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Large-scale coast-parallel displacements in the Cordillera: a granitic resolution to a paleomagnetic dilemma

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Abstract

Resolution of the 'Paleomagnetic dilemma', the discrepancy between large paleomagnetically determined dextral displacement of outboard portions of the northern Cordillera, and much smaller offsets implied by mapping and stratigraphic correlations, is fundamental to understanding the tectonic evolution of the Cordillera. This paper presents structural orientation data from the middle Cretaceous Dawson Range batholith of west central Yukon and its wallrocks, and suggests that some of the 'missing' displacement may be found in intrusions. The elongate northwest-trending batholith has a margin-parallel foliation, a sub-horizontal stretching lineation, and records syn-intrusive dextral shearing. In country rocks adjacent to the batholith, north-trending lineations are deflected clockwise into near parallelism with the batholith's margins; lineations from wallrock screens within the batholith are all aligned parallel with the batholith's long axis. The Big Creek strike-slip fault forms the north-margin of the batholith and accommodated a minimum of 20 km of dextral slip. These observations imply that the batholith invaded an active dextral shear zone, accommodated shearing while crystallizing, and focused post-crystallization fault development. The batholith is conservatively estimated to have accommodated 45 km of syn-intrusive shearing. Collectively, middle Cretaceous intrusions of the northern Cordillera may account for >400 km of previously unrecognized dextral displacement. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

An enduring enigma in the study of the Cordillera of North America is the discrepancy between paleomagnetically determined orogen-parallel displacements, and those based on mapping and cross-fault correlations (Cowan et al., 1997). Paleomagnetic results for post-accretionary Cretaceous intrusions and layered volcanic sequences of the Intermontane and Insular portions of the Cordillera (Fig. 1) record anomalously low magnetic inclinations relative to North America (Irving and Wynne, 1991; Irving et al., 1995). These data imply that the crust containing these units lay far to the south (1000–2000 km, and >3000 km, respectively) during crystallization. These interpretations conflict with regional and detailed mapping which has yet to reveal the faults along which these displacements occurred. Correlation of stratigraphy and structures across those faults that have been mapped, suggests that they have insufficient offset to account for the paleomagnetic data. Either the paleomagnetic data is being incorrectly interpreted, or structures accommodating some of the displacement are being systematically overlooked.

Recent plate-motion models and multi-disciplinary studies of flood basalts of the Cordillera have provided strong support for large-scale orogen-parallel displacements. Plate-motion models indicate that during the middle and Late Cretaceous, the motion of the oceanic plates that bound the Cordillera to the west included a large component of orogen-parallel, northward (dextral) displacement relative to North America (Engebretson et al., 1985; Johnston et al., 1996). Relative velocities peaked between 80 and 60 Ma, exceeding 20 cm/a to the north. At these rates, even

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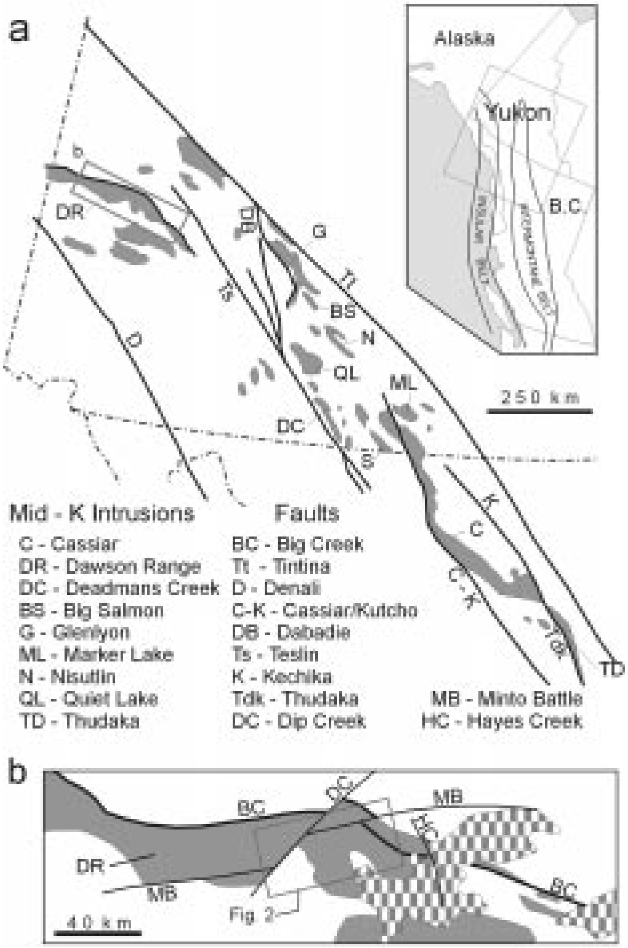

Fig. 1. (a) Distribution of mid-Cretaceous batholiths (grey) and associated faults in the northern Cordillera, after Woodsworth et al. (1991). Figure location, and Intermontane and Insular belts are indicated on inset map. (b) Detail of the Dawson Range batholith (grey). Metamorphic wallrocks in white, and Upper Cretaceous volcanics in stipple. Map location in (a).

partial coupling of the outboard portions of the Cordillera with the adjacent, north-moving oceanic plates can account for the paleomagnetically determined offsets.

During the Cretaceous, North America moved west in the hotspot reference frame, migrating over the Yellowstone hotspot. Mantle plume generated flood basalts erupted above the hotspot at 70 Ma (the Carmacks Group; Johnston et al., 1996) and 52 Ma (the Coast Range basalts; Babcock et al., 1992), providing pinning points for measuring subsequent orogen-parallel displacements. Crust onto which the Carmacks Group erupted was subsequently displaced 2000 km north of the hotspot track (Johnston et al., 1996), consistent with anomalously low magnetic inclinations recorded by this flood basalt (Wynne et al., 1999). The Coast Range basalts have experienced only minor northward translation.

Large-scale orogen-parallel displacements in the Cordillera are, therefore, a prediction of known plate motions. Independent confirmation of the large-scale orogen-parallel displacement is provided by offset of the Yellowstone hotspot-derived flood basalts. Thus, an increasing body of evidence indicates that the paleomagnetically determined offsets are correct. How then to account for the missing displacement? Sufficiently detailed map coverage exists to discount the idea that one or more major faults have been overlooked. In the northern Cordillera, many of the transcurrent faults responsible for accommodating some of the orogen-parallel displacements are spatially associated with elongate Cretaceous intrusions (Fig. 1). Previously these plutons have been interpreted as markers, and their displaced portions used to estimate fault offsets. Here I examine the tectonic setting and structure of the Dawson Range batholith of central southwest Yukon, and pose the question "Is a large proportion of the 'missing' orogen-parallel displacement in the Cordillera to be found in intrusions?".

2. The Dawson Range batholith

The Dawson Range batholith, west-central Yukon, is one of a large number of middle Cretaceous plutons that crop out across the northern Cordillera (Fig. 1). The elongate, west-northwest-trending batholith is ~250 km long by ~50 km wide, with a surface area of $>10\,000$ km^2. It intrudes north-dipping Devonian–Mississippian amphibolite-grade rocks of the pericratonic Yukon–Tanana terrane, and flat-lying mid-Cretaceous volcanic sequences, and is disconformably overlain by the Upper Cretaceous volcanic sequences of the Carmacks Group. The batholith includes equigranular quartz diorite and porphyritic granitic phases. U–Pb zircon age determinations imply crystallization of the quartz diorite phase at 105 Ma. K–Ar hornblende and biotite cooling ages of 100 Ma, from quartz diorite and granite, limit the magmatic event to a duration of 5 Ma (geochronological data summarized in Johnston, 1995). The batholith is cut by a number of strike-slip faults (Fig. 1).

The quartz diorite phase forms the bulk of the batholith, ranges from hornblende quartz diorite to biotite hornblende granodiorite, and is commonly coarsely crystalline and equigranular with 15–20% mafic minerals. Weak to moderately well-developed planar and linear fabrics, described below, are commonly developed. Quartz diorite forms concordant lenses that parallel the moderately north-dipping foliation in the metamorphic wallrocks. Because the metamorphic rocks are disconformably overlain by flat-lying mid-Cretaceous volcanic sequences, it is assumed that their north dip is a pre-mid Cretaceous feature, established

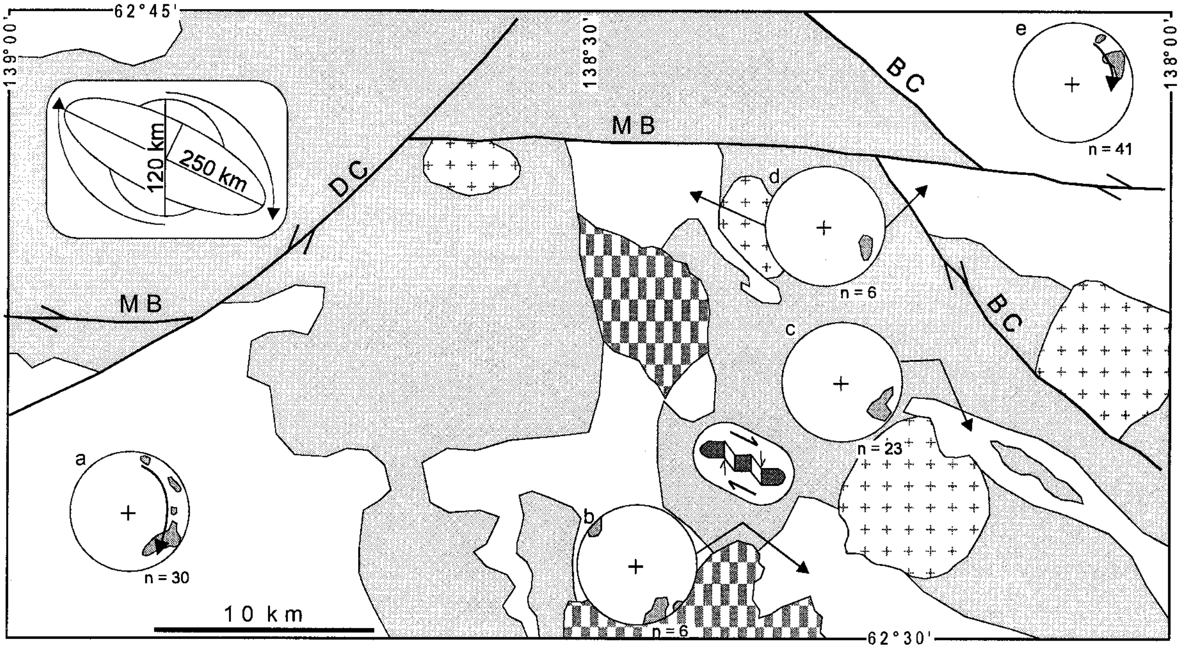

Fig. 2. Detail of part of the Dawson Range batholith (grey—quartz diorite; crosses—granite). Figure location in Fig. 1(b). Metamorphic wallrocks in white, and Late Cretaceous volcanics in stipple. Acronyms as in Fig. 1. Primary data source—Payne et al. (1987). Additional data from Johnston and Hachey (1993), Johnston (1995), and Johnston and Shives (1995). Stereonet plots show orientation data for lineations in metamorphic rocks. Domains a and e, which extend away from the batholith, show rotation of lineations (indicated by arrows) from regional north trend into parallelism with the batholith. Domains b–d immediately adjacent to and within the batholith (screens) are characterized by batholith-parallel lineations only. Insets show: a close-up of a hornblende grain (dark grey) pulled apart by extensional shears in a dextral sense; and a schematic diagram showing the stretch required to produce the elongate shape of the batholith (see text for discussion).

prior to intrusion. Contact-parallel screens of metamorphic rock >300 m thick and several kms in length are locally present within the batholith (Johnston and Shives, 1995). The coarse-grained equigranular texture of the quartz diorite, together with the concordant geometry of the intrusions, is consistent with emplacement at moderate crustal levels.

The granitic phase ranges from granite to quartz monzonite, and forms a volumetrically minor amount of the batholith. Pegmatitic and porphyritic textures are common, as are breccia and miarolitic cavities. Granite forms discordant dykes, veins and circular plugs. The porphyritic to pegmatitic texture, the presence of breccia and miarolitic cavities, and the discordant geometry of the intrusions, is consistent with emplacement at shallow crustal levels.

3. Structural elements

3.1. Wallrocks

The main planar fabric in the metamorphic rocks of the Yukon–Tanana terrane, consists of an Early Jurassic schistosity (Johnston and Erdmer, 1995) that dips homoclinally north to north-east throughout much of the Dawson Range (Johnston, 1995). A lineation defined by quartz rods, and aligned, elongate and stretched minerals pitches steeply, plunging regionally north to northeast (Tempelman-Kluit, 1974; Johnston and Erdmer, 1995). However, lineations from wallrocks adjacent to, and from screens within the batholith, trend dominantly east-southeast, parallel with the long axis of the batholith (Payne et al., 1987; Johnston, 1995). The wallrocks typically include a small number of lineations aligned parallel with the regional north trend, as well as a spread of lineations oriented between the regional trend, and the long axis of the batholith (Fig. 2).

3.2. Dawson Range batholith

Weak to moderately well developed planar and linear fabrics are restricted to the quartz diorite phase of the batholith. The foliation is defined by alignment of magmatic hornblende and plagioclase, and parallels and increases in intensity toward the margins of the batholith. Interstitial quartz is commonly strained, indicated by undulose extinction, reduced grainsize and sutured grain boundaries. In well foliated rocks, a weakly developed mineral lineation, defined by alignment of hornblende grains, parallels the long axis of the batholith (Payne et al., 1987). Locally cm-scale extensional shears have resulted in extension of horn-

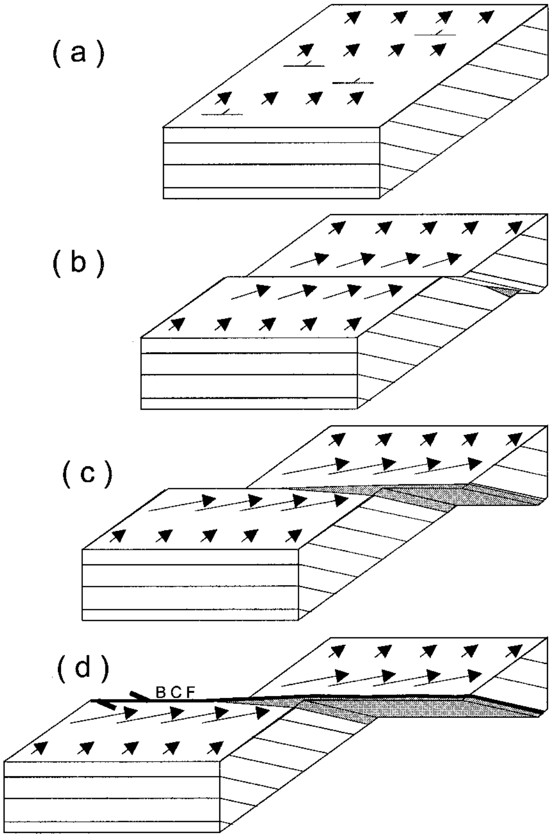

Fig. 3. Simplified model of syn-kinematic intrusion of the Dawson Range batholith (grey). (a) Pre-intrusion. Metamorphic terrane characterized by north dipping schistosity with a down-dip lineation (arrows). (b) Initial stages of intrusion. Wallrocks above the intruding batholith deform in a ductile manner (shear zone shown schematically as a discrete feature). Lineations are rotated into parallelism with the dextral shear zone. (c) Intrusion of the batholith. Dextral transcurrent motion accommodated by ductile to brittle–ductile shear of the crystallizing intrusion. (d) Post-crystallization. Continued dextral transcurrent motion results in the developement of the brittle Big Creek fault (BCF). The total dextral translation is more than double the measured offset along the BCF.

blende grains. Gaps in these elongated hornblende grains have been filled in by quartzo-feldspathic material (Fig. 2).

3.3. Faults

The Dawson Range batholith is cut by the Big Creek Fault, a west-northwest-trending, dextral strike-slip fault characterized by fractured, brecciated and mylonitized rock, that extends >300 km across central west Yukon (Figs. 1 and 2). Dextral displacement is indicated by offset markers, and by related macro- and micro-structures (Carlson, 1987; Payne et al., 1987). The fault is unconformably overlain by and pre-dates Upper Cretaceous basalt flows of the Carmacks Group (Fig. 1). For much of its length, the fault runs along and forms the northern boundary of the Dawson Range batholith. The amount of slip along the fault is poorly constrained. Restoration of a concave sliver of the batholith lying north of the fault to a position where it formerly formed a northward extending bulge (hence why it was cut off by the fault) requires a minimum of 20 km of dextral offset.

The batholith, the Big Creek fault, and the Carmacks Group, are cut by a number of Upper Cretaceous faults including the north-trending dextral Hayes Creek, the east-trending dextral Minto-Battle, and the southwest-trending sinistral Dip Creek faults (Johnston and Hachey, 1993; S. Johnston, unpublished data, 1995).

4. A model of syn-kinematic intrusion

Because the Dawson Range batholith is cut by the Big Creek fault, it is commonly considered to pre-date dextral, orogen-parallel translation of the outboard portions of the Cordillera. However, I propose that the batholith intruded during, and may in part have initiated, dextral shearing (Fig. 3). This model is suggested by the deflection of wallrock lineations, by the fabric development in quartz diorite, by the shape of the batholith, and by the association of the batholith with the Big Creek fault.

The southeasterly trends of wallrock lineations adjacent to the batholith are attributable to solid body rotation during ductile shearing. Prior to intrusion, lineations throughout the Dawson Range paralleled the regionally developed north plunge. Thermal softening of the terrane above the uprising magma may have localized ductile shearing, resulting in solid-body rotation of pre-existing structures. Shear-zone development in the area now occupied by the batholith is consistent with the observed spread of lineations from those preserving the original north trend, to those fully rotated into parallelism with the incipient shear.

The continued uprise of magma, indicating an overall extensional environment, subsequently engulfed the ductile shear zone, preserving the most highly rotated lineations within screens in the batholith. Extension may have been localized by a bend in the shear zone, or may have reflected a regional transtensional regime (cf. Gabrielse, 1985; Hansen et al., 1991). Fabric development within the batholith, including the alignment of magmatic grains and the development of a mineral lineation parallel with the long axis of the batholith, is attributable to dextral shearing of the mostly liquid intrusion.

Crystallization of quartz diorite initiated the transition from ductile to brittle deformation. Initial brittle deformation occurred while melt was still present in the system, resulting in quartzo-feldspathic in-fillings in brittle shears cutting hornblende grains. Ductile deformation of quartz probably occurred during the final stages of crystallization. Uplift of the batholith during this period, indicated by the shallow level of emplacement of the late stage granitic melts, was probably the result of crustal thinning within the overall transtensional environment. The development of the Big Creek Fault marked the final transition to brittle accommodation of the transcurrent motion (Fig. 3). Parallelism of the batholith and the fault imply little change in the orientation of the prevailing stress field.

Calculation of the amount of dextral slip accommodated during intrusion is difficult. The $>90°$ rotation of wallrock lineations during shearing requires a high degree of strain during ductile simple shear of the wallrocks. Dextral slip accommodated by the partly molten batholith and by late brittle–ductile deformation, accounts for the elongate shape of the batholith, its foliation, and the presence of a weak mineral lineation. The amount of slip necessary to produce these features is unknown. If it is assumed that the elongate shape of the intrusion is entirely attributable to syn-intrusive shearing, then the length of the batholith (250 km) provides a maximum estimate of syn-intrusive slip. This undoubtedly is an over-estimate: heterogeneity of the wallrocks, and regional extension probably contributed to the shape of the batholith. A cross-section of a cylindrical intrusion of the same volume as the Dawson Range batholith, would have a radius ≈ 60 km. A stretch factor of ~ 4, implying dextral slip of about 130 km, is required to elongate this circular section into an ellipse the length of the batholith (Fig. 2). If it is conservatively assumed that 35% of the elongate shape of the batholith is attributable to shearing, 45 km of dextral shear may have been accommodated by the batholith during intrusion. Given the maximum 5 Ma duration of the Dawson Range magmatic event, this amounts to a conservative slip rate of <1 cm/a.

Mid-Cretaceous intrusions, including the Dawson Range batholith, form the most voluminous plutonic suite in the northern Cordillera. Like the Dawson Range batholith, many of these plutons and batholiths are elongate, with length to width ratios of greater than 2.5, and are spatially associated with strike-slip faults (Fig. 1). For example, the Cassiar–Kutcho transcurrent dextral shear zone forms the west margin of the 350-km-long by 40-km-wide Cassiar batholith, and is characterized by a broad zone of mylonitization and brittle faulting. It is likely that, like the Dawson Range batholith, the bulk of these plutonic bodies are syn-kinematic intrusions. Estimates of the amount of displacement accommodated by their associated faults may, like the Dawson Range batholith and the Big Creek fault, be small in comparison to the amount of displacement accommodated by the intrusions themselves. The aggregate length of middle Cretaceous intrusions, including the Dawson Range batholith, is in excess of 2000 km. Assuming that the conservative ratio of displacement to length calculated for the Dawson Range batholith (0.2) is broadly applicable to all these intrusions, then they together account for >400 km of heretofore 'missing' displacement.

Calculation of the amount of slip accommodated by the Big Creek fault during the final brittle stage of dextral translation in the vicinity of the Dawson Range batholith is difficult. The long strike-length of the fault implies that the 20 km required to restore the offset portion of the batholith is a minimum. Either a greater amount of slip is required for proper restoration of the offset portion of the batholith, or the fault along which displacement of a portion of the batholith occurred is a late splay; the main branch of the fault may run along the north margin of the batholith for its entire length.

The large number of Upper Cretaceous faults spatially associated with the Dawson Range batholith–Big Creek fault, suggests that the mid-Cretaceous structures subsequently acted as zones of weakness, localizing younger displacements.

5. Conclusions

The Dawson Range batholith is estimated to have accommodated 45 km of dextral shear during syn-kinematic intrusion, double the minimum estimate of displacement (20 km) on the associated Big Creek fault. This conservative estimate does not take into account displacement attributable to pre-intrusive ductile shear responsible for the rotation of wallrock lineations. Nor does it adequately address the shearing accommodated by the batholith while in a largely liquid state. It is likely that the bulk of the intrusions of the middle Cretaceous plutonic suite are syn-kinematic; together they may have accommodated more than 400 km of dextral transcurrent slip.

The significant amount of displacement carried by syn-kinematic middle Cretaceous intrusions may account for at least some of the paleomagnetically determined estimates of northward translation of the outboard portions of the Cordillera. These findings suggest that cross-fault stratigraphic correlations that have been used to argue against the paleomagnetic data are incorrect. However, paleomagnetic studies of Upper Cretaceous layered volcanic sequences require a significant amount of post-70 Ma displacement (Johnston et al., 1996). The structures along which this displacement occurred have not been identified, and suitable syn-kinematic intrusions, in which the missing displacement might be located, are few. The spatial association of middle and Upper Cretaceous transcurrent faults within the Dawson Range suggests that the search for these younger structures should concentrate adjacent to identified middle Cretaceous structures.

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