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# On Determining Paleohorizontal and Latitudinal Shifts: Paleomagnetism of Spences Bridge Group, British Columbia

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The Spences Bridge Group of late Albian age (palynology and U/Pb zircon date of 104.5 Ma) is situated in the Intermontane Belt of the southern Canadian Cordillera. Zeolite-grade andesite lavas and interbedded volcaniclastic rocks have been sampled through a thickness of about 2900 m. Sampling has been confined to localities whose bedding attitudes are well defined and to rocks that have not undergone internal deformation. Of the 27 sites studied, 25 gave single-component magnetizations with well-grouped directions, high coercivities and high unblocking temperatures. Applying corrections for geological tilt to all 25 sites yielded minimum dispersion after 65% untilting. Analysis indicates that this is a consequence of the interaction of two modes of behavior, one (exhibited by *Y* magnetizations at 8 sites) in which minimum dispersion occurs after 35% untilting, and one (*X* magnetizations at 17 sites) in which minimum dispersion occurs after 100% correction. (Actually the dispersion is essentially constant in the range 88 to 100% correction). The *Y* magnetizations are uninterpretable in terms of the paleofield because no estimate of paleohorizontal can be made. Because of their positive response to the tilt test, the *X* magnetizations were acquired before tilting, and it is argued that geologically determined bedding planes are good estimators of paleohorizontal at the time of remanence aquisition. There may be errors because of paleoslope, but arguments are presented for believing that these are small. On this basis, the best estimate of the mean direction of the paleofield in Spences Bridge time is estimated to be $D, I$ (declination, inclination) = 38.7°, 63.9° (17 sites, $k = 44$ compared with $k = 11$ in situ, $\alpha_{95} = 5.4°$) with a paleopole at 64.4°N, 321.0°E ($K = 24$ compared with $K = 5$ in situ, $A_{95} = 7.5°$). When compared with the cratonic reference field for mid-Cretaceous time, this pretilting magnetization indicates a clockwise rotation of the study area of 66.3° ± 11.8 ($P = 0.05$), and an apparent displacement from the south of 15.5° ± 7.1 (1725 ± 790 km). When these, and other data previously obtained from Cretaceous rocks of the Pacific Northwest, are compiled, they show an increase in apparent displacement from east to west across the Cordillera. This result is discussed in terms of three hypotheses: (1) no translation but systematic tilts of about 30° to the southwest; (2) translation of a substantial part of the Pacific Northwest (referred to as Baja British Columbia and is defined more exactly in the text) by variable amounts up to more than 2000 km from the south together with clockwise rotations; and (3) lesser translation of Baja British Columbia by about 1500 km combined with variable tilting predominantly to the south. It is concluded that paleomagnetic data, as they are presently known, are consistent with hypotheses 2 and 3, but, unless serious sources of error are present, are not consistent with hypothesis 1. The most likely candidate for such errors is the uncertainty in estimating initial dip of beds (paleoslope) in volcanic rock units.

## INTRODUCTION

Success in interpreting paleomagnetic data depends critically on being able to determine the attitude of the paleohorizontal plane at the time of remanence acquisition. Unless this can be done, paleolatitudes and hence displacements cannot be determined accurately. In this paper we describe new data from the bedded mid-Cretaceous Spences Bridge Group of British Columbia that relate to this general problem and to possible northward displacements in the Pacific Northwest.

Paleomagnetic directions (paleodirections) from mid-Cretaceous plutonic rocks of the Western Cordillera of North America commonly do not agree with those from coeval rocks of cratonic North America. In the Pacific Northwest, systematic discordances have been found in the rock bodies labelled AX, CS, P, SP, MS in Figure 1 where their names are given. All but one of these bodies contain no internal evidence of the attitude of the paleohorizontal. Their directions of magnetization

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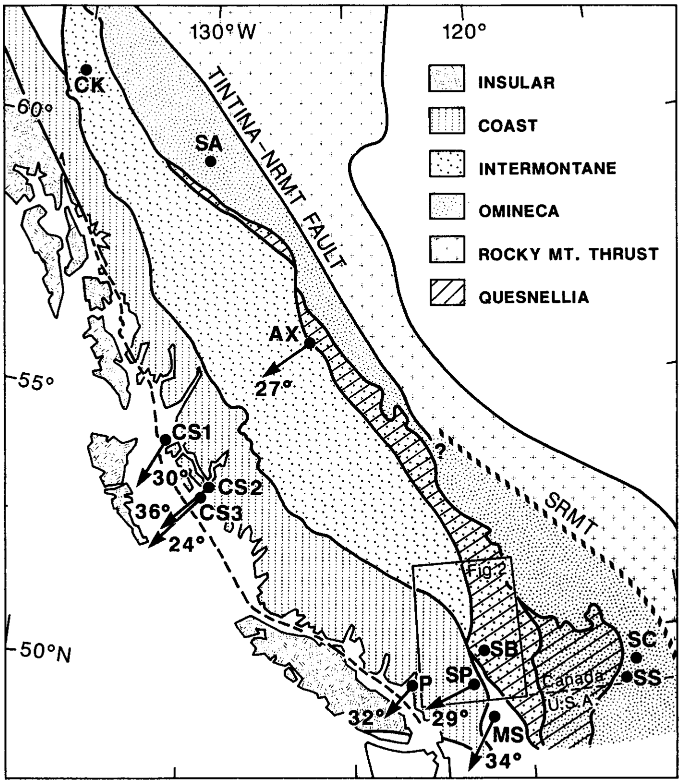

**Fig. 1. Morphotectonic belts of Cordillera of Canada and northern Washington and the Quesnellia Terrane. Locations of paleomagnetic studies of Cretaceous rocks labeled as in Table 4. Localities in plutonic rocks have arrows denoting the direction and magnitude of the tilt required to make their mean paleodirections agree with those expected from mid-Cretaceous rocks of the craton. These arrows represent the tilt hypothesis (hypothesis 1). NRMT and SRMT are the Northern and Southern Rocky Mountain Trenchs, respectively. Quesnellia straddles two belts.**

cannot therefore be corrected accurately for postemplacement tilt, and, as a consequence, the discordances are open to several interpretations [*Beck and Noson*, 1972; *Beck et al.*, 1981*a, b; Irving et al.*, 1985; *Butler et al.*, 1989]: (1) that there has been systematic tilting by about 30° down to the southwest over an area of about 600 km by 300 km (Figure 1); (2) that there has been 60° clockwise rotation and more than 2000 km coastwise translation of the region from the south; and (3) that some combinations of translation and tilting has occurred.

The absence of evidences of relict Late Cretaceous or Tertiary ocean basins between the region exhibiting discordant magnetizations and ancestral North America indicates that if northward motion (hypotheses 2 and 3) has occurred, then it was likely to have been in a coastwise sense. Such motion is likely to have been driven, either by transform motion as Baja California is today [*Atwater*, 1970], or by oblique convergence of oceanic plates and North America, analogous to the tectonics of the present day Sunda Arc [*Fitch*, 1972; *Beck*, 1983, 1986]. This hypothetical northward moving region, which comprises the Insular, Coast and Intermontane belts of Figure 1, has been referred to as Baja British Columbia [*Irving*, 1985; *Umhoefer*, 1987; *Umhoefer et al.*, 1989*b*; *Irving and Wynne*, in press]. Baja British Columbia is not envisaged as a rigid plate but is considered to have undergone extensive faulting and attenuation during its movement northward [*Irving et al.*, 1985].

A solution to this problem is important to our understanding of Cordilleran tectonics. Systematic tilts (hypothesis 1) could have been produced by extension resulting in the segmentation and rotation of crustal blocks [*Wernicke*, 1985] above northeast-dipping crustal shears. Such shears, which have not been identified, would have to be first-order structures. Similarly, if tilting was caused by compression, as *Irving and Massey* [1990] have inferred in intrusions of the Metchosin Complex of southern Vancouver Island, then such rotations would provide important constraints on possible mechanisms of contractional deformation. On the other hand, if large-scale northward translation and clockwise rotation occurred (hypotheses 2 or 3), they will have had profound influence on the tectonic evolution of the entire North American Cordillera [*Umhoefer*, 1987; *Umhoefer et al.*, 1989*a*, *b*].

There are several ways in which attempts may be made to solve this problem. One approach is to seek for geological confirmation of one or other of the hypotheses. Unfortunately, geological opinion is widely divided. Compare, for example, geological analyses of *Umhoefer* [1987] and *Umhoefer et al.* [1989*b*] who wrote favorably about large-scale northward displacement of Baja British Columbia, with those of *Price and Carmichael* [1986] and *Butler et al.* [1989] who argued against it. Another approach, and one with which we will be principally concerned herein, is to attempt a separation of the effects of translation and tilt by obtaining paleodirections from bedded sequences whose tilt can be measured. Conceptually simple, this task is proving to be technically very difficult because of the common occurrences in the Cordillera of pretilt, syntilt or postilt magnetizations often in the same bedded sequence [*Granirer et al.*, 1986].

Recently *Marquis and Globerman* [1988] have estimated 1500 ± 950 km of northward movement from the paleomagnetism of bedded volcanic rocks of the Carmacks Group (70 Ma) of the northern Intermontane Belt (CK of Figure 1). Their data pass the tilt test, so that syntilting and posttilting magnetizations are either absent or neglible. One weakness in their argument, which they acknowledged, was that the cratonic reference field for the latest Cretaceous is less secure than that for mid-Cretaceous time. This weakness has to some extent been lessened by the recent publication of new cratonic data as will be described below [*Swenson and McWilliams*, 1989]. The Carmacks Group is 30 Ma younger than plutons from which the discordances of Figure 1 have been observed. The data we are about to describe are from a 2900-m sequence of bedded mid-Cretaceous rocks, the Spences Bridge Group, that are essentially coeval with these plutons. The rocks are located in the southern part of the Intermontane Belt (SB of Figure 1).

## TECTONIC SETTING

Traditionally, the Canadian Cordillera has been divided into five morphogeologic belts arranged in a generally NW-SE configuration. These belts are distinguished on the basis of their geology and physiography, and have complex geological histories extending from Precambrian to present. More recently it has been recognized that the region may be subdivided into numerous terranes, i.e., fault-bounded regions that are geologically distinct from one another [*Monger et al.*, 1982; *Coney et al.*, 1980]. Some terranes are confined within a single belt; others overlap adjacent belts. Quesnellia, one of the largest terranes, lies on both sides of the boundary between the Intermontane and Omineca belts (Figure 1). Our paleomagnetic sampling area is located in the western part of the Quesnellia, within the Intermontane Belt (SB of Figures 1 and 2).

As indicated by linkages, such as sedimentary provenance and stratigraphic overlap, many terranes were amalgamated with one another and accreted (not necessarily in their present positions) to ancestral North America by mid-Cretaceous time [e.g., *Monger et al.*, 1982; *Thorkelson and Smith*, 1989]. Subsequently, this tectonic collage evolved, by continuing tectonism and magmatism [*Armstrong*, 1988] to form the five morphogeologic belts.

## GEOLOGY, AGE, SAMPLING

The Spences Bridge Group is a mid-Cretaceous (late Albian, see below) volcanic succession in southwestern British Columbia (Figures 2 and 3). It is preserved in the Nicoamen synclinorium as a 215-km long belt, extending from near the Canada-United States border to almost 51°N [*Monger*, 1985, 1986; *Thorkelson and Rouse*, 1989]. There it is cut by the Fraser fault system (ffs of Figure 2), along which about 100 km of dextral strike-slip occurred

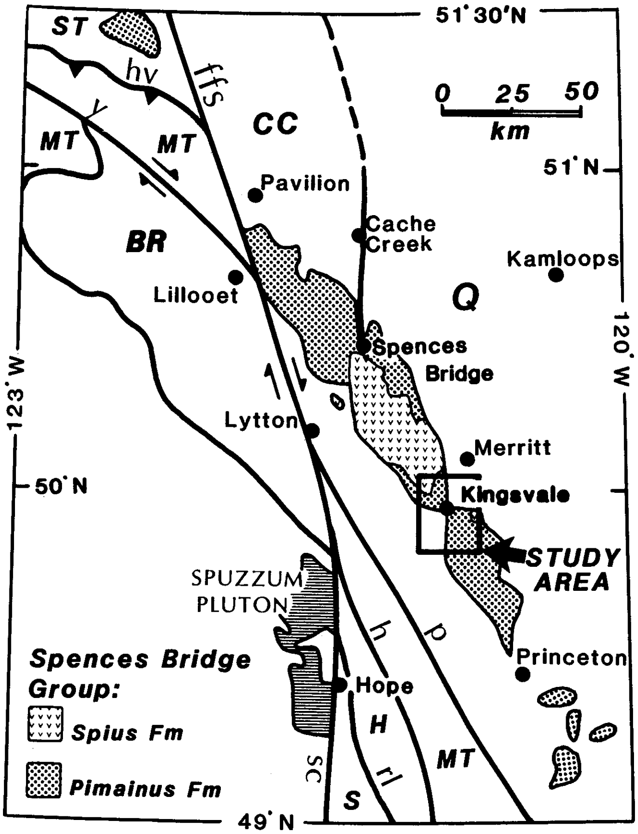

Fig. 2. Distribution of the Spences Bridge Group (and correlative rocks) and the position of Spuzzum pluton in relation to major tectonic elements of southwestern British Columbia. Terranes: Q = Quesnel; CC = Cache Creek; ST = Stikine; MT = Methow-Tyaughton; BR = Bridge River; H = Hozameen; S = Skagit. Faults: ffs = Fraser fault system; sc = Straight Creek; hv = Hungry Valley; y = Yalakom; rl = Ross Lake; h = Hozameen; p = Pasayten. Modified from *Monger* [1985] and *Kleinspehn* [1985].

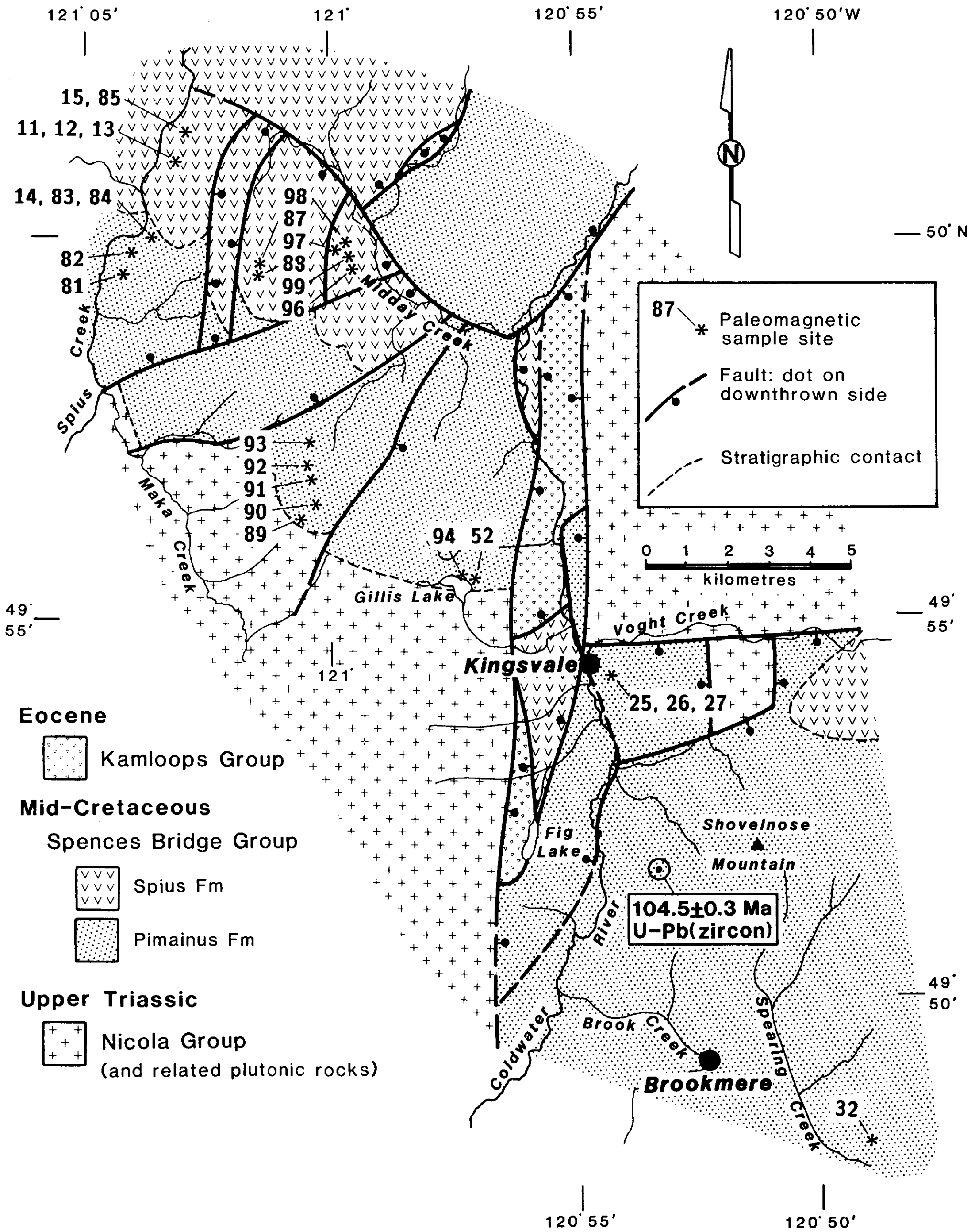

**Fig. 3.** Geology of the study area and location of paleomagnetic sample sites. Faults bounding Eocene Kamloops Group strata were active during the Eocene. Other faults may also be of Eocene age, but a protracted history of activity is probable as explained in text. Modified from *Thorkelson* [1985].

in Paleogene time [*Mathews and Rouse*, 1984; *Kleinspehn*, 1985; *Monger*, 1985, 1986]. An outlier of mid-Cretaceous volcanic rocks west of the Fraser fault system and north of the Hungry Valley fault (hv on Figure 2) depositionally overlies the southern tip of Stikinia [*Wheeler and McFeely*, 1988]. Reversing the offset on the Fraser fault system places this outlier adjacent to the truncated northern end of the Spences Bridge Group. If this outlier and the Spences Bridge Group are correlated, as suggested by *Mathews and Rouse* [1984], *Thorkelson and Smith* [1989] and K. Green (personal communication, 1990), then the volcanic belt overlaps parts of the Quesnel, Cache Creek and Stikine terranes, linking them together by late Albian time.

## *Stratigraphy and Petrology*

The Spences Bridge Group comprises two formations (Figure 4), the lower of which, the

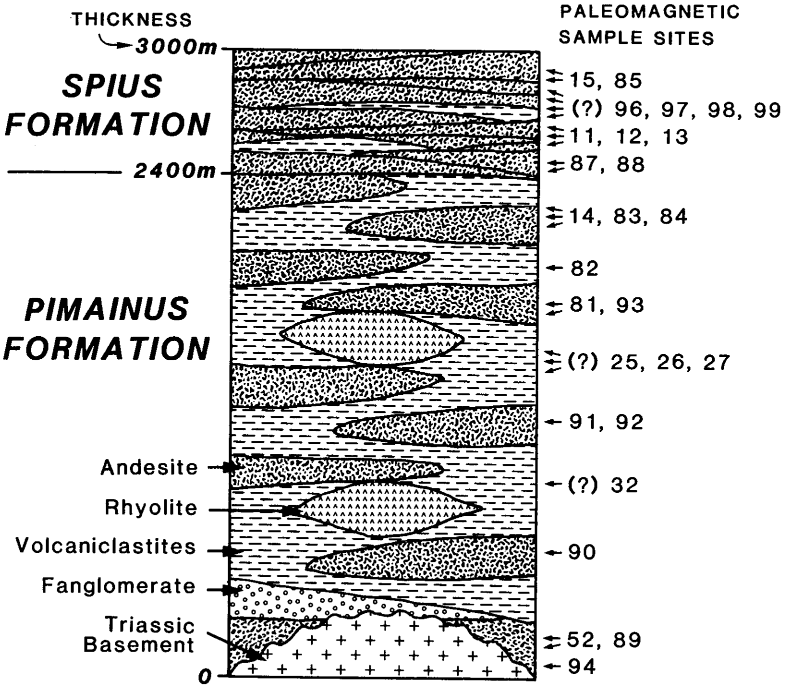

**Fig. 4.** Generalized stratigraphy of the Spences Bridge Group in the study area, showing approximate stratigraphic positions of sample sites. Question marks denote poorly constrained or speculative assignments. Points of interest are (1) the lithologic diversity of the Pimainus Formation and relative homogeneity of the Spius Formation; (2) the unconformity between the Pimainus Formation and Triassic basement; (3) the fanglomerate, rich in basement clasts, above the basal andesitic unit; (4) the conformable relations between Pimainus and Spius formations; and (5) the thinner and more amygdaloidal lava flows of the Spius Formation.

Pimainus Formation, is a composite succession of basaltic to rhyolitic lavas and intercalated clastic rocks [*Rice*, 1947; *Duffell and McTaggart*, 1952; *Thorkelson and Rouse*, 1989]. The mafic lavas are generally dense and contain phenocrysts of plagioclase, orthopyroxene, clinopyroxene and magnetite (Figure 5*a*). In hand specimen the andesites are gray with a bluish or reddish tinge. During drilling the mud produced varies from gray to reddish brown. Finely disseminated hematite is a common constituent. Primary volcanic textures are preserved, and there is no evidence of secondary petrofabrics [*Devlin*, 1981; *Thorkelson*, 1986]. Metamorphic grades are within the zeolite facies [*Devlin*, 1981]. None of the flows sampled show evidence, in either thin section or in outcrop, of internal deformation. In places slickensides are associated with some faults, but such outcrops have been deliberately avoided. Clastic deposits, which constitute about half of the formation, include air-fall and ash-flow tuff, lahar, conglomerate, sandstone and shale. Calc-alkaline major and trace element characteristics suggest a subduction-generated origin [*Thorkelson*, 1985, 1987; *Smith*, 1986; *Thorkelson and Smith*, 1989].

The overlying Spius Formation is geographically located in the center of the main Spences Bridge Group outcrop, but correlative rocks may occur in the northwestern outlier (Figure 2, K. Green, personal communication, 1990). It differs in several ways from the Pimainus. It is more uniform, lava flows are entirely andesitic, and intercalated epiclastic rocks are scarce. Compared to lavas in the Pimainus, the Spius flows tend to be thinner and much more amygdaloidal, and commonly they contain serpentine pseudomorphs of olivine phenocrysts (Figure 5*b*). Greater concentrations of high field strength trace elements suggest derivation from mantle that was less affected by subduction than that from which Pimainus magmas were derived [*Thorkelson and Smith*, 1989].

### *Age*

The age of the Pimainus Formation, as determined by palynomorphs and fossil leaves, is late Albian, about 100 Ma [*Thorkelson and Rouse*, 1989]. Greater abundance and diversity of early angiosperm palynomorphs in the Spius than in the Pimainus Formation suggests that the Spius was deposited in latest Albian time. Hence Spences Bridge Group deposition probably spanned a few million years, sufficient to average paleosecular variation.

Rock for U-Pb dating was collected from plagioclase-quartz phyric rhyolitic lava of the Pimainus Formation on the western slope of Shovelnose Mountain (Figure 3). The rhyolite forms part of a composite succession, locally

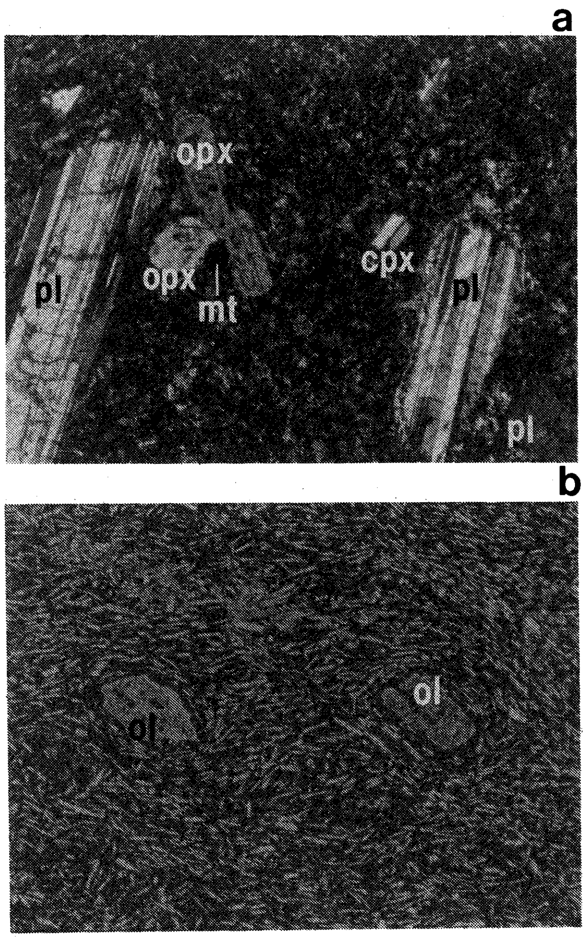

Fig. 5. Photomicrographs of the Spences Bridge Group: (*a*) typical andesite of the Pimainus Formation, showing phenocrysts of plagioclase (pl), clinopyroxene (cpx), magnetite (mt), and chloritized orthopyroxene (opx), in groundmass of plagioclase, pyroxene and magnetite (crossed polarizers); (*b*) basaltic andesite of Spius Formation, showing serpentinized phenocrysts of olivine (ol) within groundmass of flow-aligned microlites of plagioclase (plane light). Length of both photographs is 3 mm.

dominated by felsic flows, which unconformably overlies older Mesozoic plutonic rocks, and to the northeast conformably underlies amygdaloidal lavas of the Spius Formation. Its exact stratigraphic position within the Pimainus is uncertain.

Zircons, separated from 15 kg of rock, were selected for analysis on the basis of their clarity, igneous euhedral character, and relative lack of inclusions. All zircons were abraded by the method of *Krogh* [1982] and subsequently were processed at the Geological Survey of Canada geochronological laboratory, using procedures described by *Parrish et al.* [1987]. The data are given in Table 1 and Figure 6. Errors have been calculated by the method of *Roddick* [1987], in which an attempt is made to include all sources of uncertainty. Pb and U blanks were 10 and 5 pg, respectively.

Two out of three analyses (*A* and *C*) are concordant, yielding an age of 104.5 ± 0.3 Ma, the error reflecting the general overlap with the concordia curve. We interpret this date as the age of zircon crystallization and lava eruption. The age is in excellent accord with that determined from fossils. It is also consistent with slightly younger K/Ar hornblende (97 Ma) and biotite (97 and 98 Ma) dates from granitic stocks that cut the Spences Bridge Group 40 km to the southeast of the sampling area [*Preto*, 1979]. A third zircon fraction (*B*) is discordant, and reflects zircon inheritance in the magma. A line from 104.5 Ma through this discordant fraction intersects concordia at 544 ± 80 Ma, which may indicate contamination by Paleozoic or possibly older rocks present beneath the sampling area, but its actual significance is uncertain.

### *Structure*

The Spences Bridge Group was unconformably deposited, in a terrestrial environment, on older stratified and plutonic rocks. The Pimainus Formation may have formed as a set of coalescing stratovolcanoes and intervening fluvio-lacustrine waterways. The Spius Formation, dominated by eruptions of fluid andesite, probably accumulated to form a large shield. The rocks are deformed into open folds and fault-bounded tilted blocks [*Duffell and McTaggart*, 1952; *Monger and McMillan*, 1984; *Monger*, 1985]. Contact relations between the formations vary, from unconformable near Spences Bridge [*Devlin*, 1981], to conformable and gradational near Kingsvale [*Thorkelson*, 1985]. These relationships suggest that at least some of the deformation occurred during accumulation [*Monger*, 1985]. Such synvolcanic deformation may have partly controlled volcanomorphology, stratigraphic thicknesses and facies distributions.

The study area was chosen because it has been mapped in detail, bedding attitudes are known well, and because it represents the thickest known section of the group, about 2900 m. Oriented drill core samples were taken from 27 sites (Figure 3, Table 2). Each sampling site is either a single lava flow or a sedimentary bed. Almost all sites are from different stratigraphic levels. The lavas may be expected to represent separate points in time. However, we cannot definitely rule out the possibility that some sequences of lava flows, especially those along Spius Creek where intercalated rocks are scarce, acted as single cooling units. Massive unfractured rock was always chosen, and no samples were taken near faults or in areas showing signs of metasomatism or metamorphism above zeolite grade. Twenty-two of the sites were in andesitic lava flows. The remaining five sites (11, 25, 26, 27, 32) were in well-bedded epiclastic rocks. Bedding attitudes at each site were known either from previous mapping [*Thorkelson*, 1986] or

**TABLE 1. U-Pb Age of Zircons From Rhyolite of the Pimainus Formation**

| Fraction | *A* | *B* | *C* |
|---|---|---|---|
| Weight mg* | 0.101 | 0.204 | 0.150 |
| U, ppm | 200.4 | 183.8 | 178.1 |
| Pb,† ppm | 3.387 | 3.244 | 3.019 |
| 206Pb/204Pb‡ | 1058 | 1895 | 1643 |
| Pb§pg | 20 | 22 | 17 |
| $^{208}$Pb† % | 12.8 | 13.2 | 13.0 |
| $^{206}$Pb/$^{238}$U | 0.01634<br>(±0.09) | 0.01698<br>(±0.09) | 0.01635<br>(±0.10) |
| $^{207}$Pb/$^{235}$U | 0.1083<br>(±14.0) | 0.1137<br>(±12) | 0.1085<br>(±12) |
| Correlation coefficent | 0.8139 | 0.8729 | 0.8380 |
| $^{207}$Pb/$^{206}$Pb | 0.04806<br>(±0.09) | 0.04857<br>(±0.06) | 0.04812<br>(±0.07) |
| 207/206 age, Ma | 102.2<br>(+4.1/-4.1) | 127.0<br>(+2.9/-2.8) | 105.2<br>(+3.1/-3.2) |

See Figure 3 for locality. Standard errors of means are given in percent except the 207/206 age error which is twice the standard error of the mean,

*Weighing error 0.002 mg,

†Radiogenic Pb,

‡Measured ratio, corrected for spike and fractionation,

§Total common Pb in analysis corrected for spike and fractionation.

from investigations at the time of sampling. Dips of up to 65° occur in a variety of directions. The approximate stratigraphic position of each site is indicated in Figure 4.

The study area is dissected by numerous block faults. Some of these, notably the north-trending strands bounding Eocene strata near Kingsvale, were active in Eocene time [*Thorkelson,* 1989]. Elsewhere syndepositional faulting is indicated by the presence of granitoid clasts, derived from the underlying Triassic basement, in fanglomerate overlying the basal andesitic lava near Gillis Lake

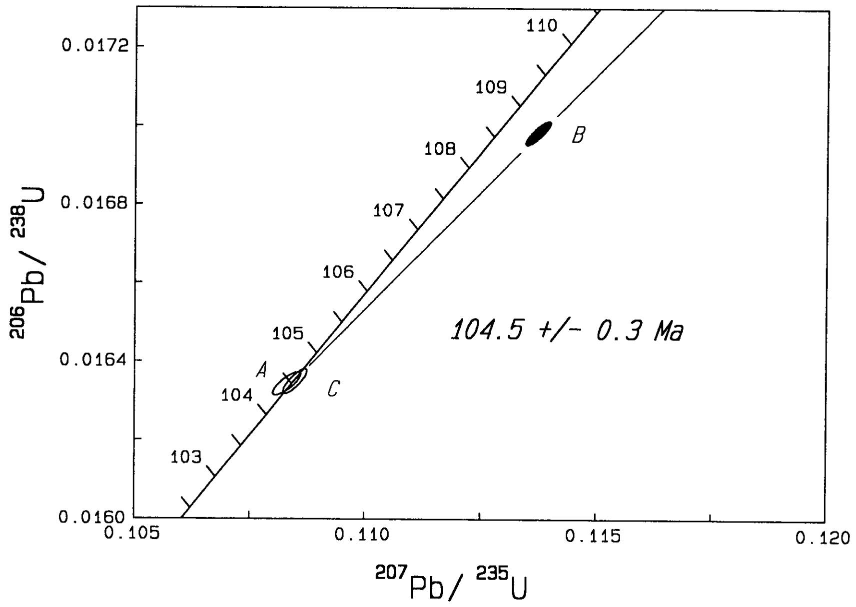

Fig. 6. U-Pb concordia diagram for zircons from sample PCA-TI-88-SB. The age and error indicated are derived from the overlap of analyses *A* and *C* with the concordia curve. Ellipses are 2 standard errors of the means (see Table 1 for details).

TABLE 2. Data by Sites

| Site | Rock | lat.°N, long.°W | BD°, BDDA° | n, s | $D°_0, I°_0$ | $D°_c, I°_c$ | $k$ | $\alpha^{\circ}_{95}$ | $d^{\circ}_1$ | $d^{\circ}_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *X Magnetization, Predominantly Pretilting* | | | | | |
| 32 | vol.ss. | 49°48.0', 120°49.2' | 17, 058 | 6, 9 | 024, 72 | 041, 58 | 127 | 6 | 12 | 9 |
| 52 | and. | 49°55.5', 120°57.2' | 65, 010 | 5, 10 | 147, 49 | 053, 49 | 42 | 8 | -2 | -1 |
| 81 | and. | 49°59.4', 121°04.5' | 40, 090 | 6, 10 | 303, 64 | 051, 68 | 50 | 7 | 9 | 6 |
| 82 | and. | 49°59.8', 121°01.2' | 40, 090 | 6, 8 | 284, 66 | 071, 72 | 168 | 4 | 10 | 5 |
| 85 | and. | 50°01.4', 121°02.3' | 23, 331 | 7, 12 | 081, 69 | 024, 65 | 56 | 6 | 6 | 9 |
| 87 | and. | 49°59.7', 121°01.5' | 25, 049 | 6, 10 | 285, 74 | 008, 69 | 631 | 2 | -12 | -15 |
| 88 | and. | 49°59.4', 121°01.6' | 25, 049 | 5, 6 | 200, 79 | 068, 74 | 201 | 5 | -12 | -14 |
| 89 | and. | 49°56.2', 121°00.5' | 28, 045 | 6, 10 | 053, 83 | 047, 55 | 161 | 4 | 14 | 11 |
| 90 | and. | 49°56.5', 121°00.3' | 28, 045 | 7, 10 | 329, 80 | 026, 58 | 88 | 5 | 8 | 5 |
| 91 | and. | 49°56.8', 121°00.5' | 28, 035 | 5, 8 | 013, 81 | 029, 54 | 78 | 6 | 15 | 13 |
| 92 | and. | 49°56.9', 121°00.6' | 29, 054 | 5, 10 | 311, 81 | 035, 62 | 481 | 2 | 7 | 3 |
| 93 | and. | 49°57.2', 121°00.7' | 27, 045 | 4, 5 | 313, 72 | 009, 58 | 817 | 3 | -2 | -6 |
| 94 | and. | 49°55.6', 120°57.3' | 65, 010 | 6, 6 | 138, 52 | 051, 43 | 49 | 10 | 0 | 3 |
| 96 | and. | 49°49.5', 120°59.6' | 30, 134 | 5, 7 | 349, 53 | 039, 70 | 168 | 5 | 4 | 2 |
| 97 | and. | 49°49.8', 120°59.9' | 30, 134 | 7, 13 | 347, 57 | 049, 73 | 49 | 6 | 9 | 7 |
| 98 | and. | 49°49.9', 120°59.7' | 30, 134 | 9, 11 | 338, 47 | 012, 71 | 105 | 5 | -9 | -12 |
| 99 | and. | 49°49.7', 120°59.5' | 30, 134 | 7, 8 | 351, 58 | 054, 71 | 148 | 5 | 13 | 10 |
| | | | | | *Y Magnetization, Posttilting or Syntilting* | | | | | |
| 11 | vol.ss. | 50°00.9', 121°03.4' | 25, 345 | 6, 12 | 021, 73 | 010, 66 | 201 | 3 | 28 | 28 |
| 12 | and. | 50°00.9', 121°03.4' | 25, 345 | 7, 13 | 056, 81 | 022, 76 | 216 | 3 | 18 | 19 |
| 13 | and. | 50°00.9', 121°03.4' | 25, 345 | 7, 14 | 068, 80 | 030, 76 | 165 | 3 | 16 | 17 |
| 14 | and. | 50°00.1', 121°03.8' | 30, 345 | 5, 10 | 086, 73 | - | 23 | 10 | - | - |
| 15 | and. | 50°01.6', 121°02.5' | 23, 345 | 7, 12 | 086, 57 | - | 13 | 13 | - | - |
| 25 | tuff | 49°54.4', 120°54.2' | 28, 165 | 5, 6 | 346, 72 | 347, 81 | 127 | 6 | 49 | 49 |
| 26 | tuff | 49°54.4', 120°54.2 | 28, 165 | 5, 10 | 007, 54 | 014, 63 | 53 | 7 | 17 | 16 |
| 27 | tuff | 49°54.3', 120°54.2' | 28, 165 | 5, 8 | 011, 63 | 026, 71 | 181 | 4 | 34 | 32 |
| 83 | and. | 50°00.1', 121°03.8' | 30, 345 | 6, 9 | 050, 75 | 025, 68 | 38 | 8 | 25 | 27 |
| 84 | and. | 50°00.2', 121°03.8' | 30, 345 | 4, 6 | 050, 77 | 023, 70 | 62 | 9 | 24 | 26 |

Sites numbers have no stratigraphic significance. In the second column, rock -types are as follows: and. = andesite; vol. ss. = volcanigenic sandstone. BD, BDDA are the bedding dip and bedding down-dip azimuth, *n, s* are the number of oriented cores and specimens cut from them. $D°, I°$ are the declination and inclination, $D°_0, I°_0$ relative to the present horizontal plane and $D°_c, I°_c$ after application of bedding corrections required to achieve minimum dispersion of VGPs, 100% for *X* magnetization, 34% for *Y* magnetization. Fisher's estimate of precision is $k$ and $\alpha^{\circ}_{95}$ the error ($P = 0.05$). Quantities $d^{\circ}_1$and $d^{\circ}_2$ are defined in the text, respectively, relative to paleopole obtained after 100% correction of all sites ($N = 25$) and relative to mean paleopole after 100% correction for *X* data ($N = 17$ sites). Magnetizations have been obtained, either by cleaning at single field strengths or temperatures, or by least-squares line fitting (using the program LINEFIT) to data obtained within certain ranges as follows: site 11 line-fitting between 20 and 100 mT (11 specimens) and between 300° and 600°C (1 specimen); 12 20-100 mT (12), 300°-650°C (1); 13 20-100 mT (13), 150°-650°C (1); 14 20-100 mT (6), 300°-650°C (4); 15 20-100 mT (2), 300°-650°C (10); 25 20-100 mT (3), 300°-650°C (3); 26 30-100 mT (4), 400°-600°C (6); 27 20-60 mT (1), 300°-600°C (7); 32 30 mT (7), 500°C (2); 52 81 40 mT (9), 550°C (1); 82 60 mT (7), 550°C (1); 83 60 mT (8); 550°C (1); 84 60 mT (5), 500°C (1); 85 20-100 mT (11); 500°-600°C (1); 87 50 mT (9); 550°C (1); 88 40 mT (4), 550°C (2); 89 40 mT (8), 550°C (2); 90 40 mT (8), 550°C (2); 91 40 mT (6), 550°C (2); 92 40 mT (8), 550°C (2); 93 40 mT (4); 94 30 mT (5), 500°C (1); 96 60 mT (5), 500°C (2); 97 50 mT (11), 500°C (2); 98 60 mT (10), 550°C (1); 99 40 mT (7), 550°C (1).

(Figures 3 and 4). In addition to faulting, open folding related to development of the Nicoamen synclinorium also occurred [*Duffell and McTaggart*, 1952; *Monger*, 1985]. Hence the degree to which syndepositional and postdepositional deformational processes have contributed to the present bedding attitudes is generally not known.

### *Paleoslope*

Composite volcanic strata, such as those of the Pimainus Formation, commonly accumulate to form volcanoes with of slopes ranging up to 30° [*Cas and Wright*, 1987, p. 38]. The presence of paleoslopes will introduce errors into the bedding corrections applied to paleodirections. There are two questions to consider: were paleoslope angles large or small, and were paleoslopes systematic (collecting sites from the same face of volcanoes) or random (sites from several faces of volcanoes) in direction? Regarding the second, it is possible that the areal and stratigraphic extent of sampling (Figures 3 and 4) is not sufficient to average out paleoslope effects.

Pimainus samples were taken from sequences which were deposited on gently sloping surfaces probably less than 10°, perhaps near the base of a stratocone. That initial dips were low is indicated by columnar jointing in many of the lava flows, especially those at sites 89 to 93. There jointing has a consistent orientation through hundreds of meters of stratigraphic thickness and extends over 2 km along strike. Moreover, the jointing is perpendicular to flow banding that is itself parallel to bedding in intercalated volcaniclastic sandstone. At other sites, notably at 25, 26, 27 and 32, and near sites 52 and 94, clastic rocks include organic-rich siltstone and coal, which implies that paleoslopes were gentle (see photograph of site 25 by *Thorkelson and Rouse* [1989, Figure 5]. At the five remaining Pimainus sites (14, 81–84), columnar joints and clastic rocks are scarce, and it is not possible to say what the angle of paleoslope might have been. Nevertheless, in the entire sampling area northwest of Kingsvale, dykes are uncommon and stocks and rhyolitic lavas absent, implying that this part of the Pimainus was deposited away from steep-flanked eruptive edifices.

The earliest flows of the Spius Formation probably inherited gentle paleoslopes from the Pimainus Formation upon which they conformably rest. As these frothy, fluid lavas accumulated to form a large shield [*Thorkelson and Rouse*, 1989], primary dips probably remained low, perhaps less than 5° or at most 10° [*Williams and McBirney*, 1979, p. 197].

In spite of these evidences that the paleoslopes at the sampling sites may have had different directions and that they were small in magnitude, their effects cannot at present be quantified, and it remains a possibility that errors in bedding corrections due to paleoslope have systematically affected the data described below.

## PALEOMAGNETIC DATA

Measurements were made on Schonstedt spinner magnetometers to which are attached computer controlled devices that automate specimen manipulation and data acquisition. Batches of 15 are measured unattended. Stepwise thermal, and alternating field (AF) demagnetization was carried out using standard equipment. Cores were oriented by sun and magnetic compasses.

The intensity of natural remanent magnetization (NRM) varies from 10 to $10^{-1}$ A/m for lavas to $10^{-1}$ to $10^{-3}$ A/m for tuffaceous sedimentary rocks. Some specimens possess a small magnetization (probably a viscous remanent magnetization or VRM imposed by the Brunhes field) which is readily removed by treatment in either low AF (about 20 mT) or at low temperatures (about 300°). Single, high coercive force magnetizations dominate the remaining NRM of most specimens. This is evidenced by orthogonal plots which show linear decay to the origin. Behavior is ideal; orthogonal plots converge to the origin in AF above about 30 mT, and temperatures above about 400°C (Figures 7 to 9). Below these ranges, the lines sometimes show either slight curvature (Figure 7) or a slightly different trend (Figures 8 and 9), indicating the removal of soft Brunhes age VRMs. In these instances, the direction of principal magnetization has been obtained by choosing a single level of treatment (typically, 50 mT or 550°C) in the linear range; this is an adequate procedure because linearity is well defined. Sometimes, however, decay, although linear, is somewhat less well defined (Figure 10), and the direction of principal magnetization has been obtained by least squares line fitting, utilizing data typically in the ranges 20 to 100 mT or 300° to 600°C.

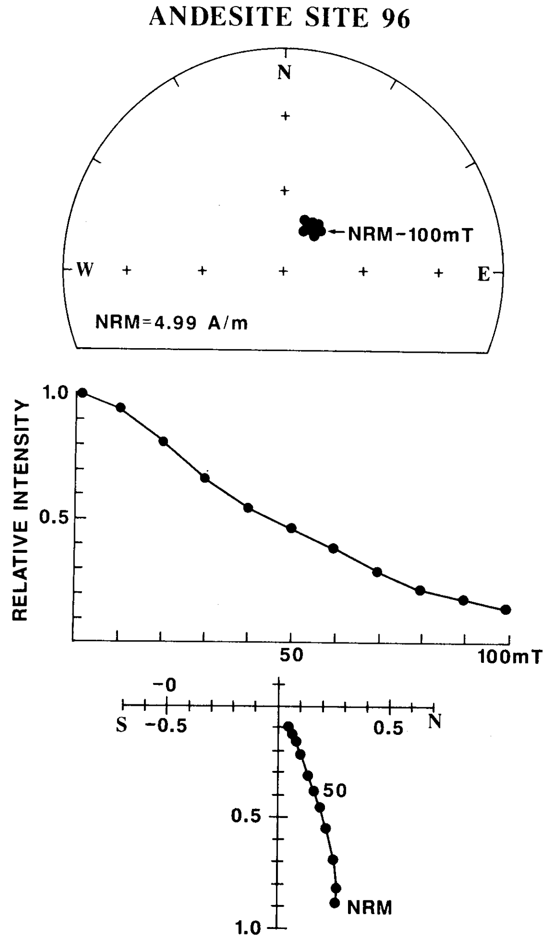

**Fig. 7.** AF demagnetisation of andesite site 96 (*X* magnetisation): (top) directions relative to bedding plane, (middle) intensities change, and (bottom) orthogonal plot in a plane perpendicular to bedding.

Unblocking temperature of the lavas fall in the range 450° to 600°C, magnetizations commonly persisting up to 600°C (Figure 8). This indicates that both magnetite and hematite are carriers of the remanent magnetization and both have the same direction. These minerals are typical products of

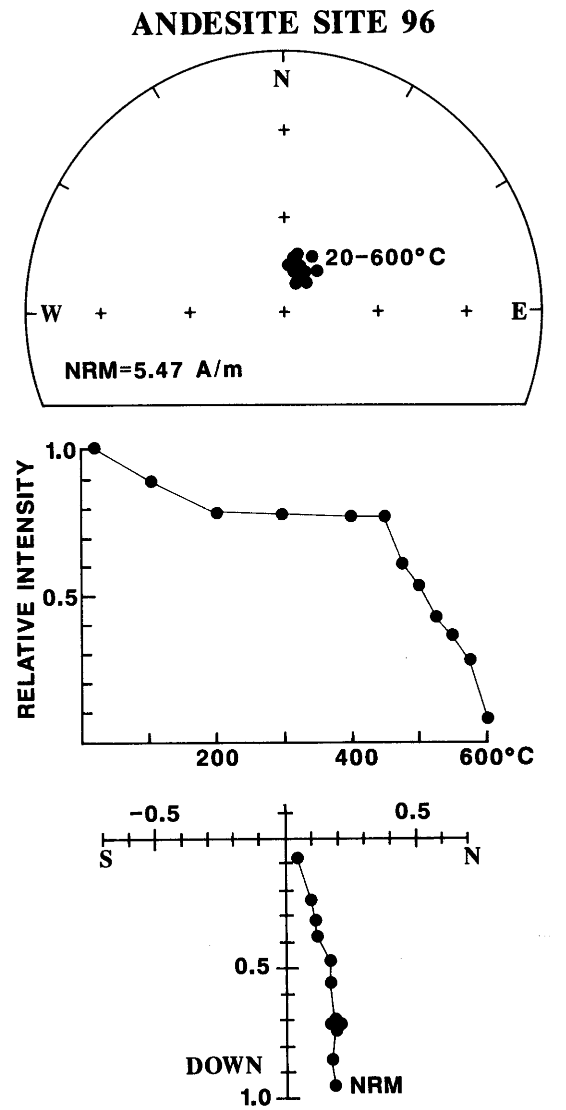

Fig. 8. Thermal demagnetization of andesite site 96 (*X* magnetization). See caption of Figure 7.

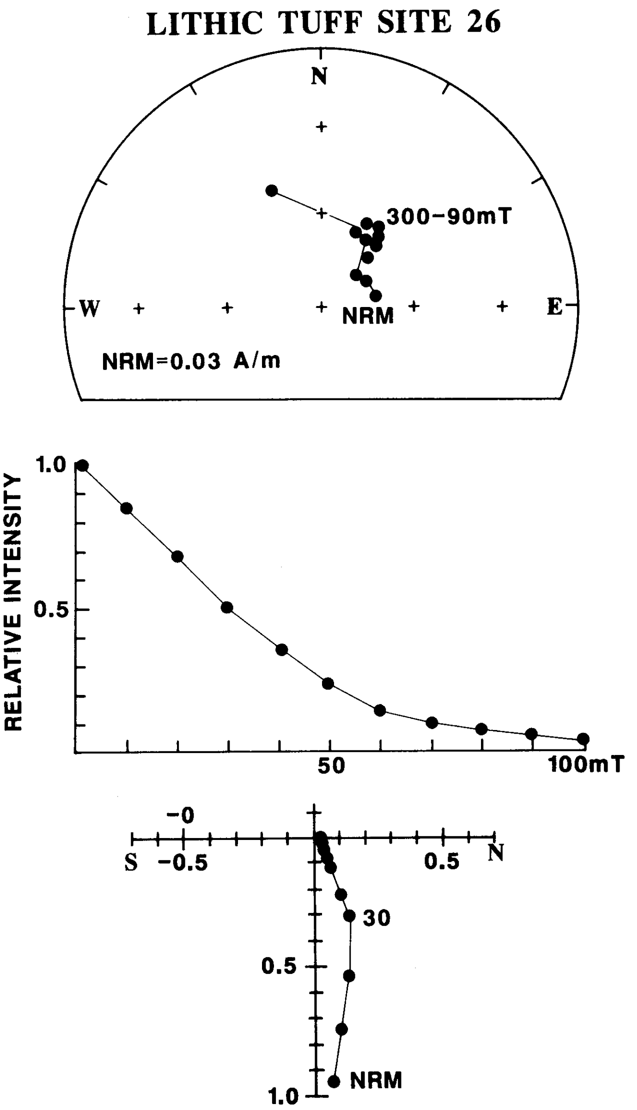

Fig. 9. AF demagnetization of lithic tuff site 26 (*Y* magnetization). See caption of Figure 7.

high-temperature deuteric alteration, and we suggest that their magnetizations are probably TRMs (thermoremanent magnetization) or high-temperature CRMs (chemical remanent magnetization). The unblocking temperature of the tuffaceous rocks are predominantly in the range of 500° to 600°C indicating that the remanence is carried mainly by magnetite (Fig. 10) and is presumably a detrital remanent magnetization.

Site mean directions, associated statistics, and experimental procedures are given in Table 2. Site mean directions have been calculated giving unit weight to specimens. Giving unit weight to individual cores changes the site mean directions by less than 2° which is insignificant. With two exceptions (sites 14 and 15), the agreement among specimens from the same site is good, and this, together with the fact that the magnetizations after removal of soft components are single component, indicates that the rocks at each site records the paleofield over a short interval of time. Apart from soft Brunhes age VRMs there are no traces of overprinting. Polarities are all normal, as would be expected for Albian age rocks deposited during the Cretaceous Normal Superchron.

Relative to present horizontal, the directions from sites 14 and 15 lie in broad bands with northerly to southeasterly declinations and intermediate to steep inclinations (Figure 11). This distribution is not caused by the presence of unresolved magnetizations because all specimens have single-component magnetizations of the types just described. Corrections for tilting move the directions toward and beyond the mean direction of the Spences Bridge Group (see below) as if magnetizations within each site were acquired over an interval of time, some before, some after, and some during tilting. A common paleohorizontal cannot be

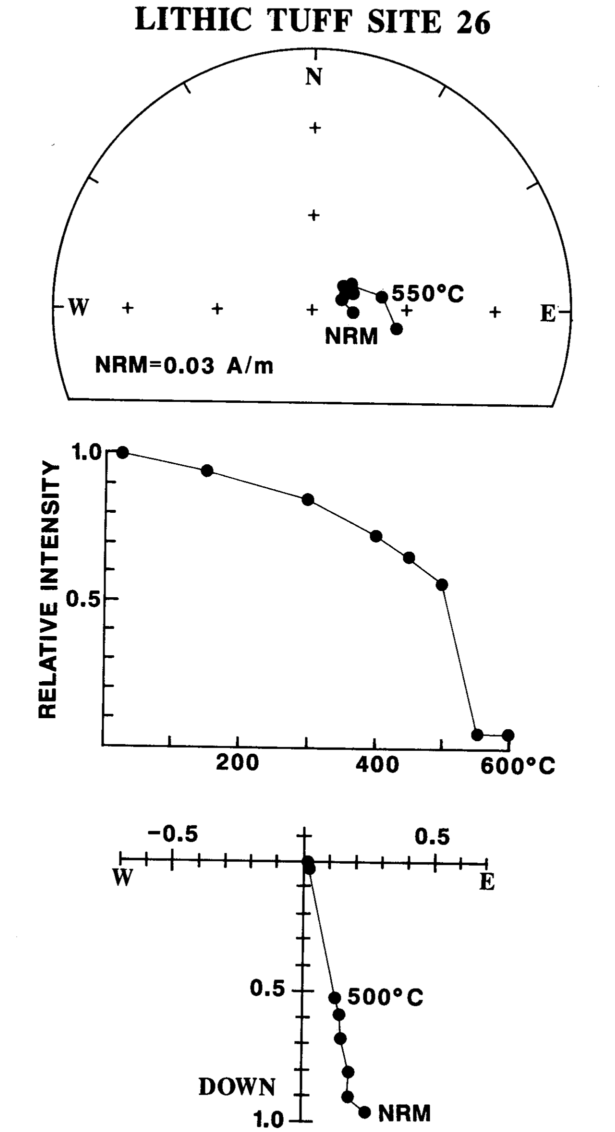

Fig. 10. Thermal demagnetization of lithic tuff site 26 (*Y* magnetization). See caption of Figure 7.

recognized, so the data from sites 14 and 15 are not considered further.

## DATA ANALYSIS

Paleomagnetic directions may be analyzed in two ways. First, site mean directions may be averaged and the paleopole calculated from this average [*Creer et al.*, 1954]; the paleosecular variation is assumed to be caused predominantly by variation in nondipole fields, model *A* of *Irving and Ward* [1964]. Second, paleodirections may be transformed into their corresponding virtual geomagnetic poles (VGPs), which are then averaged to obtain the paleopole; the paleosecular variation is assumed to be caused predominantly by wobble of the geocentric dipole about its axial position, which is model *B* of *Creer et al.* [1959] and *Cox* [1962].

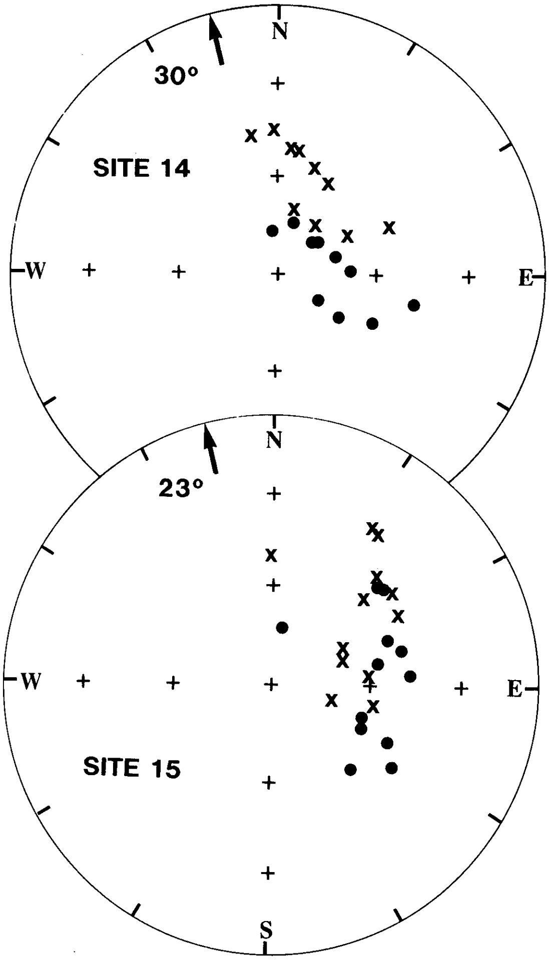

Fig. 11. Directions at site 14 and 15 before (solid circles and perimeter is present horizontal) and after (crosses and perimeter is the bedding plane) correction for tilt. All directions are on the lower hemisphere. Arrows show direction and magnitude of tilt.

The most generally used test in paleomagnetic work is the "fold" or "tilt" test of *Graham* [1949]. In his classical fold test, direction observed from a single horizon across a fold are compared. There is no need to use a paleosecular variation model. In thick sequences which span long intervals of time, comparisons are made amongst variably tilted sequences, and the paleosecular variation is likely to be a major contributor to the dispersion observed. Models have to be employed.

Paleosecular variations caused by nondipole fields may be expected to have shorter periods ($10^3$ years) than those caused by wobble ($10^4$ to $10^5$ years), so the effect of the latter may be expected to dominate in data from thick sequences, such as the Spences Bridge Group. Furthermore, during long intervals containing few or no field reversals, such as the Cretaceous Normal Superchron (duration about 30 Ma) during which the Spences Bridge Group was deposited, the ratio of nondipole to dipole field strengths may be expected to be minimal and wobble to predominate [*Brock*, 1971; *Cox*, 1968]. Hence if dipole wobble rather than nondipole sources is the major cause of paleofield dispersion, then the appropriate procedure, when carrying out tilt tests in thick rock sequences, would be to minimize the dispersion of VGPs rather than site directions, that is to use model *B* rather than model *A*. We shall present calculations using both models.

The 25 site mean directions are plotted in Figure 12, and summary statistics in Table 3. Minimum dispersion occurs not after 100% application of the tilt correction as would be expected if all sites satisfied the tilt test, but after 65% correction (Figure 13). When directions are transformed into VGPs, their dispersion is minimal after 70% corrections (Figure 13). Such variations of dispersion versus tilting could have been produced in one of two ways. First, the beds could have been tilted by approximately one third of their present dip, then magnetized, and then tilted again up to the full amount (syntilting magnetization). Second, the variations could have been produced by the

TABLE 3. Summaries of Data

| | all 100% | all 65% (SB3) | *X* 100% (SB1) | *X* 82% (SB2) |
|---|---|---|---|---|
| $N$ | 25 | 25 | 17 | 17 |
| $D^\circ_m$, | 31.6 | 25.3 | 38.7 | 35.0 |
| $I^\circ_m$ | 65.5 | 70.8 | 63.9 | 67.6 |
| $k$ | 28 | 47 | 44 | 52 |
| $\alpha^\circ_{95}$ | 5.6 | 4.3 | 5.4 | 5.0 |
| $\alpha^\circ_{63}$ | 3.1 | 2.4 | 3.0 | 2.5 |
| $\lambda^\circ$ | 69.1N | 73.8N | 64.4N | 68.2N |
| $\phi^\circ$ | 317.7E | 297.5E | 321.0E | 312.0E |
| $K$ | 13 | 18 | 24 | 23 |
| $A^\circ_{95}$ | 8.3 | 6.9 | 7.5 | 7.6 |
| $A^\circ_{63}$ | 4.7 | 3.9 | 4.2 | 4.2 |

$N$ number of sites, $D^\circ_m$,$I^\circ_m$ mean direction giving sites unit weight, $k$ precision, $\alpha^\circ$ the radius of circle of confidence ($P = 0.05$, and 0.27), $\lambda^\circ$,$\phi^\circ$ latitude and longitude of paleopole calculated as an average of site-poles, $K$ precision of site-poles (VGP's), $A^\circ$ radius of circle of confidence around paleopole ($P = 0.05$ and 0.27). Percentage untilting given at top. For reasons given in the text, the result for *X* data corrected fully (100% column three) for field-observed tilts is regarded as the best estimate of the mean paleofield in Spences Bridge time.

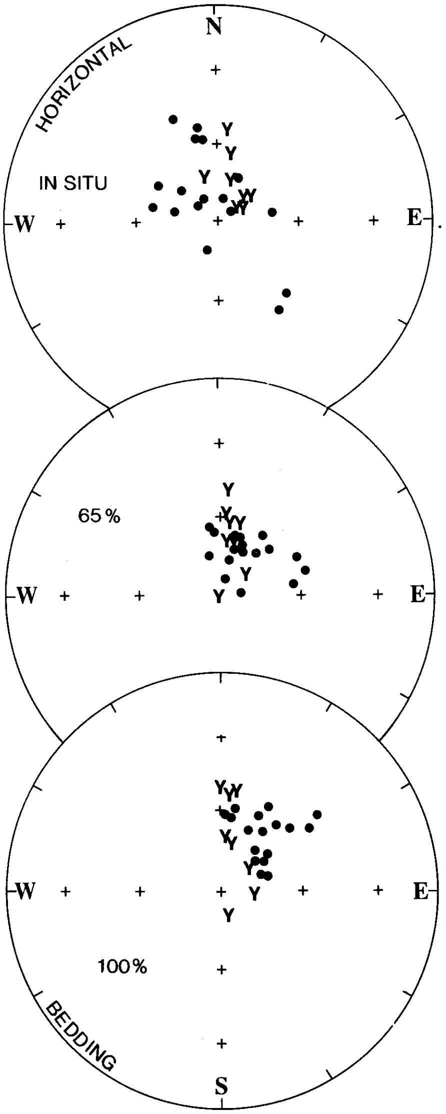

Fig. 12. Site mean directions (top) before correction, (middle) after (65%) correction, and (bottom) after full correction for dip of beds. Solid circles are *X* magnetizations. *Y* magnetizations labeled as such.

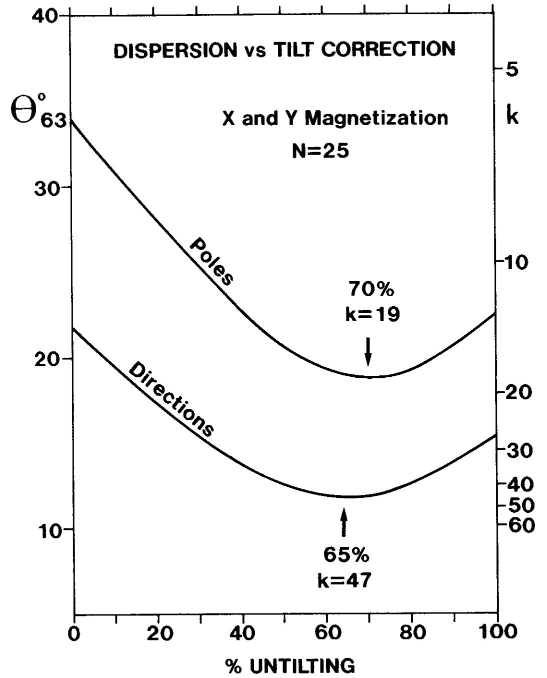

Fig. 13. Dispersion of all (25) site mean directions and VGPs as function of untilting.

interaction of two modes of behavior, one in which a proportion of beds were magnetized prior to tilting and which responded fully to the tilt test (pretilting magnetization), and one in which a proportion of beds were magnetized either during or after tilting (syntilting or posttilting) and did not respond fully to the tilt test. Figure 13 could be the sum of these two effects.

Such dual behavior has been described by *Bardoux and Irving* [1989], who found that out of 24 sites in the Eocene Marron Formation, 12 were magnetized predominantly after tilting and 12 predominantly before, so that minimum dispersion of the whole occurred after 58% correction for tilting. They argue that results obtained after 58% untilting have no tectonic or structural significance, being an artifact of applying a common simplistic procedure to physically disparate data.

The difficulties in accepting the first option for Spences Bridge data (simple minimization of dispersion) are twofold. Although tilting may have occurred in several stages, that it should have occurred in such a precise two-stage proportionate manner interrupted by the magnetization process seems to us inherently unlikely. Second, partial untilting provides no way of estimating paleohorizontal; the paleohorizontal at each site may or may not be the common plane of tilting after 65% correction. We therefore instituted a search for dual behavior, comparable to that observed in the Marron Formation, and the following analysis of VGPs was carried out.

The paths of motion of each VGP during the application of tilt corrections was determined, and the point of their closest approach to the mean after 100% correction calculated. Departures ($d_1$) of each fully tilt-corrected VGP from this point are listed in Table 2. Values of $d$ are negative or positive depending on whether the VGP is near or far sided. For some sites (e.g., 25, 83, 84) $d_1$ is large, far larger than error, and VGPs moved away from the mean during tilt correction. For other sites (e.g., 85, 93) $d_1$ is small, and the VGPs moved toward the mean during correction. Accordingly, VGPs have been divided into two groups with $d_1 \leq 15°$ and $d_1 > 15°$, which are referred to as $X$ and $Y$, respectively. The sites which have yielded the $Y$ group are from the northern part of the Spius Creek section and from the Coquihalla Highway just southeast of Kingsvale (Figure 3). The $X$ sites are much more widespread, both areally and statigraphically.

The $X$ magnetizations respond positively to the tilt test, and the VGPs (and site directions) are much better grouped after than before correction. The variations of dispersion with unfolding for $X$ and $Y$ magnetizations are quite different. $X$ magnetizations (Figure 14) yield minimum dispersion of VGPs after 93% correction (82% for directions), but the dispersion is constant within the range 88 to 100% of untilting; the standard deviation varies insignificantly from 16.4° to 16.6° and $K$ from 23.9 to 24.2. In effect, minimum dispersion occurs after full correction for geologically estimated bedding attitudes, and the $X$ magnetizations satisfy the tilt test. We conclude that the $X$ magnetizations were acquired before tilting.

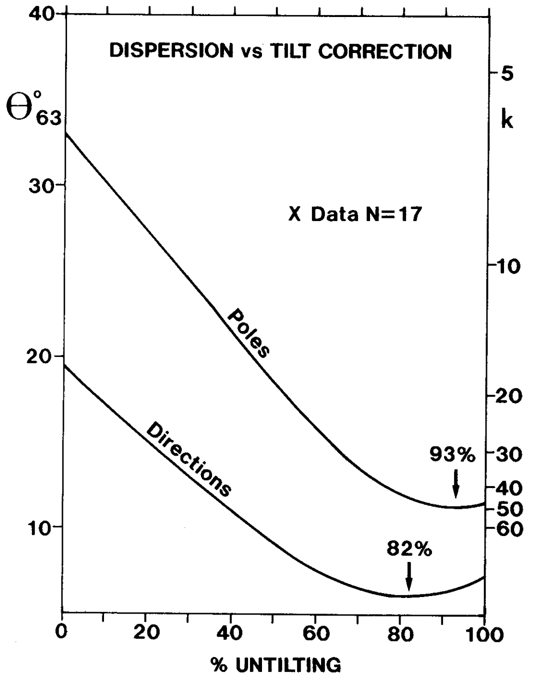

Fig. 14. Dispersion of $X$ data (17) sites mean directions and VGPs as function of untilting.

$Y$ magnetizations respond less well or negatively to the tilt test, corrections first decreasing and then increasing dispersion. Minimum dispersion occurs after 34% correction (35% for directions (Figure 15). The response of $Y$ data to untilting could be caused by large paleoslope angles, but we suggest that this is unlikely to be generally true because the largest $d$ values occur at sites (bedded coaly clastic rocks site 25 to 27, see above) at which paleoslopes are likely to have been minimal.

It might be expected that the dispersion of VGPs and site directions would vary together as tilt - corrections are incremently applied. But this would be exactly so only if the directions and magnitudes of tilts vary randomly, so that only dispersion and not the mean of sites directions would change during the correction process. In practice, however, exposures of rocks suitable for paleomagnetic work that have dips that are random in direction and magnitude often do not occur, so that the mean of site directions and the paleopole will migrate as incremental correction are made. This is so for Spences Bridge rocks (Figure 16). Changes in

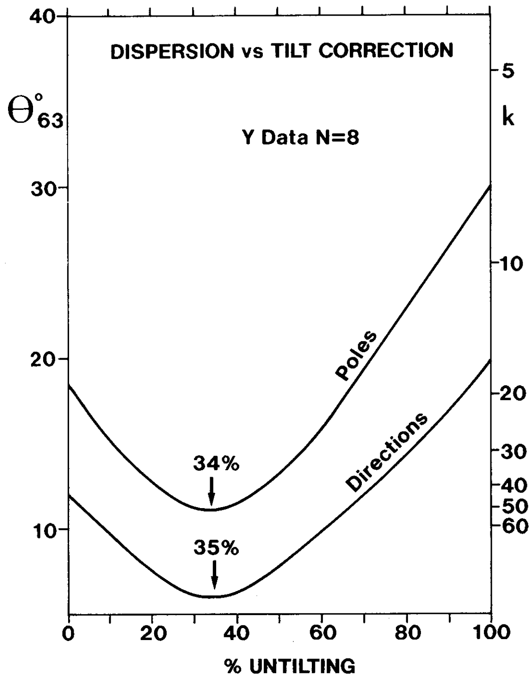

Fig. 15. Dispersion of *Y* data (8) sites mean directions and VGPs as function of untilting.

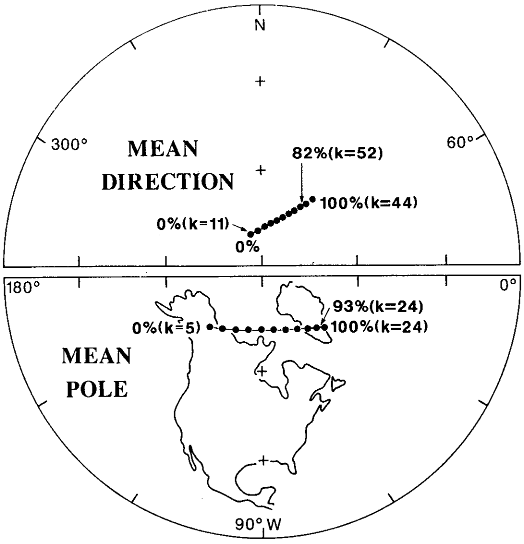

Fig. 16. Changes in (top) mean direction and (bottom) paleopole as function of tilt correction, for *X* data.

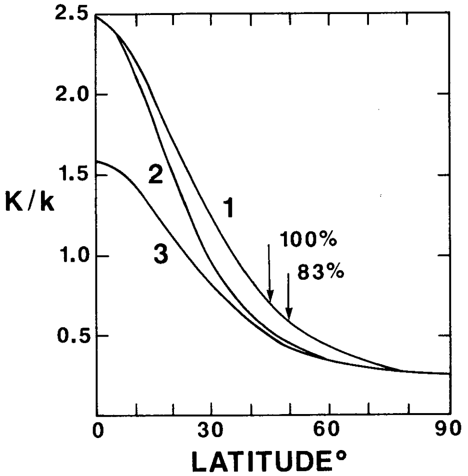

Fig. 17. The ratio $K/k$ as a function of latitude ($\lambda$). Precision of paleodirections is $k$, and $K$ is the precision of corresponding VGPs. Redrawn from *Cox* [1970]. Curves 1 and 2 are for Fisherian distribution of VGPs (model *B*). Curve 1 is given by $K/k = 0.5\ (5 - 3 \sin^2 \lambda)\ /\ (1 + 3 \sin^2 \lambda)^{-1}$ [*Creer*, 1962] and curve 2, which is more exact, by $K/k = 0.5\ (5 + 3 \sin^2 \lambda)\ /\ (1 + 3 \sin^2 \lambda)^2$ [*Cox*, 1970]. Curve 3 is for a Fisherian distribution of paleodirections (model *A*) and is given by $K/k = 8\ (5 + 18 \sin^2 \lambda + 9 \sin^4 \lambda)$ [*Cox*, 1970]. The appropriate paleolatitudes for 83% and 100% correction of paleodirections are indicated showing how the estimated precisions depend on the procedures adopted.

declination of the mean site direction do not affect the way in which the dispersions of VGPs ($K$) and site directions ($k$) vary, but changes in mean site inclination do. This is shown in Figure 17, in which the ratio $K/k$ is plotted as a function of mean geomagnetic latitude for the nondipole model (curve 3) and for the wobble model (curves 1 and 2). Curve 1 is from a relationship originally given by *Creer* [1962], curve 2 is from *Cox* [1970] and is a better approximation. Clearly, the question of whether to minimize the precisions of site directions or VGPs is important when applying the tilt test to rock units whose bedding attitudes are such that the mean inclination changes during untilting. This would be especially true of rock units laid down in middle and low latitudes in which the ratio $K/k$ varies most rapidly.

As already noted, the variation of VGP dispersion for *X* magnetizations is negligible between 88% and 100% correction. This flat response probably reflects the presence of a contribution to VGP dispersion from errors in determining site mean directions. It would appear therefore that in the Spences Bridge Group, in which sampling sites span a considerable time and reversals are absent, the dispersion of site mean directions is explained better by wobble than by nondipole sources. For these reasons, and in the absence of any geological cause that we are able to identify, we conclude that the minimal dispersion of site mean directions at 82% probably is an artifact of using an inappropriate model (paleosecular variation model *A*) of the mid-Cretaceous geomagnetic field, and that the best estimate of the paleopole for the Spences Bridge Group is obtained by applying 100% bedding correction to VGPs. That is, the best estimate of paleohorizontal at each collecting site is the bedding plane determined by standard field methods; there appear to be no grounds for applying to *X* data bedding corrections other than those estimated in the standard way. As already noted, however we do recognize the possibility that a hidden systematic paleoslope error may be present.

The age of tilting is not known accurately. Some tilting may have occurred very soon after deposition; some may be as young as Eocene. The absence of overprinting as evidenced by demagnetization data, a metamorphic grade no higher than zeolite, and the conformity of polarity with that expected, indicate that the magnetization dates from the time of deposition or shortly after in Albian time. The absence of reversed polarity suggests that the magnetizations predate the end (84 Ma) of the Cretaceous Normal Superchron.

The various analyses just described are summarized in Table 3. Result SB1 has been obtained from $X$ data after 100% bedding correction (minimum dispersion of VGPs), SB2 from $X$ data after 82% correction (minimum dispersion of site mean directions), and SB3 from both $X$ and $Y$ data lumped together after 65% correction (minimum dispersion of site mean directions). For reasons just given, we argue that SB3 is an erroneous estimate because it contains data that respond negatively to the tilt test ($Y$ data, Figure 15). Similarly, we argue that SB2 is affected by the use of an inappropriate paleosecular variation model. Moreover, the estimates of paleohorizontal made when applying partial tilt correction in SB3 (65%) and SB2 (82%) have no geological or physical basis. The $X$ data, when analyzed using model $B$ (SB1) satisfy the tilt test, so that at those sites from which these $X$ data were obtained, bedding as determined from field observations is the best currently available estimator of paleohorizontal. For these reasons, SB1 is our preferred estimate of the mean paleofield direction in Spences Bridge time.

The behavior of the remaining eight sites with $Y$ magnetization is quite different (Figure 15). Maximum precision occurs after only 34% correction, so that most, but not, all tilting had happened by the time their magnetization was acquired. It is perhaps noteworthy that $Y$ magnetization occurs predominantly in volcaniclastic sedimentary rocks (sites 12, 13) and in amygdaloidal andesites of the Spius Formation (sites 11, 25, 26, 27), rocks that are likely to be more porous than the dense massive andesite from which the bulk of our collections were made. The remaining $Y$ magnetizations are from the top of the Pimainus Formation (sites 83, 84). Chemical remagnetization during an interval of fluid flow contemporaneous with tilting is therefore not improbable. Maximum precision ($k_{39} = 135$) is very high, and this, and the fact that the samples involved are from two sections only (one along the Coquihalla Highway and the other along Spius Creek) raise the possibility that the mean may not adequately average out the paleosecular variation. It is also very unlikely that data from only two sections corrected in this way could adequately reconstruct the paleohorizontal. We conclude that it is not possible to determine the direction of the paleofield from the $Y$ magnetization. For the record, the statistics for the eight sites with $Y$ magnetization after 35% attitudinal correction are $D_m$, $I_m$ = 18°,72°, $k$ = 135, $\alpha_{95}$ = 5°. We wish to stress that we do regard this to be a meaningful estimate of the paleofield.

## TILT OR TRANSLATION?

The mid-Cretaceous reference paleopole for cratonic North America is now reasonably well established [*Mankinen*, 1978; *Globerman and Irving*, 1988]. Using this, the apparent relative paleolatitudinal displacements (ARPD) and relative rotations (ARR) of mid-Cretaceous sampling localities in British Columbia and northern Washington can be calculated (Table 4 and Figures 18 and 19 with sampling locations marked in Figure 1). Throughout, 95% errors are given.

All three estimates from the Spences Bridge (SB1, 2 and 3, Table 4) yield large clockwise rotations (53° to 66°) irrespective of the selection and analytical procedures applied. SB3 yields no significant paleolatitudinal displacement, whereas SB2 and SB1 yield displacements from the south of 1200 and 1700 km, respectively. We have argued above that SB3 is based in part on data that do not respond to the tilt test, and SB2 is based on what is probably an inappropriate paleosecular variation model. For neither SB3 or SB2 can a reliable estimate of paleohorizontal be made, this uncertainty being especially large in SB3. Hence we regard SB1 of Table 4, obtained by applying fully the observed geological tilts, as the best estimate of displacement of the Spences Bridge Group, namely 1700 ± 800 km ($P = 0.05$) from the south.

It is important to note that the error bars of Figure 18 are not ranges but are probability distributions. The probability is highest at the mean and diminishes away from it. For this reason the error bars are shown, not as lines of equal thickness, but as outwardly directed arrow heads, signifying the fall in probability with distance from the mean. The probability densities for those data from the Pacific Northwest for which estimates of paleohorizontal can be made, are given in more precise form in Figure 19.

In Figure 18, data from intrusions are grouped into those derived from units with no attitudinal control, and those for which there are attitudinal indicators. Data from rock units that do not average out paleosecular variation are not included; for example, data from the Albian Crowsnest Formation are not

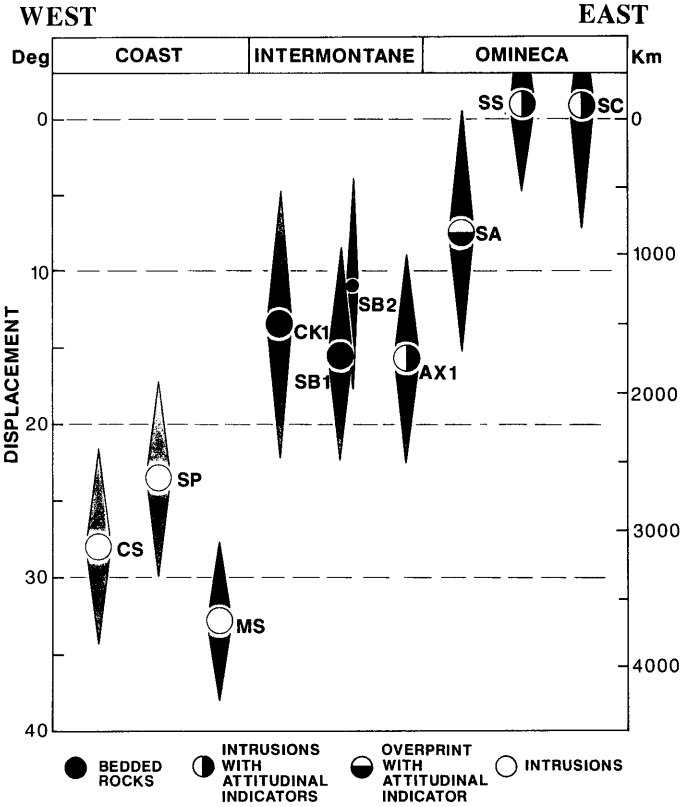

**Fig. 18. Apparent latitudinal displacements relative to the North American craton obtained from Cretaceous rocks in the Canadian Cordillera and northern Washington arranged by tectonic belts. Zero displacement indicates that the sampling region has not moved latitudinally relative to ancestral North America. Data obtained from bedded sequences and from intrusions with and without attitudinal indicators are differentiated. Points are labeled as in Table 4. SB1 is obtained after 100% tilt correction and is our preferred interpretation as explained in the text. SB2 is from 83% correction. The errors depict qualitatively the fall in probability away from the mean. A more exact representation is given in Figure 19.**

TABLE 4. Apparent Relative Paleolatitudinal Displacements (ARPD) and Rotations (ARR) for Cretaceous Rocks of the Western Cordillera in Canada and Northern Washington.

| Rock Unit | Reference Plane | Belt | ARPD° | ARR° |
|---|---|---|---|---|
| SS Summit stock, 104 Ma | bathozones | Omineca | -1.0±5.6 | 14.3±11.1 |
| SC Skelly Creek batholith, 95 Ma | bathozones | Omineca | -1.0±8.2 | -17.0±16.6 |
| SA Permian limestone, overprint | present | Omineca | 7.4±7.8 | -4.9±20.4 |
| AX2 Axelgold intrusion, 120-90 Ma | present | Intermontane | 27.2±5.6 | -64.5±11.8 |
| AX1 Axelgold intrusion, 120-90 Ma | layering | Intermontane | 15.6±5.6 | -57.5±14.1 |
| SB1 Spences Bridge Group, 104 Ma | bedding (100%) | Intermontane | 15.5±7.1 | -66.3±11.8 |
| SB2 Spences Bridge Group, 104 Ma | bedding (82%) | Intermontane | 10.8±7.2 | -62.8±12.4 |
| SB3 Spences Bridge Group, 104 Ma | bedding (63%) | Intermontane | 6.1±6.8 | -52.8±12.2 |
| CK1 Carmacks Group, 70 Ma | bedding (100%) | Intermontane | 13.4±8.5 | -10.2±20.7 |
| CK2 Carmacks Group, 70 Ma | bedding (100%) | Intermontane | 15.6±8.1 | -6.4±20.0 |
| CK3 Carmacks Group, 70 Ma | bedding (100%) | Intermontane | 13.7±9.7 | -3.4±22.9 |
| MS Mt. Stuart batholith, 100 Ma | present | Coast | 32.9±5.1 | -36.3± 8.6 |
| SP Spuzzum and Porteau plutons, 104 Ma | present | Coast | 23.5±6.3 | -57.0±10.2 |
| CS Prince Rupert plutons, 102 Ma | present | Coast | 22.1±6.3 | -44.7±10.2 |

ARPD and ARR for mid-Cretaceous rocks have been calculated using the cratonic mid-Cretaceous reference paleopole (71.1°N, 195.7°E $A_{95} = 4.9°$) given by *Globerman and Irving* [1988]. Errors ($P = 0.05$) in RPD and RR for mid-Cretaceous data have been calculated using the method of *Demarest* [1983]. Entry CK1 for the Late Cretaceous Carmacks Group have been calculated using a craton reference paleopole 77.7°N,185.8°E $A_{95} = 77°$) compiled by *Marquis and Globerman* [1988]. Entries CK2 and CK3 have been calculated using a revised Late Cretaceous cratonic reference paleople (76.9°N, 197.1°E, $N = 4$, $K = 205$, $A_{95} = 6.4°$ obtained by the average three cratonic paleopoles listed by *Marquis and Globerman* [1988, Table 4] and that from the Maudlow formation of Montana (70°, 208°, $A_{95} = 9°$, [*Swenson and McWilliams*, 1989]). Positive (negative) ARDP values indicate displacement from the south (north). Negative (positive) ARR values indicate clockwise (anticlockwise) rotations. To convert ARPD from degrees to kilometers, multiply by 111.3. SS and SC *Irving and Archibald* [1990]; SA *Butler et al.* [1988]; AX *Monger and Irving* [1980]; *Armstrong et al.* [1985]; CK1 *Marquis and Globerman* [1988]; CK2 is based on the original analysis of Carmacks Group data by *Marquis and Globerman* [1988]: CK3 is based on a revised analysis of Carmacks data by *Butler* [1990] who has applied corrections for what he considered to be redundancies in the Carmacks data. MS *Beck et al.* [1981*b*]; SP *Irving et al.* [1985]; CS *Symons* [1977]. Entries SB1, SB2 and SB3 correspond to columns 3, 4 and 2 of Table 3 respectively. For reasons given in the text, SB1 is our preferred estimate.

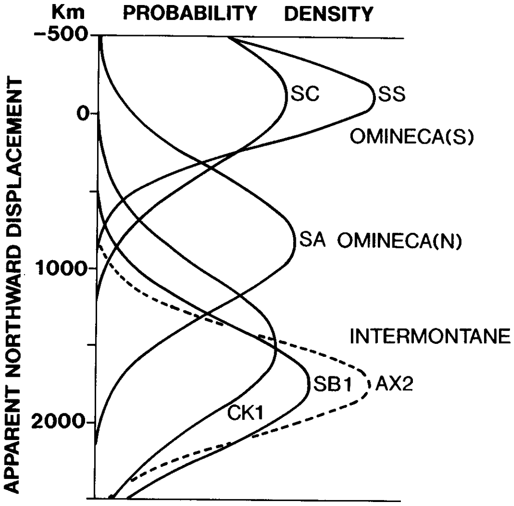

Fig. 19. Probability density distributions (solid curve) for displacement estimates made from rock units with tilt control and for which paleohorizontal can be reconstructed. Skelly Creek batholith; SS Summit stock; SA Overprint from Sylvester allochthon; CK Carmacks Group; SB1 Spences Bridge Group (*X* magnetizations after application of full bedding correction). The dashed nature of the curve for the Axelgold intrusion denotes the greater uncertainty associated with determining tilt from igneous layering. See Table 4 and Figure 18 for further details.

given because the unit probably represents a single eruption [*Irving et al.*, 1986]. With one exception, data from overprints of presumed mid-Cretaceous age (a summary of them is given by *Irving and Wynne* [1990]) also are excluded, because of uncertainty in the time of overprinting, and because of the absence of direct evidence of paleohorizontal at the time overprinting occurred [e.g., *Irving et al.*, 1985; *Rees et al.*, 1985]. The exception is the overprint observed in Permian limestones of the Slide Mountain Terrane [*Butler et al.*, 1988]. This magnetization is presumed, on reasonable grounds, to be contemporaneous with that of the nearby mid-Cretaceous Cassiar batholith, and the sub-horizontal nature of the thrust that underlies the sampling area indicates that tilting has been negligible. This datum is therefore accepted.

The most striking feature of Figures 18 and 19 is that apparent displacements increase from east to west. This is also displayed in Figure 19 in which the probability distributions of the apparent displacements obtained from tilt-corrected data migrate toward larger values with distance from cratonic North America. In the south, data from the eastern Omineca Belt, not far to the west of the southern Rocky Mountain trench (SS and SC of Figure 1), show no latitudinal displacement [*Irving and Archibald*, 1990]. Evidently, this region has remained relatively fixed to the margin of ancestral North America since mid-Cretaceous time.

In the north, the Slide Mountain terrane, which is situated west of the northern Rocky Mountain Trench fault, yields an apparent displacement of 800 ± 850 km (SA, Figure 18 and 19). This is marginally significant at $P = 0.05$, but is, nevertheless, consistent with displacement of as much as 900 km inferred by *Gabrielse* [1985, 1990] on the northern Rocky Mountain Trench and associated faults to the east of the sampling locality.

In the Intermontane Belt, apparent displacements calculated from paleomagnetic data from the Carmacks Group, and from the Spences Bridge *X* data are in agreement with one another (SB1 and CK1 of Figures 18 and 19). As already noted, the former study, like that herein, includes a positive tilt test, but unlike that herein suffers from uncertainty in the cratonic reference paleopole for Late Cretaceous time [*Marquis and Globerman*, 1988]. Very recently, new data from the Maudlow Formation of Montana (83 to 75 Ma) have provided further information on the reference field for this time [*Swenson and McWilliams*, 1989]. The revised reference paleopole calculated from the three cratonic paleopoles listed by *Marquis and Globerman* [1988] and the above is 76.9°N, 197.1°E ($N = 4$, $K = 0205$, $A_{95} = 6.4$). The four rock units from which these paleopoles were derived span the interval 83 to 63 Ma embracing the time when the Carmacks Group was deposited (70 Ma). Entry CK2 of Table 4 has been calculated from the result of *Marquis and Globerman* [1988] and the above cratonic reference paleopole. Entry CK3 has been calculated using the reanalysis of the Carmacks Group data by *Butler* [1990] who contended that there is some redundancy in them, which he has attempted to correct [see *Marquis et al.*, 1990]. CK1, CK2 and CK3 are not significantly different. All indicate significant displacement of the Carmacks Group from the south with mean values in the range 1490 to 1730 km and errors ($P = 0.05$) ranging from 900 to 1080 km. The Spences Bridge has apparently rotated clockwise, but the younger Carmacks does not appear to have undergone significant rotation (Table 4).

Displacements obtained from these two bedded sequences are also in good agreement with that estimated for the Axelgold intrusion after correction of directions to the prominent planes of layering found throughout that body [*Monger and Irving*, 1980]. If Axelgold magnetizations are assumed to have been acquired after the layers were tilted, then the estimated displacements become larger, approaching 3000 km (Table 4).

Figure 18 and Table 4 also contain apparent displacement for the Spences Bridge Group (SB2) calculated by minimizing dispersion of site mean directions (82% correction) rather than VGPs. It is less than the displacement estimated from SB1, but still significant. For reasons already given, SB1 is our preferred estimate.

Of the plutons from the Coast Plutonic Belt, Mt.

Stuart in the northern Cascade Mountains of Washington [*Beck and Noson*, 1972; *Beck et al.*, 1981*b*] has yielded the largest apparent displacement, exceeding 3500 km. Alternatively, it may have been tilted about 34° to the southwest (Figure 1). Three plutons (*Symons* [1977], detailed separately in Figure 1) in the Prince Rupert area, have a mean apparent displacements of about 3000 km, or an apparent tilt of about 30° to the west southwest. The Spuzzum and Porteau plutons in the southern Coast Ranges give an apparent displacement of about 2600 km and a mean apparent tilt of about 30° to the west southwest [*Irving et al.*, 1985]. All apparent displacements exceed those observed from the Intermontane Belt, and all apparent rotations are about 60° clockwise.

Let us compare data from the Spences Bridge Group (Intermontane Belt) with those from the nearby Spuzzum pluton (Coast Plutonic Complex of the Coast Belt). The apparent displacement of the Spences Bridge Group, as determined from data that respond positively to the tilt test, is significantly less than that of Spuzzum (Figure 18). The Spences Bridge Group is separated from the Spuzzum pluton by a series of dextral strike-slip faults, such as the Fraser and Yalakom faults, which were active in Late Cretaceous and Early Tertiary times, and which, therefore, postdate the Spences Bridge Group (Figure 2). *Monger* [1990], summarizing earlier discussions, has concluded that displacement on the Yalakom and associated faults was at least 300 km, making the total displacement (adding 100 km on the Fraser Fault) at least 400 km. *Umhoefer et al.* [1989*a*] have estimated a somewhat smaller total displacement of 250 to 300 km. Adding these displacements to that observed from the Spences Bridge Group, a total expected displacement for the Spuzzum pluton of 2000 ± 800 km is obtained using the estimate of *Umhoefer et. al.* [1989*a*], and 2125 ± 800 km using Monger's estimate. Neither are significantly different from the displacement estimated by assuming that the pluton has not tilted (2600 ± 700 km, Table 4). This comparison therefore implies that much, but not necessarily all, of the apparent displacement of the Spuzzum pluton is a real latitudinal offset and that systematic 30° tilting to the southwest is not the entire cause of its aberrant remanent magnetization.

Alternatively, one may argue that all differences between apparent displacements from the Intermontane and Coast belts are caused by variable tilting in the latter generally to the south or southeast. The tilts required to bring data from the plutons of the Coast Belt into agreement with data from bedded volcanics of the Spences Bridge Group in the Intermontane Belt are as follows: the Coastal plutons (CS of Figure 1 and Table 4) down 12° at 168°, Spuzzum pluton (SP) 8° at 176°, and Mt. Stuart batholith (MS) down 25° at 154°.

These then are three possible explanations for the abberancies of Figures 18 and 19: (1) regional tilting to the southwest by about 30° (Figure 1); (2) clockwise rotations and displacements increasing westward to over 2000 km; (3) clockwise rotations and displacement of about 1500 km, combined with variable tilting of Coast Belt plutons to the south and southeast. Data from bedded rocks of the Spences Bridge Group which respond positively to the tilt test (*X* data) are inconsistent with hypothesis 1. It should be possible to discriminate between hypotheses *1* and 3 geologically because the required tilts are approximately 90° apart in directions.

Hypotheses 2 and 3 conflict with the proposal of *Butler et al.* [1989], who contended that tilting alone best accounts for the paleomagnetic discordances. Their arguments are geological, and it is not within our competence to provide a detailed critique of them, but we do make a few brief comments. The evidence (mainly K/Ar age data) used by *Butler et al.* [1989] to invoke tilting of the Spuzzum pluton, could equally well be regarded as evidence of differential uplift along steep faults as *Irving et al.* [1985] have argued. Second, *Butler et al.* [1989] have used attitudes of the Swauk Formation at one locality as a measure of tilting of the Mt. Stuart batholith, although the contact between these two units at this locality may be a fault [*Miller et al.*, 1990]. In these and other instances cited by *Butler et al.* [1989], the geological information used to support tilting as a complete explanation can be explained in other ways.

## SOME POSSIBLE TECTONIC IMPLICATIONS

### *Quesnellia divided*?

*Irving and Archibald* [1990] have shown that when the paleohorizontal is reconstructed using bathozonal evidence the paleomagnetic data from the Skelly Creek batholith and Summit stock, which are from the eastern part of the Omineca Belt, are concordant with cratonic data (SC and SS of Figures 18 and 19). They argue further that the eastern portion of Quesnellia also was close to its present position relative to the North American craton during mid-Cretaceous time, because the compressional event that brought eastern Quesnellia and the Omineca Belt together occurred earlier, probably during Middle Jurassic time [*Price*, 1981]. Certainly, this compressional event occurred before the mid-Cretaceous, because associated thrust faults are crosscut by mid-Cretaceous plutons [*Archibald et al.*, 1984]. If these inferences are correct, then eastern Quesnellia has been sutured to ancestral North America since mid-Cretaceous time. Hence the aberrant paleolatitude and rotation obtained herein for the Spences Bridge Group (which overlies western but not eastern Quesnellia) would require that in southern British Columbia, Quesnellia is not a single unbroken unit passing continuously across the Intermontane/Omineca boundary. Its elongated semidetached form (Figure 1) implies that like the Wrangellia terrane [*Yole and Irving*, 1980], Quesnellia may have been dismembered and attenuated along a broad shear zone. If this is correct, then the present juxtaposition of eastern and western Quesnellia in southern British Columbia is fortuitous, and the western counterpart of eastern Quesnellia may have to be sought in the Intermontane Belt further north. Early Mesozoic rock units of island-arc affinities characterize the Quesnellia as a whole, but their heterogeneity is such that there is no reason for requiring them always to have been juxtaposed in their present relative positions [A. Okulitch, personal communication, 1989). So far as we are aware, it is not possible to trace definitively individual rock units of the Quesnellia Terrane across the boundary between the Omineca and Intermontane belts.

### Time of Displacement

Concordant data have now been obtained from Eocene rocks which range in age from 55 to 48 Ma and which are spread from Vancouver Island in the west to Wyoming and Montana on the craton [*Beck et al.*, 1982; *Diehl et al.*, 1983; *Shive and Pruss*, 1977; *Fox and Beck*, 1985; *Symons and Welling*, 1989; *Bardoux and Irving*, 1989; *Vandall and Palmer*, 1990; *Irving and Brandon*, 1990]. Thus the younger limit to these displacements is set by the paleomagnetic data at about 50 Ma. The older limit is set by the ages of aberrant magnetizations. These are best determined for the Spuzzum pluton and for the Spences Bridge Group. In the Spuzzum pluton the blocking temperatures are 550° to 675°C so that the magnetization acquisition age very likely lies between the K-Ar ages which range 90-103 Ma in the center and west of the body, and the U-Pb zircon age of 110 Ma [*Irving et al.*, 1985, p. 580]. For reasons given above we argue that the acquisition time of the $X$ magnetization of the Spences Bridge Group is at or soon after deposition in the mid-Cretaceous. Present evidence therefore indicates that the apparent displacements of Figures 18 and 19 occurred sometime in the interval Late Cretaceous through Paleocene.

### Shear Distributed Across the Cordilleran in Canada and Northern Washington

If the apparent latitudinal displacements of Figures 18 and 19 are correct, then there are likely to have been not one but many zones along which transcurrent motion occurred, as earlier speculated [*Monger and Irving*, 1980; *Irving et al.*, 1985]. Hence when attempts are made to reconcile paleomagnetic data to regional geology, it is important to note that the former do not predict that motion occurred only along one or even along several large faults. Very many faults, large and small, may have been involved. Moreover, the clockwise rotation observed from the Spences Bridge Group is large (63°) and shows that strain may not have been confined to large faults, and may, in part, have been accommodated within the belts themselves by block rotation. Therefore in order to make quantitive geological tests of the apparent displacements, it will be necessary to obtain estimates, with error bounds, of displacements on all Late Cretaceous and Paleocene faults and of all associated block rotations that occur west of the Rocky Mountain Trench in the north, and west of the boundary between the Omineca and Intermontane belts in the south, a formidable task. This task of determining displacements from regional geology alone is made even more difficult by the complex deformation which the region has undergone (namely, Late Cretaceous contractional and Paleogene extensional deformation) and which may have overprinted earlier transcurrent structures.

### General Conclusion

Paleomagnetic data from bedded sequences that respond positively to the tilt test ($X$ data) are not consistent with the hypothesis (hypothesis 1) that systematic tilts are solely responsible for aberrant magnetizations observed from Cretaceous plutonic rocks of the Western Cordillera in Canada and northern Washington. They are consistent with the hypothesis (hypothesis 2) that a region, comprising the Insular, Coast, and Intermontane Belts (Baja British Columbia) has undergone differential northerly motion relative to ancestral North America, the motions increasing with distance from the craton. Based on paleomagnetism, the best estimates for the magnitude of these motions from the eastern and central part of the region affected (the Intermontane Belt) are 1500 to 1700 km from the south. Farther west the displacements could approach and possibly exceed 2000 km, although the greater discordances observed in the Coast Belt could have been enhanced by variable generally southward tilts (hypothesis 3). Our discussion depends, perhaps to a disproportionate extent, on the systematic nature of the apparent displacement estimated from mid-Cretaceous plutons (120-102 Ma), on the apparent displacements estimated from the $X$ magnetizations of the mid-Cretaceous Spences

Bridge Group, and on data from the 70 Ma Carmacks Group. The Spences Bridge datum is of key importance because it falls in the critical mid-Cretaceous interval for which the cratons reference field is well established. Its weakness is, that it depends on a new selection criteria which has yet to prove its worth, and that it is subject to uncertainties regarding the magnitude of initial dip (paleoslope).

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## REFERENCES

Archibald, D. A., T. E. Krogh, R. L. Armstrong, and E. Farrar, Geochronology and tectonic implications of magmatism and metamorphism, southern Kootenay Arc and neighbouring regions, southeastern British Columbia, Mid-Cretaceous to Eocene, *Can. J. Earth Sci., 21,* 567-583, 1984.

Armstrong, R. L., Mesozoic and Early Cenozoic magma evolution of the Canadian Cordillera, *Geol. Soc. Am. Bull. Spec. Pap., 218,* 55-91, 1988.

Armstrong, R. L., J. W. H. Monger, and E. Irving, Age of magnetization of the Axelgold gabbro, north-central British Columbia, *Can. J. Earth Sci., 22,* 1217-1222, 1985.

Atwater, T., Implication of plate tectonics for the Cenozoic tectonic evolution of western North America, *Geol. Soc. Am. Bull., 81,* 3513-3536, 1970.

Bardoux, M., and E. Irving, Paleomagnetism of Eocene rocks of the Kelowna and Castlegar areas, British Columbia: Studies in determining paleohorizontal, *Can. J. Earth Sci., 26,* 829-844, 1989.

Beck, M. E., Jr., On the mechanism of tectonic transport in zones of oblique subduction, *Tectonophysics, 93,* 1-11, 1983.

Beck, M. E., Jr., Model for late Mesozoic - Early Tertiary tectonics of coastal California and western Mexico and speculations on the origin of the San Andreas fault, *Tectonics, 5,* 49-65, 1986.

Beck, M. E., Jr. and L. Noson, Anomalous palaeolatitude in Cretaceous granitic rocks, *Nature, 235,* 11-13, 1972.

Beck, M. E., Jr., R. F. Burmester, D. C. Engebretson, and R. Schoonover, Northward translation of Mesozoic batholiths of western North America: Paleomagnetic evidence and tectonic significance, *Geofis. Int., 20,* 144-162, 1981*a*.

Beck, M. E., Jr., R. F. Burmester, and R. Schoonover, Paleomagnetism and tectonics of theCretaceous Mr. Stuart batholith of Washington: Translation or tilt? *Earth Planet. Sci. Lett., 6,* 336-342,1981*b*.

Beck, M. E., Jr., R. F. Burmester, and R. Schoonover, Tertiary paleomagnetism of the North Cascade Range, Washington, *Geophys. Res. Lett., 9,* 515-518, 1982.

Brock, A., An experimental study of palaeosecular variation, *Geophys. J. R. Astron. Soc., 24,* 303-317, 1971.

Butler, R. F., "Comment on Northward motion of the Whitehorse Trough: paleomagnetic evidence from the Upper Cretaceous Carmacks Group", by G. Marquis and B. R. Globerman, *Can. J. Earth Sci., 27,* 614-616, 1990.

Butler, R. F., G. E. Gehrels, W. C. McClelland, S. R. May, and D. Klepacki, Discordant paleomagnetic poles from the Canadian Coast Plutonic Complex: Regional tilt rather than large-scale displacement, *Geology, 17,* 691-694, 1989.

Butler, R. F., T. C. Harms, and H. Gabrielse, Cretaceous remagnetization in the Sylvester Allochthon: Limits to post -105 Ma northward displacement of north central British Columbia, *Can. J. Earth Sci., 25,* 1316-1322, 1988.

Cas, R. A. F., and C. J. Wright, *Volcanic Successions, Modern and Ancient: A Geological Approach to Processess, Products and Successions,* Allen and Unwin, Winchester, Mass., 1987.

Coney, P. J., D. L. Jones, and J. W. H. Monger, Cordilleran suspect terranes, *Nature, 288,* 329-333, 1980.

Cox, A., Analysis of present geomagnetic field for comparison with paleomagnetic result, *J. Geomagn. Geoelectr., 13,* 101-112, 1962.

Cox, A., Lengths of geomagnetic polarity intervals, *J. Geophys. Res., 73,* 3247-3260, 1968.

Cox, A., Latitude dependence of the angular dispersion of the geomagnetic field, *Geophys. J. R. Astron. Soc., 20,* 253-269, 1970.

Creer, K. M., The dispersion of the geomagnetic field due to secular variation and its determination for remote times from paleomagnetic data, *J. Geophys. Res., 67,* 3461, 1962.

Creer, K. M., E. Irving, and S. K. Runcorn, The direction of the geomagnetic field in remote epochs in Great Britain, *J. Geomagn. Geoelectr. 6,* 163-168, 1954.

Creer, K. M., E. Irving, and A. E. M. Nairn, Palaeomagnetism of the Great Whin Sill, *Geophys. J. R. Astron. Soc., 2,* 306-323, 1959.

Demarest, H. H., Error analysis for the determination of tectonic rotation from paleomagnetic data, *J. Geophys. Res., 88,* 4321-4328, 1983.

Devlin, B. D., The relationships between the Spences Bridge and Kingsvale groups in southcentral British Columbia, B. Sc. thesis, 57pp. Univ. of Br. Columbia, Vancouver, 1981.

Diehl, J. F., M. E. Beck, Jr., S. Beske-Diehl, S. Jacobsen, and B. C. Hearn, Paleomagnetism of the Late Cretaceous - Early Tertiary north-central Montana Alkalic province, *J. Geophys. Res., 88,* 10, 593-10, 609, 1983.

Duffell, S., and K. C. McTaggart, Ashcroft map-area, British Columbia, *Geol. Surv. Can. Mem., 262,* 1-122, 1952.

Fitch, T. J., Plate convergence, transcurrent faults, and internal deformation of southeast Asia and the western Pacific, *J. Geophys. Res., 77,* 4432-4461, 1972.

Fox, K. F. and M. E. Beck, Jr., Paleomagnetic results for Eocene volcanic rocks from northeastern Washington and the Tertiary Tectonics of the Pacific Northwest, *Tectonics, 4,* 323-341, 1985.

Gabrielse, H., Major dextral transcurrent displacements along the northern Rocky Mountains Trench and related lineaments in north-central British Columbia, *Geol. Soc. Am. Bull., 96,* 1-14, 1985.

Gabrielse, H., Transcurrent faults, Semenof, Teslin, Thibert, Kutcho and Pinchi fault system, in *Decade of North American Geology,* vol., *The Cordilleran Orogen in Canada,* edited by H. Gabrielse, and C. J. Yorath, pp. 1990.

Globerman, B. R., and E. Irving, Mid-Cretaceous paleomagnetic reference field for North America: Restudy of 100 Ma intrusive rocks from Arkansas, *J. Geophys. Res., 93,* 11,721-11,733, 1988.

Graham, J. W., The stability and significance of magnetism in sedimentary rocks, *J. Geophys. Res., 54,* 131-167, 1949.

Granirer, J. L., R. F. Burmester, and M. E. Beck, Jr., Cretaceous paleomagnetism of the Methow-Pasayten Belt, Washington, *Geophys. Res. Lett., 13,* 733-736, 1986.

Irving, E., Whence British Columbia?, *Nature, 314,* 673-674, 1985.

Irving, E., and D. A. Archibald, Bathozonal tilt -corrections to paleomagnetic data from mid-Cretaceous plutonic rocks: Examples from the Omineca Belt British Columbia, *J. Geophys. Res., 95,* 4579-4585, 1990.

Irving, E., and M. T. Brandon, Paleomagnetism of the Flores volcanics; Vancouver Island in place by Eocene time, *Can. J. Earth Sci. 27,* 818-819, 1990.

Irving, E., and N. W. D. Massey, Paleomagnetism of ocean layers 2 and 3, evidence from the Metchosin Complex, Vancouver Island, *Phys. Earth Planet Sci.,* 1990.

Irving, E., and M. A. Ward, A statistical model of the geomagnetic field, *Pure Appl. Geophys., 57,* 25-30, 1964.

Irving, E., G. J. Woodsworth, P. J. Wynne, and A. Morrison, Paleomagnetic evidence for displacement from the south of the Coast Plutonic Complex, British Columbia, *Can. J. Earth Sci., 22,* 584-598, 1985.

Irving, E., and P. J. Wynne, Paleomagnetism of the Canadian Cordillera: Tectonic implications, appear in *Decade of North American Geology,* vol., *The Cordilleran Orogen, Canada,* edited by H. Gabrielse, and C. J. Yorath, pp. 1990.

Irving, E., and P.J. Wynne, Paleomagnetic evidence bearing on the evolution of the Canadian Cordillera, *Phil. Trans. Roy. Soc.,* A 331, 487-509, 1990.

Irving, E., P. J. Wynne, M. E. Evans, and W. Gough, Anomalous magnetism of the Crowsnest Formation of the Rocky Mountains, *Can. J. Earth Sci., 23,* 591-598, 1986.

Kleinspehn, K. L., Cretaceous sedimentation and tectonics, Tyaughton-Methow Basin, southwestern British Columbia, *Can. J. Earth Sci., 22,* 154-174, 1985.

Krogh, T. E., Improved accuracy of U-Pb ages by the creation of more concordant systems using an Air-abrasion technique, *Geochim. Cosmochim. Acta, 46,* 637-649, 1982.

Mankinen, E. A., Paleomagnetic evidence for a Late Cretaceous deformation of the Great Valley sequence, Sacramento Valley, California, *J. Res. U. S. Geol. Surv., 6,* 383-390, 1978.

Marquis, G., and B. R. Globerman, Northward motion of the Whitehorse Trough: Paleomagnetic evidence from the Upper Cretaceous Carmacks Group, *Can. J. Earth Sci. 25,* 2005-2016, 1988.

Marquis, G., E. Irving, and B. R. Globerman, Reply "Northward motion of the Whitehorse Trough: Paleomagnetic evidence from the Upper Cretaceous Carmacks Group", *Can. J. Earth Sci. 27,* 617-618, 1990.

Mathews, W. H., and G. E. Rouse, The Gang Ranch - Big Bar area, south-central British Columbia: Stratigraphy, geochronology, and palynology of the Tertiary beds and their relationship to the Fraser Fault, *Can. J. Earth Sci., 21,* 1132-1144, 1984.

Miller, R. B., S. Y. Johnson, and J. W. McDougall, Comment on "Discordant paleomagnetic poles from the Canadian Coast Plutonic Complex: regional tilt rather than large displacement?" by *Geology,* 1990.

Monger, J. W. H., Structural evolution of the southwestern intermontane belt, Ashcroft and Hope map areas, British Columbia, Current Research, Part A, *Geol. Surv. Can. Pap. 85-1A, pp.* 349-358, 1985.

Monger, J. W. H., Geology between Harrison Lake and Fraser River, Hope map area, southwestern British Columbia, Current Research, Part A, *Geol. Surv. Can. Pap. 86-18,* pp. 699-706, 1986.

Monger, J. W. H., Yalakom, Pasayten, Harrison and Ross Lake Fault Systems, in *Decade of North American Geology,* vol. entitled *The Cordillera Orogen in Canada,* edited by H. Gabrielse, and C. J. Yorath, pp. 1990.

Monger, J. W. H. and W. J. McMillan, Bedrock geology of Ashcroft (92I) map area, *Geol. Surv. Can., Open File, 980,* 1984.

Monger, J. W. H., and E. Irving, Northward displacement of north-central British Columbia, *Nature, 285,* 289-293, 1980.

Monger, J. W. H., R. A. Price, and D. J. Tempelman-Kluit, Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera, *Geology, 10,* 70-75, 1982.

Parrish, R. R., J. C. Roddick, W. D. Loveridge, and P. W. Sullivan, Uranium-lead analytical techniques at the geochronological laboratory, Geological Survey of Canada, *Geol. Surv. Can. Pap. 87-2,* pp. 3-7, 1987.

Preto, V. A., Geology of the Nicola Group between Merritt and Princeton, *Br. Columbia Minist. of Energy Mines Pet. Res., Bull., 69,* 1-90, 1979.

Price, R. A., The Cordilleran foreland thrust and foldbelt in the southern Canadian Rocky Mountains, *Spec. Publ. Geol. Soc. London, 9,* 427-441, 1981.

Price, R. A. and D. M. Carmichael, Geometric test for Late Cretaceous - Paleogene intracontinental transform faulting in the Canadian Cordillera, *Geology, 14,* 468-471, 1986.

Rees, C. J., E. Irving, and R.L. Brown, Secondary magnetization of Triassic-Jurassic volcaniclastic rocks of the Quesnel terrane, Quesnel Lake, B.C., *Geophys. Res. Lett., 12,* 498-501, 1985.

Rice, H. M. A., Geology and mineral deposits of Princeton map area, British Columbia, *Geol. Surv. Can. Mem., 234,*1-136,1947.

Roddick, J. C., Generalised numerical error analysis with applications to geochronology and thermodynamics, *Geochim. et Cosmochim. Acta, 51,* 2129-2135, 1987.

Shive, P. N., and E. F. Pruss, A paleomagnetic study of basalt flows from the Absaroka Mountains, Wyoming, *J. Geophys. Res., 82,* 3039-3048, 1977.

Smith, A. D., Isotopic and geochemical studies of Terrane I, south-central British Columbia, Ph.D. thesis, pp. 1-195, Univ.of Alberta, Edmonton, 1986.

Swenson, P., and M. McWilliams, Paleomagnetic results from the Upper Cretaceous Mandlow and Livingston Formations, southwest Montana, *Geophys. Res. Lett., 16,* 669-672, 1989.

Symons, D. T. A., Geotectonics of Cretaceous and Eocene plutons in British Columbia, a paleomagnetic fold test, *Can. J. Earth Sci., 14,* 1246-1262, 1977.

Symons, D. T. A., and M. R. Welling, Paleomagnetism of the Eocene Kamloops Group and the cratonization of Terrane I of the Canadian Cordillera, *Can. J. Earth Sci., 26,* 821-828, 1989.

Thorkelson, D. J., Geology of the mid-Cretaceous volcanic units near Kingsvale, southwestern British Columbia, Current Research, Part B, *Geol. Surv. Can. Pap., 85-18,* 333-339, 1985.

Thorkelson, D. J., Volcanic stratigraphy and petrology of the mid-Cretaceous Spences Bridge Group near Kingsvale, southwestern British Columbia, M. Sc. thesis, pp. 1-119, Univ. of Bri. Columbia, Vancouver, 1986.

Thorkelson, D. J., Magma mixing and alteration of tectonic affinity in the Spences Bridge Group, southwestern British Columbia, *Geol. Assoc. Can. Progr. Abstr., 96, 210,* 1987.

Thorkelson, D. J., Eocene sedimentation and volcanism in the Fig Lake Graben, southwestern British Columbia, *Can. J. Earth Sci., 26,* 1368-1373, 1989.

Thorkelson, D. J., and G. E. Rouse, Revised stratigraphic nomenclature and age determinations for mid-Cretaceous volcanic rocks in southwestern British Columbia, *Can. J. Earth Sci., 26,* 2016-2031, 1989.

Thorkelson, D. J., and A. D. Smith, Arc and intraplate volcanism in the Spences Bridge Group: Implications for Cretaceous tectonics in the Canadian Cordillera, *Geology,* 1093-1096, 1989.

Umhoefer, P. J., Northward translation of "Baja British Columbia" along the Late Cretaceous to Paleocene margin of western North America, *Tectonics, 6,* 377-394, 1987.

Umhoefer, P. J., J. I. Ganier, P. Schiarizza, and J. K. Glover, The Late Cretaceous to Early Tertiary Yalakom Fault System southwestern British Columbia, *Geol. Soc. Am. Cordilleran Mtg. Abstr.* 1989*a*.

Umhoefer, P. J., J. Dragovich, J. Cory, and D. C. Engebretson, Refinements of the "Baja British Columbia" plate-tectonic model for northward translation along the margin of western North America, in *Deep Structure and Past Kinematics of Accepted Terranes, Geophys. Monogr. Ser. vol.* 50, edited by J. W. Hillhouse, pp. 101-111, AGU, Washington, D.C., 1989*b*.

Vandall, T. A., and H. C. Palmer, Upper limit of docking time for Stikinia and Terrane 1: Paleomagnetic evidence from the Eocene Ootsa Lake Group, British Columbia, *Can. J. Earth Sci., 27,* 212-218, -1990.

Wernicke, B., Uniform-sense normal simple-shear of the continental lithosphere, *Can. J. Earth Sci., 22,* 108-125, 1985.

Wheeler, J. O., and P. McFeely, Tectonic assemblage map of the Canadian Cordillera and adjacent parts of the United States of Amercia, *Geol. Surv. Can., Open File Map, 1565*, 1988.

Williams, H., and A. R. McBirney, *Volcanology*, Freeman, Cooper, San Francisco, Calif., 1979.

Yole, R. W., and E. Irving, Displacement of Vancouver Island paleomagnetic evidence from the Karmutsen Formation, *Can. J. Earth Sci., 17,* 1210-1128, 1980.

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