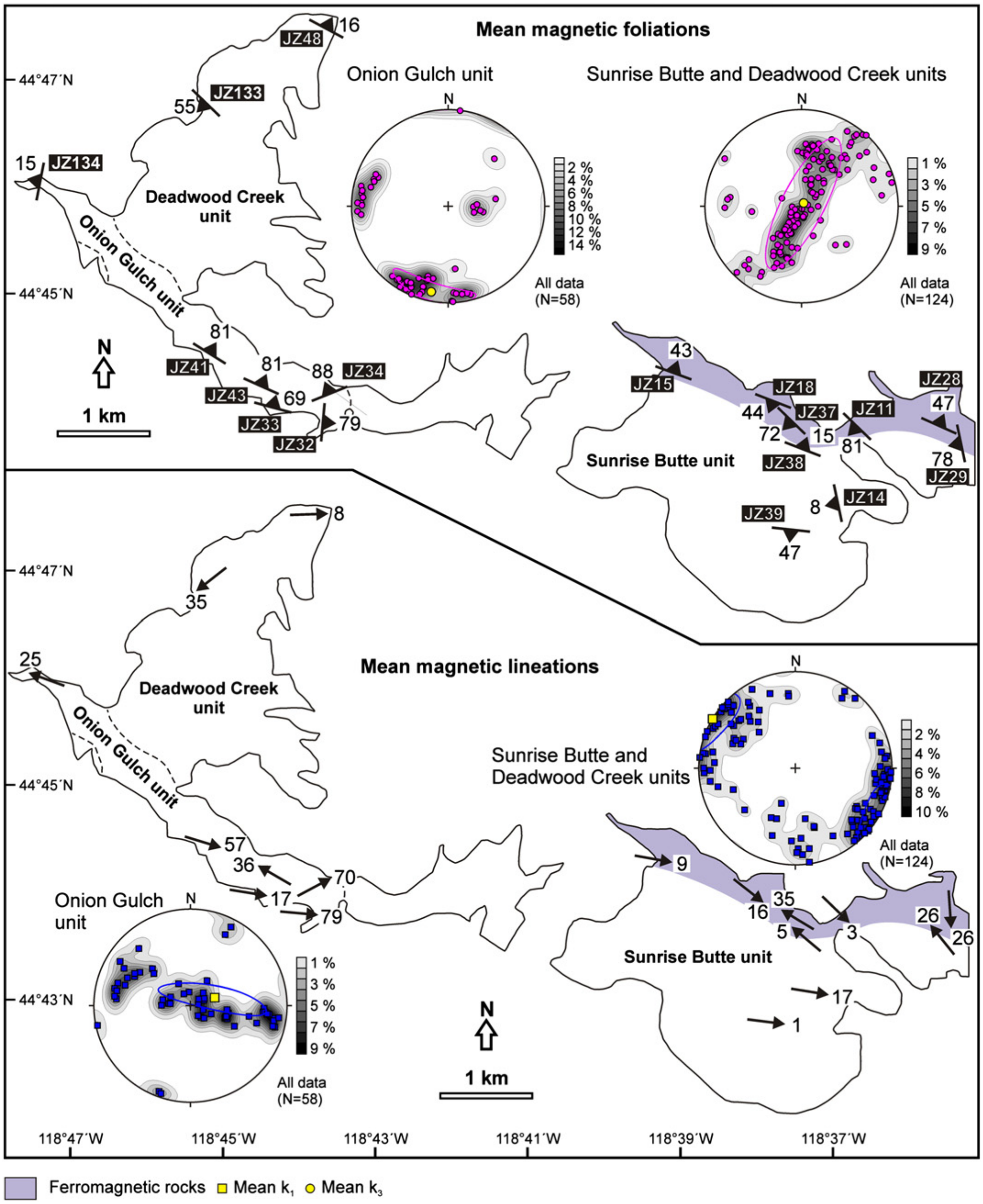

Fig. 4. Maps of the composite Sunrise Butte pluton showing orientation of mean magnetic foliations and magnetic lineations at each station. Synoptic stereonets are equal area, lower hemisphere projections and show the minimum and maximum principal susceptibilities of all specimens and respective mean directions with 95% confidence ellipses.

T = 0 axis in the P–T plot (Fig. 3c) and a weak tendency toward the neutral (triaxial) shape of the AMS ellipsoids.

4.1.2. Sunrise Butte, Deadwood Creek, and Onion Gulch units

The most conspicuous feature in the magnetic fabric of the ~146–147 Ma Sunrise Butte and its correlative Deadwood Creek, and Onion Gulch units are subhorizontal, predominantly ~NW–SE-trending magnetic lineations that were revealed at most stations (Fig. 4). This lineation is associated with ~NW–SE-striking magnetic foliations that dip moderately to steeply to the ~SW or ~NE (Fig. 4); in two cases, foliations are subhorizontal (JZ14, JZ38). In a synoptic stereonet, poles to magnetic foliation (the k_3 axes) from all the specimens define a pronounced girdle about the subhorizontal, strongly clustered magnetic lineations (Fig. 4), suggesting an overall uniaxial (prolate) fabric symmetry dominating the ~146–147 Ma intrusive units.

At two stations, magnetic fabric differs in orientation from that described above. At station JZ32 (the Onion Gulch unit), magnetic foliations are subvertical and strike ~N–S and are associated with subvertical magnetic lineations (Fig. 4). This locality is ~35 m from the pluton margin and the foliations seem to parallel the local orientation of the contact. Another magnetic fabric orientation was measured at station JZ29 in the eastern part of the Sunrise Butte unit, where subhorizontal magnetic lineations plunge gently to the ~S and magnetic foliations strike ~N–S at variable dip (k_3 axes scatter around the well-clustered k_1 axes; Figs. 4, 6).

Furthermore, the K_m, P, and T parameters reveal significant magnetic fabric gradients in the ~146–147 Ma intrusive units of the pluton. The northeastern part of the exposure is characterized by the mean susceptibilities on the order of 10^{-2} SI, weakly to strongly prolate AMS ellipsoids (87% of specimens; T ranges from −0.877 to 0.437), and an elevated degree of anisotropy (P = 1.030–1.259, corresponding to 3–26% anisotropy; Fig. 5). In the remainder of the Sunrise

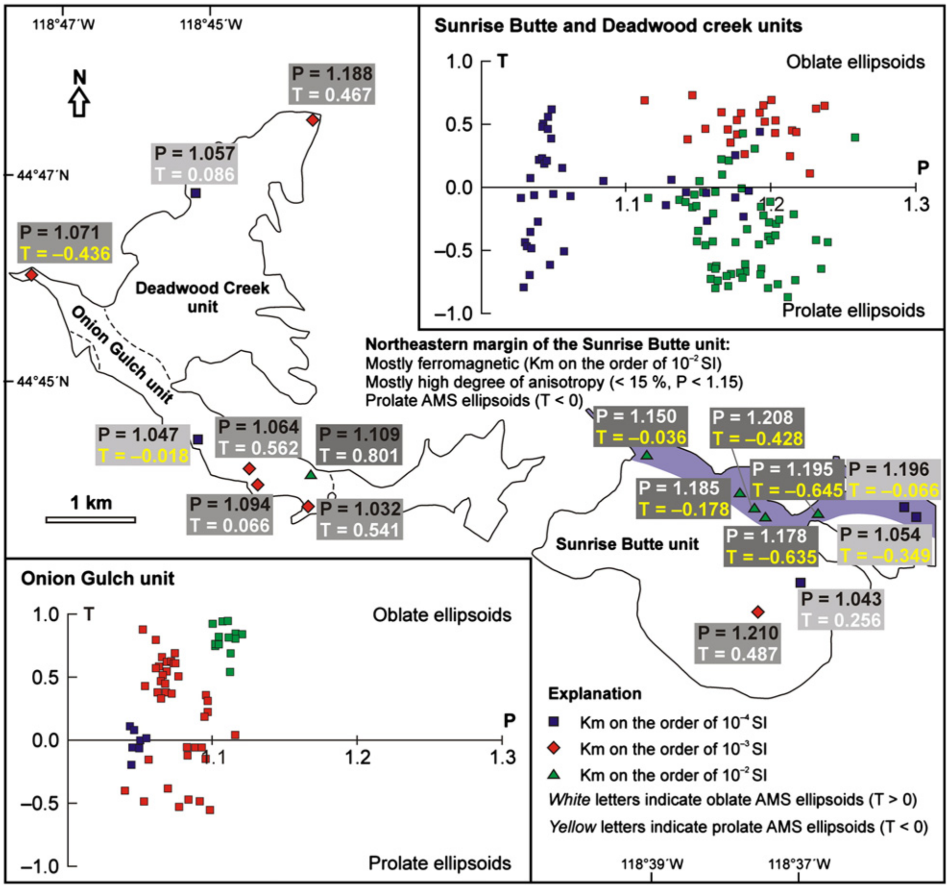

Fig. 5. Map of the composite Sunrise Butte pluton showing average degree of anisotropy (P) and shape parameter (T) at each station and magnetic susceptibility P–T plots of all analyzed specimens.

Butte, Deadwood Creek, and Onion Gulch units the mean susceptibility varies from one station to another over three orders of magnitude (10^{-4} to 10^{-2} SI), showing no spatial pattern and bearing no relationship to a particular fabric orientation or P and T parameters (Fig. 5). With the exception of stations JZ41 and JZ134 where 98% specimens yield prolate AMS ellipsoids (T ranges from −0.558 to 0.179), the AMS ellipsoids change from prolate to strongly oblate to the south and southwest in the southern half of the Sunrise Butte and in the Onion Gulch units (Fig. 5; T ranges from −0.441 to 0.944, 90% of specimens yield oblate AMS ellipsoids), while the degree of anisotropy generally decreases (Fig. 5; P = 1.031–1.297, corresponding to 3–30% anisotropy).

4.2. Magnetic fabric of the Dixie Butte plutons

In the ~162 Ma Dixie Summit pluton, the principal susceptibilities scatter widely at stations JZ118 and JZ119 with only a very weak tendency toward subhorizontal to moderately dipping foliation. In the remaining four stations along the southern margin of the pluton, the data are more clustered about the respective mean directions. Magnetic foliations strike ~N–S (station JZ120) to ~ NNE–SSW (station JZ131) and dip steeply to moderately to the ~E and ~WNW, respectively, while magnetic lineations vary from nearly down-dip in the pluton interior (station JZ120) to subhorizontal near the pluton margin (stations JZ117, JZ121, JZ131; Fig. 6).

The ~160 Ma Equity pluton reveals intriguing magnetic fabrics at stations JZ114 and JZ116 where the well-defined steep magnetic foliations strike ~ N–S or ~NW–SE, are associated with predominantly subhorizontal lineations, and are thus almost perpendicular to the nearby intrusive contact (Fig. 6). At the other station (JZ115), the principal susceptibilities are highly variably oriented and the mean directions are ill-defined.

Both the Dixie Summit and Equity gabbros and diorites are paramagnetic as indicated by a low mean susceptibility on the order of 10^{-4} SI, exhibit prolate and oblate shapes of the AMS ellipsoids with oblate being dominant (75% of the analyzed specimens in the former, 77% in the latter), and have a very low degree of anisotropy (see Supplementary content to this article). The P parameter ranges from 1.002 to 1.120 (the Dixie Summit pluton, corresponding to 0.2–12% anisotropy) and from 1.002 to 1.028 (the Equity pluton, 0.2–0.3% anisotropy). Most of the specimens (84%) exhibit less than 2% anisotropy in both plutons ($P < 1.018$).

Magnetic fabric in the ~157 Ma Standard Creek pluton is characterized by foliations that seem to parallel, or are at a low angle to, the outer pluton margin (Fig. 6). The foliations exhibit various dip but in most cases dip outward beneath the host rock. In the map, the foliations define a cupola type pattern expressed also in a synoptic stereonet, where the k_3 axes form a circular girdle around the stereonet center (Fig. 6). Magnetic lineations vary from subhorizontal (e.g., station JZ127) to down-dip (e.g., station JZ124). The AMS ellipsoids are predominantly oblate (84% of the analyzed specimens) with the shape parameter ranging from −0.478 to 0.871 (see Supplementary content to this article). The mean susceptibility varies from one station to another from 10^{-4} SI (station JZ125) through 10^{-3} SI (stations JZ122, JZ123) to 10^{-2} SI (stations JZ124, JZ126, JZ127), however, there is a clear correlation among the mean susceptibilities, degree of anisotropy, and the orientation distribution of the principal directions. For specimens with K_m on the order of 10^{-4}, the P parameter is low (1.007–1.013) and the principal susceptibilities scatter widely while for K_m on the order of 10^{-2} the P parameter is elevated

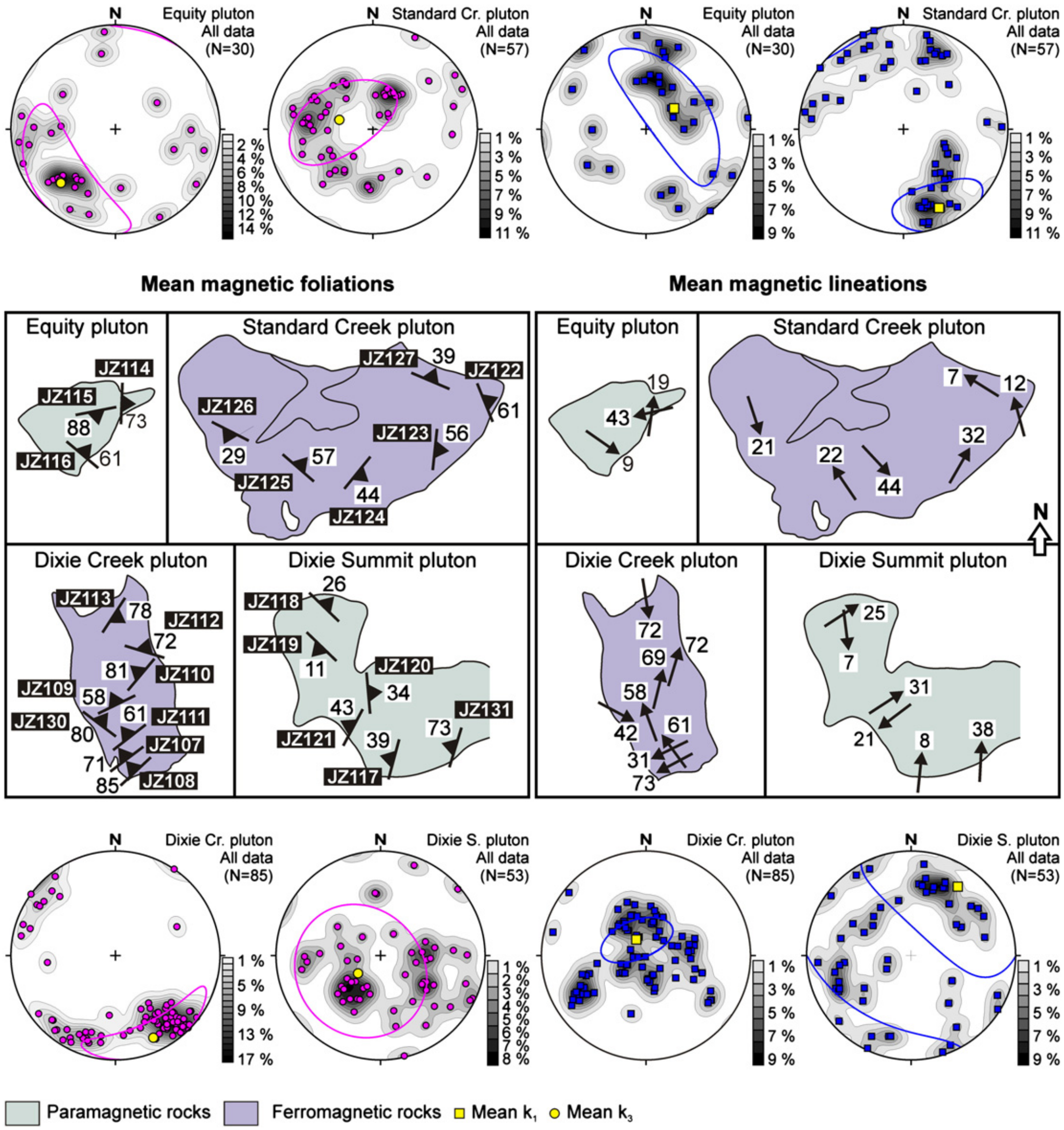

Fig. 6. Maps of the Dixie Butte plutons showing orientation of mean magnetic foliations and magnetic lineations at each station. Synoptic stereonets are equal area, lower hemisphere projections and show the minimum and maximum principal susceptibilities of all specimens in each unit and respective mean directions with 95% confidence ellipses. Only pluton outlines are shown for clarity, geographic coordinates and scale can be read in Fig. 2b.

(1.017–1.063) and the principal susceptibilities are well clustered about their mean directions.

The ~146 Ma Dixie Creek pluton is characterized by steeply to moderately plunging magnetic lineations that define a prominent maxima around the center of the synoptic stereonet (Fig. 6). The exception is station JZ107 where lineations plunge gently to the ~SW (Fig. 6). Magnetic foliations dip steeply and are either roughly parallel to the local orientation of the intrusive contact (stations JZ108, JZ113, JZ130), or strike ~NE–SW (at a high angle to the contact) in the southern half of the pluton. The AMS ellipsoids are mostly oblate (81% of the data) but compared to the above plutons the degree of anisotropy scatters widely from 1.003 (0.3% anisotropy) up to 1.212 (21% anisotropy). The mean susceptibilities are on the order of 10^{-2} SI throughout the pluton, indicating that ferromagnetic *s.l.* carriers dominate the AMS. Importantly, both the site-averaged shape parameter and degree of anisotropy increase toward the pluton margins (see Supplementary content to this article) from $T=-0.158$–0.652 and $P=1.052$–1.146 (stations JZ109, JZ110, JZ111, JZ113) to $T=0.125$–0.709 and $P=1.113$–1.197 (stations JZ107, JZ108, JZ112, JZ130).

5. Discussion

5.1. Interpretation of the AMS data

Numerous studies have shown that granitoid plutons may behave as rheologically weak inclusions in the crust during some part of their magmatic 'life time' (e.g., Pavlis, 1996; Paterson et al., 1998). Consequently, the internal pluton fabrics could provide 'snapshots' of regional tectonic strain even in the brittle upper crust, where regional deformation is otherwise largely localized along narrow fault zones that accommodate the overall deformation but may be located well away from the plutons (e.g., Callahan and Markley, 2003). In particular, Benn (2010) recently emphasized the crucial importance of magmatic and/or magnetic lineations (the latter determined using the AMS) for interpreting the principal stretching directions in magmatic rocks, either resulting from magma flow, regional deformation, or both. Moreover, using the example of the Mount Stuart batholith (Cascades Crystaline Core), Benn et al. (2001) have shown that under certain circumstances, both mesoscopic and magnetic fabric patterns in plutons may be used to infer regional kinematics and even past plate motions. The latter approach involves two important assumptions: (1) on a specimen scale, the AMS axes are assumed to coincide with the principal strain axes (e.g., passive model of Hrouda and Lanza, 1989; also note that the AMS axes themselves provide no information on shear sense) and (2) on a regional scale, the principal strain axes inferred from the AMS are assumed to reflect plate movements in such a way that magnetic lineations are parallel to the overall tectonic transport direction and parallel to the plate motion vector (Benn et al., 2001). This may not be the case, however, in partitioned transpressional or transtensional settings whereby orientations of principal strains and hence magnetic fabric axes may vary significantly (e.g., Tikoff and de Saint Blanquat, 1997; Tikoff and Greene, 1997; de Saint Blanquat et al., 1998; Chardon et al., 1999; Dewey, 2002; Andronicos et al., 2003).

Keeping the above limitations in mind, we believe that the AMS data presented in this paper may provide information on the changing strain fields in the Greenhorn subterrane from ~160 to ~146 Ma and, in turn, the orientation of the principal AMS (and inferred strain) axes with respect to the terrane or subterrane boundaries may help to elucidate the kinematics of terrane convergence and collision in the BMP during the Middle to Late Jurassic. Analysis of the AMS data from the Sunrise Butte composite pluton reveals important spatial trends in the orientation of principal susceptibilities in relation to the magnetic fabric parameters. The most conspicuous feature in the Desolation Creek unit is the presence of two subgroups of magnetic lineations plunging gently to moderately to the ~NE (mean k_1 for this data subgroup is 36°/37°) and to the ~E (mean k_1 is 98°/39°; Fig. 3a) whereas magnetic foliations scatter widely but statistically define a mean foliation dipping moderately to the ~NE (mean k_3 is 228°/41°; Fig. 3a). With the exception of one station (JZ6), the northeast-plunging lineations occur in the eastern exposure (dated at ~160 Ma) dominated by paramagnetic mineralogy and characterized by low degrees of anisotropy and oblate AMS ellipsoids (Fig. 3b, c). On the other hand, the east-plunging lineations occur in the northwestern exposures (unknown radiometric age) dominated by ferromagnetic *s.l.* mineralogy, with high degrees of anisotropy and prolate AMS ellipsoids (Fig. 3b, c). The latter fabric characteristics are also remarkably similar to those measured in the ~146 Ma Sunrise Butte unit, where mean k_1 is 301°/00° (Fig. 4), and together they are suggestive of recording a reorientation of magnetic lineations from ~NE–SW through ~E–W to ~WNW–ESE, associated with a change in the AMS ellipsoid shape from oblate to prolate (Figs. 3, 6).

The following criteria suggest that the AMS in the Sunrise Butte composite pluton records chiefly tectonic and not emplacement-related (intrusive) strain or some other processes. First, magnetic lineations in the eastern exposure of the Desolation Creek unit are at a high angle to the nearby generally ~E–W-trending intrusive contacts (Fig. 3a). Similarly, magnetic lineations in the Sunrise Butte unit bear no relationship to the geometry and local irregularities of the exposed intrusive contact (Fig. 4). Second, the subhorizontal magnetic lineations show the same ~WNW–ESE trend in different units of the pluton (Fig. 4). Two exceptions, where the AMS presumably reflects intrusive strain, are stations JZ32 and JZ34 where lineations are subvertical and in the former case magnetic foliations are steep and clearly parallel to local ~N–S orientation of the intrusive contact (Fig. 4). Third, the principal susceptibilities show a remarkable inter-site consistency in orientation in most cases and especially in the Sunrise Butte unit (see Figs. 3a, 4, and Supplementary content to this article). For instance, magnetic lineations are homogeneously oriented at the pluton scale and also exhibit consistent orientation in various lithologies with the bulk susceptibility varying by two orders of magnitude (from 10^{-4} to 10^{-2}; Figs. 3–5). These findings strongly support a close relationship among the AMS and strain axes as it is difficult to reconcile such fabric homogeneity with post-magmatic alteration or with the presence of minerals possesing inverse' magnetic fabric. Hence, considering magnetic lineations as representing the principal stretching axis (X) of the finite strain ellipsoid, our interpretation is that they indicate a switch from tectonic stretching at a high angle to the ~NW–SE-trending Bourne and Greenhorn subterrane boundaries at around 160 Ma to boundary-subparallel subhorizontal stretching at around 146 Ma.

The above magnetic fabric differs from that documented in the Dixie Butte area. The Dixie Summit and Equity plutons are dominated by paramagnetic and the Standard Creek and Dixie Creek plutons by ferromagnetic *s.l.* mineralogy (Fig. 6), corroborating a compositional shift in the plutonism from ~162 Ma to ~146 Ma as suggested by whole rock geochemistry (LaMaskin et al., 2009; Schwartz et al., 2011b). However, the principal susceptibilities scatter widely at most documented stations and vary from one pluton to another showing no regionally consistent pattern (Fig. 6). In some cases, magnetic foliations and lineations delineate the plutons' margins (the Standard Creek and Dixie Creek plutons; Fig. 6) and are associated with an inward decrease in the degree of anisotropy for the bulk susceptibility on the same order, as particularly exemplified by the Dixie Creek pluton. In the latter case, most magnetic lineations also plunge steeply (Fig. 6). Therefore, we interpret magnetic fabric in the Dixie Butte plutons as predominantly intrusive (non-tectonic), recording a random to very weak mineral alignment (either primary or caused by greenschist-facies alteration) or more intense emplacement-related strain (margin-perpendicular shortening and subvertical stretching).

5.2. Implications for kinematics of terrane accretion in the Blue Mountains

Several conflicting hypotheses have been proposed for the Mesozoic tectonic evolution of the Blue Mountains Province (see Dorsey and LaMaskin, 2007 and Schwartz et al., 2010, 2011a, for recent reviews and discussions). According to the most recent hypothesis of Schwartz et al. (2010, 2011a), Molucca Sea-type doubly vergent subduction was active between the converging Wallowa outboard oceanic arc and Olds Ferry fringing arc at ca. 162 Ma. Island arc collision at ~159–154 Ma was followed by the initiation of another subduction system beneath the Baker terrane and Olds Ferry arc at ~148–141 Ma (westward in the restored coordinates; Schwartz et al., 2011a). The latter subduction accommodated closure of a narrow oceanic basin as the amalgamated Wallowa–Baker–Olds Ferry superterrane approached the North American craton followed by its final attachment to the craton at around 128 Ma (Schwartz et al., 2011a).

We suggest that our AMS data may further refine this hypothesis. The ~NE–SW magnetic lineations are oriented at a high angle (almost perpendicular) to the nearby ~NE–SW bend of the Bourne/Greenhorn subterrane boundary (compare Figs. 1b and 3a). Ferns and Brooks (1995) and Schwartz et al. (2010, 2011a) have documented that the Wallowa/Baker terrane and Bourne/Greenhorn subterrane boundaries dip to the southwest; that is, the terrane and subterrane boundaries are antithetic with respect to the magnetic lineations and to the average' magnetic foliation documented in this study. As the AMS axes can provide only the inferred strain axes and not the sense of shear, such AMS orientation could be interpreted as resulting from either normal or reverse movements. Given that the overall setting was contractional during Middle to Upper Jurassic (Schwartz et al., 2010, 2011a), our interpretation is that the lineations may record strain related to top-to-the-southwest back thrusting onto the Olds Ferry arc (Fig. 7) at around 160 Ma (zircon age of the Desolation Creek unit). Subsequently, this terrane-perpendicular stretching switched to terrane-parallel stretching (Fig. 7) which lasted until at least ~146 Ma as suggested by the ~WNW–ESE magnetic lineations in the Sunrise Butte unit (Fig. 4). Again, kinematics of this event cannot be determined solely from the AMS data. In contrast, coeval plutons in the Dixie Butte area have not recorded these regional strains, either because the deformation was localized elsewhere (closer to the

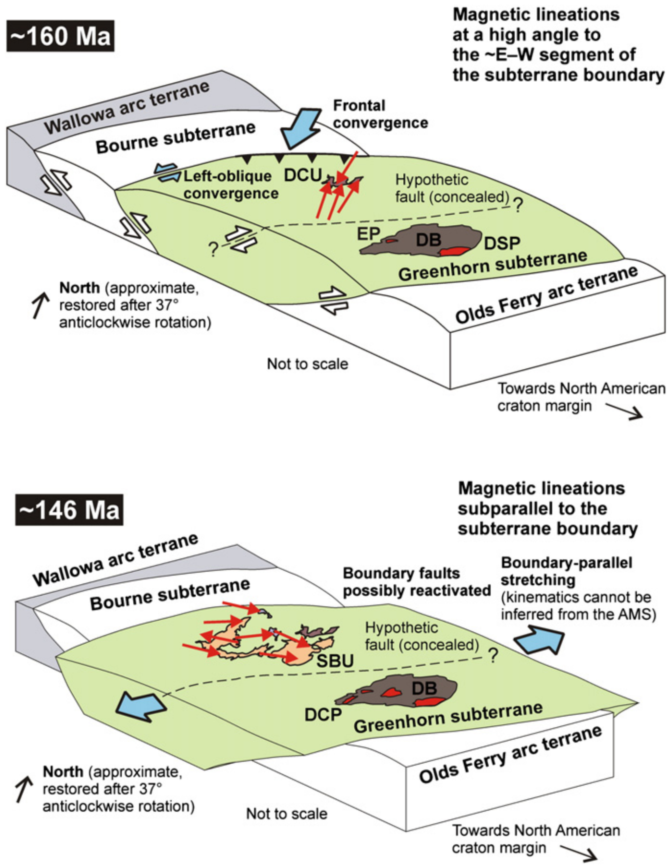

Fig. 7. Interpretative, greatly idealized blockdiagrams to show the terrane kinematics during syn-convergent emplacement of the Sunrise Butte plutons at around 160 Ma and 146 Ma as inferred from the AMS data; see text for discussion. Geologic units: DCU Desolation Creek unit, DB Dixie Butte Meta-andesite, DCP Dixie Creek pluton, DSP Dixie Summit pluton, EP Equity pluton, SBU Sunrise Butte unit.

subterrane boundary) or due to their comparably smaller sizes and hence very fast cooling rates.

An intriguing picture emerges when the AMS data and the above inferrences are discussed in the framework of paleogeographic reconstructions and other structural and paleomagnetic studies from the BMP. It is important to note, however, that no paleomagnetic data nor paleohorizontal control exist from the plutonic rocks in question. In the following discussion, we may thus only suspect that the component units of the Sunrise Butte pluton have not been significantly tilted or rotated relative to each other and that the paleomagnetic constraints can be extrapolated from elsewhere in the BMP to our study area. The former assumption is justified by the absence of throughgoing pluton-scale faults between the key intrusive units with contrasting magnetic fabrics (Desolation Creek and Sunrise Butte). The latter assumption, requiring little to no differential rotations and tilts of the BMP terranes or their fault-bounded parts, is strengthened by the continuous regional trends of folds, foliations, and lineations suggesting little to no disruption by rotations of individiual blocks (see structural maps in Avé Lallemant, 1995).

Whereas the post-Cretaceous paleogeography of the Cordilleran terranes has been fairly well constrained (Engebretson et al., 1985), the earlier (Triassic to Jurassic) terrane displacements and their original positions are much more difficult to constrain (e.g., Engebretson et al., 1985; Avé Lallemant and Oldow, 1988; Johnston, 2001; Dickinson, 2004, 2008). In this paper, we have shown that the mean k_1 and inferred principal stretching directions in the ~160 Ma Desolation Creek unit is 36°. After restoration of the clockwise terrane rotation, this ~160 Ma inferred principal stretching becomes ~N–S (359° if rotated by 37° according to the estimation of Housen and Dorsey, 2005) or even ~NNW–SSE if the 66° rotation is invoked (mean k_1 becomes 340°). We argue that the restored principal stretching directions and their obliquity with respect to the terrane/subterrane boundaries are compatible with the overall sinistral, but also locally frontal, subduction and convergence of the Wallowa and Olds Ferry arc terranes at around 160 Ma (note that the terrane and subterrane boundaries are curved as shown in Fig. 1b and schematically sketched in Fig. 7). Our AMS data thus provide another independent data set to support the interpretation that the early displacement of the Blue Mountains terranes was southward along the truncated North American continental margin (e.g., Avé Lallemant et al., 1985; Avé Lallemant and Oldow, 1988; Avé Lallemant, 1995). The ~146 Ma terrane-parallel stretching is highly oblique to the continental margin even after restoration (present-day mean k_1 of 120° trends 83° or 54° in the restored coordinates, depending on the amount of back-rotation, see above). This may result from strain partitioning whereby a part of the Greenhorn subterrane was extruded laterally parallel to the terrane boundaries (Fig. 7) after the Wallowa and Baker terranes collided and further boundary-perpendicular shortening was hindered in the amalgamated terranes.

Schwartz et al. (2011a) recently proposed that the Wallowa distal arc, Baker paired oceanic mélange-bearing accretionary wedge/forearc, and Olds Ferry fringing arc terranes may represent the southern extension of correlative terranes of the Intermontane Superterrane of the Canadian Cordillera (Stikinia, Cache Creek terrane, and Quesnellia, respectively, Fig. 1a; e.g., Johnston and Borel, 2007; Piercey and Colpron, 2009) and suggested that the terrane collisions were diachronous from north to south. Taken together, the latter interpretation is consistent with the AMS data presented in this paper, all suggesting that both the Intermontane and Blue Mountains Superterranes were displaced southward and amalgamated during overall left-oblique convergence with respect to the North American craton during Middle to Late Jurassic time.

6. Conclusions

1. The AMS data (and particularly magnetic lineations) from the Middle to Late Jurassic plutons in the Greenhorn subterrane of the Baker terrane indicate a switch in the tectonic regime (but not necessarily in plate kinematics) from flattening-type with principal stretching at a high angle to the Bourne and Greenhorn subterrane boundary at around 160 Ma to constrictional with boundary-subparallel subhorizontal stretching at around 146 Ma.
2. The former magnetic fabric is compatible with magnetic lineations recording strain related to the top-to-the-southwest back-thrusting onto the Olds Ferry arc. In contrast, the ~146 Ma boundary-parallel stretching may record strain partitioning whereby a part of the Greenhorn subterrane was extruded laterally parallel to the terrane boundaries after the terrane collision.
3. After removal of the clockwise post-mid-Cretaceous terrane rotation by 37° or 60°, the ~160 Ma restored principal stretching directions are only compatible with the overall left-oblique subduction and convergence of the Wallowa distal and Olds Ferry fringing arc terranes and support the interpretation that the early displacement of the Blue Mountains superterrane and its correlative Intermontane superterrane of the Canadian Cordillera was southward along the truncated North American continental margin in the Middle to Late Jurassic times.

Acknowledgments

We gratefully acknowledge Bernie Housen and one anonymous reviewer for their constructive comments that helped significantly to improve the original manuscript, and Mark Ferns for discussions, helping with maps, and taking care of our samples and field equipment. The research was supported through post-doctoral grant of the Grant Agency of the Czech Republic No. 205/07/P226 (to Jiří Žák) and from the Ministry of Education, Youth and Sports of the Czech Republic through Research Plan No. MSM0021620855. Partial financial support for this work was also provided by NSF grant EAR-0911681 (to Joshua Schwartz) and NSF grant EAR-0911735 (to Kenneth Johnson).

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