Magmatic Fabrics in Batholiths as Markers of Regional Strains and Plate Kinematics: Example of the Cretaceous Mt. Stuart Batholith

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Abstract. The Cretaceous Mt. Stuart batholith was syntectonically emplaced within amphibolite grade metasedimentary rocks of the Cascades Crystalline Core, Washington State. The northern part of the batholith defines a NW-SE trending antiformal fold. We present fabric data from that part of the batholith, collected during field mapping and anisotropy of magnetic susceptibility (AMS) measurements. The significance of the data is discussed in terms of regional tectonic deformation and plate kinematics. The data were collected from rocks with well preserved igneous textures and the fabrics therefore formed during magmatic deformation. The AMS provides measurements of the preferred orientations of Fe-rich minerals (biotite ± hornblende ± traces of pyrrhotite and magnetite) which are consistent with field measurements of the mesoscopic fabrics defined by plagioclase, biotite and hornblende crystals. The magnetic fabrics are also consistent with the orientations of folds, mineral fabrics and boudinage structures that record high-temperature subsolidus deformation in the margin of the pluton and in its host rocks. The lineations are parallel to the stretching direction associated with small increments of strain that occurred during deformation of the magmatic arc, as the batholith was crystallizing and deforming in the tectonic stress field, ca. 93 Ma. The fabrics in the Mt. Stuart batholith are used to infer emplacement in a magmatic arc during either 1) plate displacement perpendicular to a NW-SE trending plate margin, or 2) wrench dominated transpression. In the second case the analysis suggests a nearly N-S plate vector along the western North American margin during plutonism. The results demonstrate the potential usefulness of magmatic fabrics in syntectonic plutons for plate tectonic analyses of orogenic belts.

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and Gleizes, 1995; Benn et al., 1997; Gleizes et al., 1997; Benn et al., 1999; Pignotta and Benn, 1999). In the Pyrenees, several studies have proposed that the fabrics in syntectonic plutons emplaced during Hercynian contraction can be used to interpret a bulk regional dextral transpression, based on the oblique orientations of the pluton fabrics with respect to the orogenic belt and on dextral deflections of the fabrics near the pluton margins (Leblanc et al., 1996; Gleizes et al., 1997; Gleizes et al., 1998).

Another example of the application of pluton fabrics to studying synemplacement tectonics comes from the southern Slave Province, Canada. There, Berm et al. (1998) suggested that the pervasive magnetic lineation mapped in the Late Archean Sparrow pluton indicates the orientations of regional shortening and stretching directions during a contractional, possibly transpressive tectonic event. The fabric information was especially useful since the strain field information could not be obtained directly from the metamorphic country rocks of the southern Slave Province, which have undergone several phases of deformation resulting in fold interference patterns and a complicated finite strain picture.

The documentation of tectonic signatures in the magmatic fabrics of some syntectonically emplaced plutons raises the following two important questions. First, can the magmatic fabrics in plutons and batholiths, which are often mapped using magnetic anisotropy techniques, be widely applicable as indicators of regional, synmagmatic deformations? Second, if pluton fabrics are related to regional deformations, might they also be used to interpret the kinematics of tectonic plate interactions at plate margins, during the period when the plutons were emplaced and the magmatic fabrics were frozen in as the plutons solidified? Pluton emplacement and solidification likely occurs in about about $10^9$ years, and isotopic dating methods allow the crystallization ages of plutons to be determined precisely. Therefore, pluton fabrics have the potential to provide a "snapshot" of strain, and possibly of plate kinematics, during a relatively short period of orogenic evolution.

To further investigate the tectonic significance of pluton fabrics, this contribution presents two fabric data sets (field and AMS measurements) from the Cretaceous Mt. Stuart batholith, situated within the Cascades Crystalline Core, Washington State. The Cascades Crystalline Core is considered to be the southern extension of the Coast Plutonic Complex (Fig. 1), the largest magmatic arc terrane in the North American Cordillera. The geology of the country rocks and of the batholith are well documented providing a framework within which the pluton fabrics may be analyzed.

Maps of the mesoscopic and magnetic foliations and lineations are presented for the northern part of the Mt. Stuart batholith, which was deformed into an apparent fold during magma crystallization. Comparisons of the pluton fabrics with the structures in the country rocks are used to demonstrate that the igneous fabrics in the batholith record tectonic deformation of the Mt. Stuart magmas as they were emplaced and crystallized, and that the magnetic lineation indicates a stretching direction parallel to regional fold axes. The results of this study confirm the tectonic significance of the internal fabrics of the Mt. Stuart batholith, and point towards the general usefulness of the magmatic fabrics in plutons for terrane analyses. The fabric and structural data from the batholith and its wall rocks are used to propose constraints on the kinematics of the plate displacements along the North American margin during plutonism, ca. 93 Ma.

2. Tectonic setting and geology

The Mt. Stuart batholith is the largest of the mid-Cretaceous plutons within the Cascades Crystalline Core, in Washington State (Fig. 1). The Cascades Crystalline Core is considered to be the southern extension of the Coast Plutonic Complex, British Columbia (Fig. 1). It is made up of deformed and variably metamorphosed Upper Paleozoic to Mesozoic rocks, including sedimentary and volcanic rocks and ophiolitic slices.
that were accreted to the western North American margin during mid-Cretaceous to Paleogene orogenesis (Brown, 1987; Miller et al., 1993). Accretion may have resulted from the collision of the Insular and Intermontane superterranes, resulting in the regional shortening accommodated by the Northwest Cascades Thrust System and in burial metamorphism (McGroder, 1991). Alternative models suggest the Cascades Crystalline Core represents the exhumed roots of a mid-Cretaceous magmatic arc built upon previously amalgamated terranes (Brown and Talbot, 1989; Kriens and Wernicke, 1990; Walker and Brown, 1991). The Cretaceous tectonics are recorded in the metamorphic rocks of the Cascades Crystalline Core by thrust faults, by upright to overturned NW-SE trending gently plunging folds and by pervasive NW-SE trending extension lineations (Brown and Talbot, 1989; Miller and Paterson, 1992; Miller and Paterson, 1994).

The Mt. Stuart batholith (93 Ma) crops out as two closely spaced massifs (Fig. 2). The western portion is an elliptical body composed of tonalite and granodiorite. The main body of the Mt. Stuart batholith lies to the east, and has been informally subdivided into the northern "hook", the central narrow NW-SE striking portion referred to as "the sill", and the southernmost part which is referred to as "the mushroom" because of its shape in map view. The hook region has been interpreted to be an antiformal fold plunging gently to the northwest (Paterson et al., 1994; Paterson and Miller, 1998a). The host rocks of the Mt. Stuart batholith consist of the metapelitic and metapsammitic Chiwaukum Schist, and the Ingalls ophiolite complex which overlies the Chiwaukum Schist on a thrust contact (Windy Pass Thrust, Fig. 2). The regional metamorphic grade of the country rocks ranges from greenschist in the rocks enclosing the mushroom region, to upper amphibolite in the Chiwaukum Schist that hosts the hook and sill regions (Miller et al., 1993). Aluminum-in-hornblende geobarometry on the rocks of the Mt. Stuart batholith suggests the depth of emplacement was between 6 and 12 km (Ague and Brandon, 1992; Anderson, 1997).

The main phases of the Mt. Stuart batholith consist of biotite (+ hornblende) tonalite and granodiorite with metaluminous and marginally peraluminous compositions. Trace element signatures suggest an origin within a calc-alkaline volcanic arc setting (Anderson, 1992; Paterson et al., 1994). The tonalite locally grades into diorite and gabbro in the southern part of the batholith (Fig. 2). A slightly older (95.5 Ma) mafic unit called the Big Jim complex (Fig. 2) is not volumetrically significant relative to the main phases of the Mt. Stuart batholith.

Previous structural studies of the Mt. Stuart batholith documented a foliation and a mineral lineation that are most strongly developed near the NE margin of the pluton, where they record magmatic deformation and a locally developed high-temperature subsolidus overprint (Miller and Paterson, 1992; 1994). The magmatic and high-temperature subsolidus fabrics are parallel, and, based on numerous field and microstructural observations, they are interpreted to record a
continuum in magmatic to subsolidus deformation that occurred as the batholith crystallized and began to cool from the solidus. In the hook and the sill, the mesoscopic foliation generally strikes NW–SE, and at different localities it dips moderately to steeply either to the NE or to the SW. The lineation has a shallow plunge, and it is generally parallel to the axes of magmatic to subsolidus folds documented in the NE margin of the batholith (Miller and Paterson, 1994). The foliation, the lineation and the folds within the batholith margin have orientations similar to tectonic folds and fabrics in the metamorphic host rocks of the Chiwaukum Schist. The lineations are also parallel to the direction of the maximum principal stretch indicated by boudinaged dykes of Mt. Stuart magmas within the Chiwaukum schist (Miller and Paterson, 1994), and to the NW–SE instantaneous stretching direction indicated by the preferred orientation of magma-sealed joints within the batholith (Fig. 18 in Paterson et al., 1994). In the interior of the hook and sill regions, the foliation and lineation are of magmatic origin, and they are less intensely expressed than near the pluton margin.

The magmatic fabrics in the mushroom region of the batholith define a different pattern from the one observed in the hook and the sill. We interpret the difference in fabric pattern to be due to the fact that the mushroom region is hosted by greenschist grade ophiolitic peridotites and gabbros that responded in a less ductile fashion to regional deformations than the amphibolite grade metasedimentary rocks that host the hook and the sill. Hence in the mushroom region the magmatic foliations show a concentric pattern parallel to the pluton margin, suggesting they may record internal flow of the magmas within an already constructed magma chamber (Paterson et al., 1994); the fabrics may have been isolated from tectonic stresses by the rigid host rocks. In this study, we concentrate on the fabrics in the hook and sill regions, which were emplaced within highly ductile country rocks. In those parts of the batholith, the magmatic fabrics have a predominantly tectonic signature, probably due to a small difference in viscosity between the batholith and its ductile host at the time of fabric formation, which allowed the magmas to deform with the country rocks.

3. Microstructures

We have studied the magmatic fabrics that are preserved within rocks with pristine igneous textures, indicating that the mineral orientations were frozen into the rocks when they solidified and were not subsequently reworked by solid state deformations. The criteria for identifying igneous textures are well known and have been described in detail (Paterson et al., 1989; Bouchez et al., 1990). They include the preservation of well developed crystal faces on early crystallizing minerals such as feldspar, micas and amphiboles, and the lack of extensive dynamic recrystallization of the minerals. Similar microstructural criteria are used to identify the presence of crystallized melt within the leucosomes of migmatites (Vernon and Collins, 1988).

Igneous textures are well preserved throughout much of the Mt. Stuart batholith (and in all of the studied samples), with only a very weak and locally developed suprasolidus to subsolidus overprint. Some plagioclase crystals exhibit concentric igneous zonation, and most have euhedral to subhedral crystal habits (Fig. 3A), indicating that the rocks we sampled for this study have not been affected by significant high-temperature subsolidus strain and recrystallization. Some plagioclase–plagioclase grain boundaries are lobate and cuspatc suggesting minor plagioclase grain boundary migration occurred, either during or immediately following the latest stages of crystallization. Minor intracrystalline plastic deformation is also manifested in a small fraction of the plagioclase crystals by the presence of kinked deformation twins (Fig. 3B). However, since euhedral to subhedral plagioclase crystal shapes and igneous compositional zonation are well preserved, we interpret that the studied rocks did not
undergo extensive subsolidus strain and recrystallization.

4. AMS method

Oriented blocks (and a few oriented drill cores) were collected at seventy-five stations in the study area. Oriented drill cores were extracted from the blocks using a specially outfitted drill press at the Geological Survey of Canada, in Ottawa. At least three drill cores of approximately 7 cm length were obtained for each sampling station, and two or more cylindrical specimens of 10.8 cm³ were cut from each core, providing a sample of at least 64.8 cm³ for each station. The AMS measurements were performed using a Kappabridge KLY-2 instrument (AGICO, Czech Republic) at the University of Ottawa. The KLY-2 is an a.c. bridge operating at 920 Hz with an internal field intensity of 300 A/m (r.m.s. value). The magnetic susceptibility is measured along the axis of the pick-up coil with the specimen being placed in fifteen predetermined orientations. The resulting data allow calculation of the orientation of the anisotropy ellipsoid and the values of the principal susceptibilities along each of the principal axes \( K_1 > K_2 > K_3 \). The average AMS ellipsoid was calculated for each sampling site using a tensor averaging method (Jelinek, 1978).

5. Magnetic mineralogy

Determination of the magnetic mineralogy is of critical importance in magnetic fabric studies, since the presence of certain minerals may lead to anomalous AMS fabrics that cannot be related to the petrofabrics of interest in a simple and straightforward way. Anomalous AMS may occur because the formation of magnetic minerals post-dates (and, therefore, their orientations may not record) the magnetic fabric forming event (e.g. magnetite of metamorphic or hydrothermal origin; Benn et al., 1993), or because the intrinsic anisotropies of some minerals are anomalous, leading to AMS orientations that do not correspond to the shape preferred orientations of the igneous minerals (Rochette et al., 1992; Rochette et al., 1994; Borradaile and Henry, 1997). It is, of course, critical to be aware of the presence of such minerals in the sample suite since, in many cases, the AMS is used to measure fabric orientations that could not be routinely verified by other means.

Petrographic inspection of thin sections reveals that two paramagnetic Fe-bearing silicate phases are present in the studied rocks. Biotite is present in all of the samples and hornblende is locally present. Opaque minerals were also observed in some samples. Petrological data suggest the principal igneous Fe-rich opaque phase in the Mt. Stuart batholith is pyrrhotite (Anderson and Paterson, 1991). Recently acquired data on the remanence-bearing magnetic mineralogy in the batholith (S.P.L. and colleagues, work in progress) suggest that igneous pyrrhotite is the principal carrier of the NRM that was acquired during emplacement of the Mt. Stuart batholith. The data show that the primary NRM is carried by pyrrhotite, and that a slightly later NRM is recorded by pyrrhotite and secondary magnetite. Thermal demagnetization curves that reveal blocking temperatures of 400°C and less, and alternating-field demagnetization spectra confirm the presence of pyrrhotite. The ongoing study of magnetic mineralogy in the Mt. Stuart batholith suggests that magnetic is limited to relatively restricted regions, which might correspond to regions where high oxygen fugacity magmas crystallized, to zones of deuteric alteration that occurred shortly after emplacement, or in some cases to anomalously high paleo-pressures resulting from loading of the crust above parts of the batholith shortly following its emplacement (Brown and Walker, 1993; Paterson et al., 1994).

Based on these data, we conclude that the AMS fabrics in the studied sample suite are most likely controlled by a combined contribution of biotite ± hornblende ± pyrrhotite at most of the sampling sites. The orientations of those igneous minerals should record the strain that affected the batholith as it crystallized, and locally a very minor component of strain acquired as the rocks cooled from the solidus (see previous section on microstructure). Fine-grained secondary magnetite may also contribute to the AMS signal at some of the sites.

6. Fabric results

The mesoscopic mineral foliation and lineation, and the AMS, were mapped throughout the hook and sill regions of the Mt. Stuart batholith, which represent a large-scale, shallowly plunging antiformal fold that has also been mapped out in the country rocks (Fig. 2). The orientations of the mesoscopic and magnetic fabric elements are compiled on the maps and the accompanying lower-hemisphere equal-area projections in Fig. 4.

The poles to the mesoscopic and magnetic foliations define NE–SW point distributions, tending to partial girdles in the equal-area projections (Fig. 4A,C). The average foliation orientations are parallel to the axial surface traces of the NW–SE trending regional folds that have affected the host rocks and that gave rise to the outcrop pattern of the hook region of the Mt. Stuart batholith. Hence the igneous foliation within the batholith is consistent with the NW–SE shortening
event that is recorded in its host rocks, and it is in essence an axial-planar fabric.

The magnetic lineations in the batholith trend NW–SE and, on average, the plunge is subhorizontal (Fig. 4B). This orientation is parallel to the shallowly plunging axes of the regional folds, and to the axes of the small-scale folds documented in the margins of the batholith (Miller and Paterson, 1994). The average orientations of the mesoscopic-scale lineations and magnetic lineations are very similar to the pole to the best-fit plane calculated for the magnetic foliation poles (compare equal-area projections in Fig. 4A,B).

Some of the scatter in the orientation distribution of the magnetic foliation poles might be explained as the effect of magnetic mineralogy. For instance, the presence of small amounts of secondary magnetite could result in the misorientation of the magnetic foliation with respect to the foliation defined by mineral shapes (Benn et al., 1997; Benn et al., 1998; Pignotta and Benn, 1999). On the other hand, a similar degree of scatter of the mesoscopic foliation poles (Fig. 4C), measured in the field, suggests the orientations of the magnetic and mesoscopic foliations may be more complicated at a local scale than is suggested by the compiled measurements for the study area. For instance, small-scale folding of the magmatic foliation, which is difficult to observe in most outcrops, has previously been documented in the Mount Stuart batholith and in other plutons of similar ages in the Cascades Core (Paterson et al., 1998). Also, somewhat complicated foliation patterns in parts of the Mt. Stuart batholith, close to remnants of host rocks that overlie the pluton and in the vicinity of large stoped blocks (Paterson and Miller, 1998b), may have escaped reworking by tectonic deformation of the crystallizing intrusion. It may be that some of the magnetic and field measurements presented here were gathered from regions of magmatic folding, or near to unexposed stoped blocks, or in regions where early-formed fabrics due to internal convection of the magmas or to

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Fig. 4. Compiled data for the orientations of the magnetic (A, B) and field (C, D) measurements for the hook and sill regions of the Mt. Stuart batholith.
emplacement flow were not entirely overprinted by syncrystallization deformation. The scatter in the magnetic lineation orientations may also be in part a mineralogical effect, but a similar orientation distribution exists for the field measurements of the mesoscopic lineation, defined by plagioclase and hornblende crystals (Fig. 4D). Therefore we cannot rule out the presence of an early-formed igneous mineral lineation, that has not been entirely overprinted by subsequent deformation of the crystallizing magmas.

In summary, a predominant NW-SE striking foliation and a subhorizontal NW-SE trending lineation in the study area are well defined in the equal-area projections. They indicate that a steeply dipping, NW-SE striking foliation and a shallowly plunging NW-SE trending mineral lineation are prevalent throughout the hook and sill regions of the Mt. Stuart batholith. Those predominant fabric orientations most likely record syncrystallization tectonic deformation of the batholith.

7. Discussion

The results of this fabric study are consistent with previous structural and microstructural analyses of the Mt. Stuart batholith (Miller and Paterson, 1992; 1994). Based on the parallelism of magmatic and high-temperature subsolidus fabrics within and adjacent to the NE margin of the batholith, those authors suggested a continuum in the deformation of the granitoids and their host rocks during emplacement. They showed that, within the high-temperature deformed NE margin of the batholith, the mineral and extension lineations are parallel to 1) the axes of small-scale folds of the igneous fabric within the granitoids, 2) the axes of the folded metamorphic fabrics in the host rocks and 3) a NW-SE stretching direction indicated by boudinaged granitoid dikes within the country rocks. They also showed the lineations are perpendicular to the average orientation of magma-sealed joints within the batholith, suggesting the lineations are also parallel to the late increments of stretching during solidification of the batholith.

The present study provides an extensive mapping of the igneous fabrics throughout the hook and sill regions of the Mt. Stuart batholith. Application of the AMS technique provided lineation measurements throughout the hook region, where outcrop conditions are generally poor, and confirmed the numerous field measurements of the mineral lineation in the sill region where the outcrop conditions are more conducive to field mapping. The results in Figs. 4B,D show that the hook and sill regions of the Mt. Stuart batholith have an average magmatic lineation that is parallel to the magmatic and subsolidus fabrics documented within its deformed NE margin. It is interpreted that the fabric patterns shown in Fig. 4 were acquired during the syn-crystallization deformation that resulted in the present outcrop pattern of the hook and sill regions, which are suggestive of an antiformal fold, and in a pervasive stretching of the crystallizing magmas parallel to the fold axis. According to the results of Miller and Paterson (1992) and Miller and Paterson (1994), the deformation of the batholith was concentrated along its margins once it had fully crystallized and begun to cool below the solidus.

Having demonstrated the signature of syn-crystallization regional deformation preserved by the igneous mineral fabrics in the Mt. Stuart batholith, we now discuss the usefulness of the data for establishing interpretations of the regional tectonic picture, ca. 93 Ma. First, it is argued that the predominant fabrics within the hook and sill regions can be used to infer shortening and stretching directions over a short period in the crystallization history of the batholith, such that the data can be used to approximate the principal axes of a small increment of syn-crystallization strain. Then, we speculate that the fabric data can be used to infer pluton emplacement in an arc that was characterized by either 1) plate convergence that was perpendicular to a NW-SE trending plate boundary, or 2) wrench dominated transpression due to highly oblique plate convergence. These two proposals are developed by placing the fabrics from the Mt. Stuart batholith within the context of previously published structural and plate tectonic studies of the region.

7.1. Igneous fabrics and strains

The average magnetic lineation trend in Fig. 4B (296°) is perpendicular to the average orientation of numerous extensional fractures within the batholith that are sealed by late-stage leucogranitic and pegmatitic dykes. The average pole to the late dykes is 300° (from Fig. 18 in Paterson et al., 1994). This indicates that the magnetic lineations are parallel to the maximum principal incremental stretching that caused the extensional fractures to form during the final stages of solidification of the batholith. The same parallel relationship between the incremental maximum principal stretching direction and magnetic lineations was documented in the syntectonic South Mountain batholith, Nova Scotia (Benn et al., 1997), and it is therefore possible that the relationship occurs in other granitoids emplaced within contractional orogens.

The interpretation that the magnetic lineation records an incremental stretching direction implies either that 1) it formed during a progressive pure shear deformation of the crystallizing magma body, such that the lineation remained parallel to the instantaneous stretching axis throughout a finite
magnatic strain history (of undetermined duration and intensity), or that 2) it records a relatively small increment of non-coaxial strain in the magma, such that the lineation was not rotated to any significant degree from the instantaneous stretching axis. Both interpretations are consistent with detailed studies of the igneous foliation in close proximity to stoped blocks in the Mt. Stuart batholith, that suggest the magnatic foliation formed late in the crystallization history (Paterson and Miller, 1998b).

The data do not allow us to distinguish whether the lineations in the Mt. Stuart batholith formed during a progressive pure shear or in response to a small increment of non-coaxial strain, nor can we determine the magnitude of the finite strain recorded by the fabrics. However, the parallelism between the lineations and the average pole to late dykes allows us to use the average lineation orientation to approximate the instantaneous stretching axis during the late stages of crystallization of the batholith. In the following section, the fabrics are considered within a plate tectonic context, and we speculate they can be used to suggest emplacement within an arc that was characterized either by 1) orthogonal convergence at a NW-SE trending plate boundary, or 2) by highly oblique plate convergence and associated wrench-dominated transpression.

7.2. Plate kinematics

In mid- to late-Cretaceous time, the western margin of the arc represented by the Coast Plutonic Complex (Fig. 1) was part of a west-verging fold and thrust belt extending from Washington State (the Northwest Cascades Thrust System) to southern Alaska (Rubin et al., 1990). A kinematically linked system of east-verging folds and thrusts representing a back-thrust system exists along the eastern side of the Coast Plutonic Complex in southern British Columbia (Rusmore and Woodsworth, 1991). A predominant WSW–ENE trend of extension lineations in the bounding thrusts led to interpretations that the accretionary event involved mainly are-perpendicular crustal shortening (Rubin et al., 1990; Rusmore and Woodsworth, 1991).

On the other hand, a compilation of structural patterns and geochronology has shown that, within the Coast Plutonic Complex in British Columbia, orogen parallel displacements may have been strongly partitioned into a system of steeply dipping shear zones, suggesting a possible transpressive tectonic environment (Chardon et al., 1999). Those authors propose the arc system may have undergone first sinistral, then dextral transpressional deformations due to oblique convergence of the Farallon and/or Kula plates with respect to North America (Chardon et al., 1999, and references therein). The onset of the proposed earlier sinistral transpression is poorly constrained but it would have terminated ca. 106 Ma, whereas the proposed dextral transpressive event would have begun between 106 Ma and 93 Ma ago (Chardon et al., 1999). The switch from sinistral to dextral transpression could be linked to an anticlockwise rotation (from E to N) of the relative displacement vector of the Farallon plate between 125 and 75 Ma, or to the formation of the Kula plate during this period, which had a nearly N-S oriented displacement vector with respect to North America (Engebretson et al., 1985). We can use the data from the Mt. Stuart batholith to propose some further constraints on possible plate kinematics along the part of the western margin of North America corresponding to the Cascades Crystalline Core ca. 93 Ma, during the emplacement of the batholith.

Kinematic considerations suggest that in large-scale orogenic belts such as the Mesozoic to Tertiary western North American margin, predictable relationships should exist between relative plate motions, finite strain axes and instantaneous strain axes (Tikoff and Teyssier, 1994; Teyssier et al., 1995). The theoretical predictions of those authors' kinematic modelling have been favorably compared to several natural examples of transpressive plate boundary environments, including Sumatra (Tikoff and Teyssier, 1994), the San Andreas fault system and the South Island of New Zealand (Teyssier et al., 1995; Teyssier and Tikoff, 1998) and the Coast Plutonic Complex in British Columbia (Fossen and Tikoff, 1998).

In a zone of homogeneous transpression (i.e. diffuse deformation over a broad area without strain partitioning into transcurrent shear zones) a distinction is made between, on the one hand, wrench dominated transpression where the instantaneous stretching axis ($s_1$) makes an angle greater than 35° with the zone boundary, and pure shear dominated transpression where $s_1$ makes an angle less than 35° to the zone boundary (Tikoff and Teyssier, 1994). In wrench dominated transpression, $s_1$, and the maximum finite stretch, $s_1$, are both horizontal at low strains, and $s_1$ becomes vertical at higher strains. In pure shear dominated transpression, both $s_1$ and $s_1$ are predicted to be vertical throughout the strain history. In the special case of orthogonal convergence at a plate boundary, a pure shear deformation is expected with both $s_1$ and $s_1$ vertical, and the instantaneous and finite flattening planes (and, presumably, regional foliation strikes) parallel to the plate boundary.

Based on these considerations and on our data, we can construct two plate kinematic models. In the first model, the
Mt. Stuart batholith was emplaced within the mid-crustal parts of an arc undergoing NE-SW arc-perpendicular shortening (as previously proposed by Paterson and Miller, 1998a). This model, shown schematically in Fig. 5A, would require the plate margin to be parallel to the predominant fabrics in the batholith, that record NE-SW syn-emplacement tectonic shortening perpendicular to the predominant foliation and lineation in the batholith. It would also suggest that the Cascades Crystalline Core, and the Mt. Stuart batholith, would have undergone a bulk pure shear deformation. One advantage of this model is that the interpreted plate displacement vector (Fig. 5A) is similar to the one proposed for the Farallon plate with respect to North America, between 100 and 75 Ma, based on plate reconstructions (Engebretson et al., 1985). A disadvantage is that kinematic models predict that during a bulk homogeneous pure shear, steeply plunging lineations are expected to develop. The fabrics within the Mt. Stuart batholith and structures, such as boudinaged dykes, in its wall rocks suggest that \( \sigma_1 \) and \( \sigma_2 \), were both horizontal at least during the small increments of strain that they record. The horizontal lineations preserved in the Mt. Stuart batholith might be reconciled with the plate kinematic model in Fig. 5A if vertical crustal thickening resulting from arc-perpendicular shortening in the Cascades Crystalline Core were accommodated by thrusts in the metamorphic country rocks, such as the Northwest Cascades Thrust System (McGroder, 1991), where NE-SW trending stretching lineations have been documented. Then, the lineations in the batholith might indicate lateral, arc-parallel flow of the crystallizing magmas induced by the regional shortening.

A second kinematic model calls for emplacement and crystallization within a ductile crust undergoing wrench dominated transpression. Fig. 5B presents the schematic model, assuming a homogeneous transpression. It is constrained by values of \( \theta \), the angle between the maximum instantaneous stretching axis and the plate boundary, and by \( \alpha \), the angle between the relative plate displacement vector and the plate margin (Tikoff and Teyssier, 1994). For wrench dominated transpression, \( \theta \) should have a value between 35° and 45°, and \( \alpha \) should have a value of 20° or less (Tikoff and Teyssier, 1994). In Fig. 5B, we take \( \sigma_1 \) to be approximated by the average trend of the magnetic lineation (296°). To demonstrate the proposed model, a value of \( \theta = 35° \) (the lowest predicted value for wrench dominated transpression) is arbitrarily chosen in Fig. 5B, which suggests a paleo-plate boundary trending 331°, similar to the trend of the Coast Plutonic Complex and of several major regional shear zones within it (Chardon et al., 1999). In Fig. 5B, the maximum possible angle of 20° is chosen for \( \alpha \), and a plate displacement vector of 351° is derived. Note that if a value of 45° was chosen for \( \theta \), the determined plate boundary trend would be 341°, and then the interpreted plate displacement vector would be oriented 001°.

Plate reconstructions suggest that between 100 Ma and 75 Ma, the displacement vector of the Farallon plate with respect to North America underwent a clockwise rotation from about 035° to about 028° (Engebretson et al., 1985; Kelley and Engebretson, 1994). During the same period, the Kula plate may have been formed and would have undergone a relative displacement trending about 005° (Engebretson et al., 1985). If the plate kinematic analysis in the previous paragraph is correct, it would suggest that at 93 Ma, the relative displacement vector for the plate lying outboard of that part of the North American margin corresponding to the Cascades...
Crystalline Core would have been trending between 351° and 001°. Comparing to the interpretations of Engebretson et al. (1985): 1) if the Farallon plate was outboard of the study area during emplacement of the Mt. Stuart batholith, then our analysis would suggest the plate displacement vector may have undergone a greater rotation than proposed by the plate reconstructions, 2) if the Kula plate was outboard of the study area at that time, then our interpretations suggest a similar plate displacement vector to the one indicated by the plate reconstructions, which is 005°. Hence our analysis of the wrench dominated kinematic model, summarized above and in Fig. 5B, would be most compatible with a northward displacement of the Kula plate with respect to the southern extension of the Coast Plutonic Complex at 93 Ma.

The above plate kinematic analyses and the derivations of possible plate displacement vectors are based mainly on the fabric and structural analysis of the Mt. Stuart batholith, and they assume either a homogenous bulk regional pure shear, or a homogeneous transpression, ca. 93 Ma within the Cascades Crystalline Core. Furthermore, the second kinematic model (Fig. 5B) excludes partitioning of the transpression into transcurrent shear zones (Teyssier et al., 1995). If one or more of the major transcurrent shear zones, such as the Coast shear zone, that may have accommodated plate boundary-parallel displacements in the Coast Plutonic Complex in Cretaceous time (Hollister and Andronicos, 1997; Chardon et al., 1999) extended as far south as the Cascades Crystalline Core, then plate boundary-parallel displacements could have been partitioned into the shear zones during possible Cretaceous transpression. As a result, the plate boundary would be constrained to be oriented more closely to the maximum instantaneous strain axis (s1) (Teyssier et al., 1995), i.e. it would be rotated clockwise with respect to the plate boundary indicated in Fig. 5B. However, to our knowledge, no large-scale transcurrent shear zones of Cretaceous (or earlier) age have been mapped as far south as the present study area. Therefore, if a wrench dominated transpression model is applicable to the Cascades Crystalline Core, then we interpret Fig. 5B to be a reasonable approximation of plate kinematics at the time of emplacement of the Mt. Stuart batholith, based on the present data set.

8. Conclusions

Magnetic and field measurements of the pervasive magmatic foliation and lineation in the Cretaceous Mt. Stuart batholith suggest it underwent a NE–SW shortening and NW–SE stretching, parallel to regional folds, during emplacement and solidification ca. 93 Ma. Comparison of the results with previous structural and fabric analyses within and adjacent to the Mt. Stuart batholith suggests that the magnetic fabrics may record a small increment of finite strain, and that the fabric orientations can be interpreted to approximate the orientation of the instantaneous strain during the final stages of crystallization. The fabric and structural data have been used to fit the Mt. Stuart batholith, and the Cascades Crystalline Core, into the plate tectonic history along the North American margin, ca. 93 Ma. The results may indicate that the Mt. Stuart batholith was emplaced within part of an arc subjected to NE–SW shortening, orthogonal to a NW–SE trending plate boundary. Alternatively, based on considerations of the kinematics of transpressional deformations, the fabrics may indicate a boundary between either the Farallon or Kula plate and North America that had a NNW–SSE trend, and a NNW to N relative displacement vector for the outboard plate at the time of crystallization of the batholith.

The results demonstrate the potential usefulness of igneous fabrics and other magmatic structures in syntectonic plutons for analyses of regional deformations in orogenic belts, and possibly for determinations of plate kinematics associated with orogens. An extension of this type of tectonic analysis could involve mapping the magmatic fabrics in plutons of different ages within an orogenic belt, in order to investigate the strain history during successive short periods corresponding to the emplacement and crystallization of the magma bodies. Such future studies may provide information on the incremental strain histories of orogens.

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