PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Palaeomagnetic Evidence Bearing on the Evolution of the Canadian Cordillera [and Discussion]

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Palaeomagnetic evidence bearing on the evolution of the Canadian Cordillera

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Palaeomagnetic data from Permian, Triassic and Jurassic bedded rocks, to which attitudinal corrections can be applied, yield palaeolatitudes concordant with those of ancestral North America, but very large predominantly anticlockwise rotations about vertical axes. Data from Cretaceous rocks yield apparent palaeolatitudinal displacements that increase westward. Small or negligible displacements are obtained from the Omineca Belt. Intermediate displacements (1000–2000 km) from the Intermontane Belt, are based on data from Cretaceous bedded sequences. Further to the west in the Coast Belt, larger apparent displacements (greater than 2000 km) have been obtained from plutons for which no attitudinal control is yet available. Data from Eocene rocks are concordant.

Possibilities to consider are as follows: (*a*) little or no displacement and tilting to the southwest at about 30°; (*b*) large (greater than 2000 km in the Coast Belt) northward displacement since mid-Cretaceous time preceded by southward displacement of comparable magnitude in Juro–Cretaceous time; (*c*) lesser (1000–2000 km) overall displacement coupled with variable and lesser tilts to the south and southeast of plutons of the Coast Belt. Under hypothesis (*a*) the western Cordillera was formed and has remained in approximately its present position relative to ancestral North America; data from bedded volcanics of the Intermontane Belt are not consistent with this hypothesis. From the evidence currently available we favour hypotheses (*b*) or (*c*), although more data from bedded sequences are required. It is noteworthy that hypotheses (*a*) and (*c*) predict tilt directions that differ by about 90° and hence ought to be distinguishable by geological studies.

1. Introduction

Our purpose is to review the palaeomagnetic evidence that bears on the evolution of the Pacific Northwest sector of the North American Cordillera. We are concerned mainly with data from British Columbia, Yukon and adjacent areas of Alaska and Washington, but we review also Cretaceous data from California and Baja California.

Palaeopoles calculated from the directions of magnetization (palaeodirections) observed in rock-units laid down contemporaneously on the craton of North America and in the Cordillera should agree if both have formed in their present relative positions. If they do not, and if post-depositional tilting of the rock-units can be estimated, then the palaeolatitudinal displacement and rotation relative to the craton of the Cordilleran locality can be calculated. The accuracy of determinations depends on the accuracies with which cordilleran and cratonic reference palaeopoles can be positioned and dated. The errors are such that displacements less than about 500 km and rotations less than 5° are unlikely to be identified. Relative palaeolongitudinal displacements cannot be determined by this method.

Terranes and belts

The Western Cordillera in British Columbia and adjacent areas of northern Washington and Alaska comprise several morpho-geologic belts which trend general NNW to SSE (figure 1). Within each belt are several fault-bounded terranes (figure 2). Some terranes are confined within a single belt, others are not. For example, the Wrangellia terrane straddles the boundary between the Intermontane and Coast belts, and Quesnellia occurs on both sides of the boundary between the Intermontane and Omineca belts (compare figures 1 and 2).

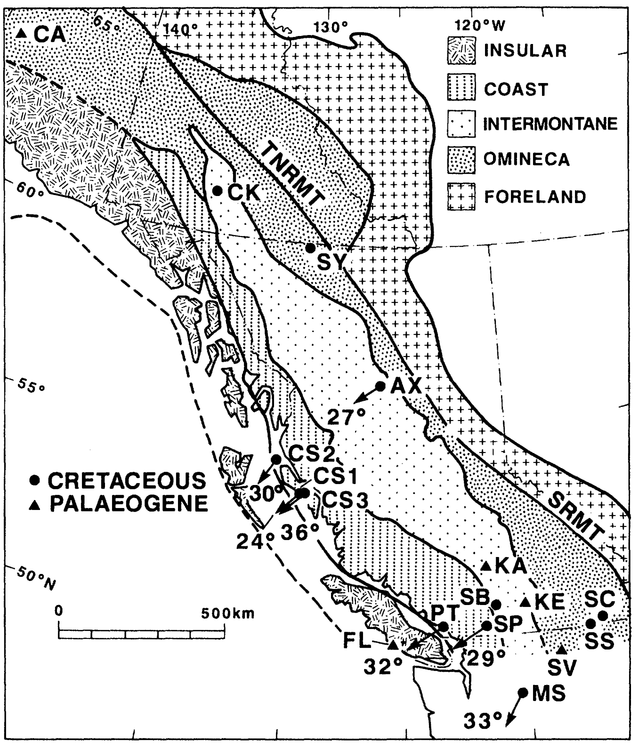

FIGURE 1. Morpho-geological belts showing sampling localities in Cretaceous and Lower Tertiary rocks. Arrows at localities of Cretaceous plutons in the Coast and Intermontane belts indicate the direction and magnitude of tilting required to explain their anomalous palaeodirections. Localities labelled as in table 2. NRMT and SRMT are the northern and southern sections of the Rocky Mountain trench.

The concept of terranes, as it applies to the Canadian Cordillera, relates to the formation and subsequent amalgamation of geologically distinct and tectonically separate rock assemblages, processes that happened mainly during Triassic through early Cretaceous time (Monger *et al.* 1982). Belts, on the other hand, are defined largely on the basis of physiography, and have been produced by the accretion of terranes to North America and their subsequent deformation.

Although the accretion of some young westerly terranes (the Crescent Terrane for example) occurred in the Eocene and overlapped in time the processes that created the morpho-geologic belts, the distinction between an earlier period of terrane formation and amalgamation, and a later period during which belts were established is valid for most of the Canadian sector of the Cordillera. Hence, we consider palaeomagnetic data from older rock-units (Permian through Lower Jurassic) in the terrane context, and data from younger rock-units (mid-Cretaceous through Eocene) in the context of the distribution of belts.

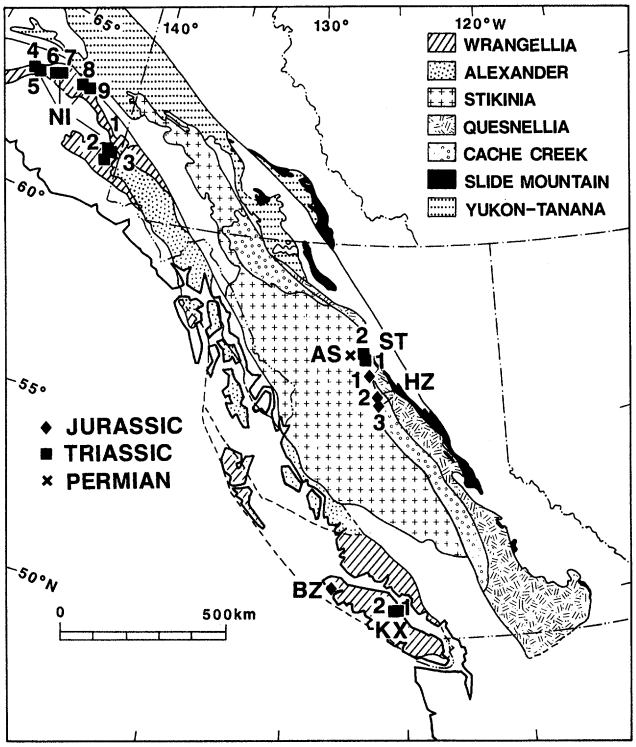

FIGURE 2. Major terranes with sampling localities in Permian, Triassic and Jurassic rocks.

Themes

Discussions of Cordilleran palaeomagnetism have centred about four main themes, beginning with the discovery of large rotations about vertical axes. These were first observed as aberrant declinations in bedded Eocene volcanic rocks (Cox 1957), although not at the time recognized as indicative of tectonic rotations (Cox 1980). Subsequent work has shown rotations to be common, typically clockwise in Cretaceous and Palaeogene rocks, and often anticlockwise in older sequences (Beck 1976, 1980; Monger & Irving 1980; Irving & Yole 1987).

The second theme concerns the apparent displacement from the south of some elements of the Cordillera by as much as 2000 km since mid-Cretaceous time. The idea that such late displacements could have occurred emerged from the work of Beck & Noson (1972) on the Mount Stuart batholith of the northern Cascade Mountains of Washington (MS of figure 1), and of Tiessere & Beck (1973) on the Peninsular Batholith of southern California (SA of figure 5). Both intrusions are approximately 100 Ma old, and both yielded anomalously low inclinations (i.e. low palaeolatitudes). Several years later similar discordant magnetizations were observed in the Cretaceous Axelgold intrusion, a body which is located in the eastern part of the Intermontane Belt of British Columbia (Monger & Irving 1980). This and other evidence led Monger & Irving (1980) and Irving *et al.* (1980) to propose that about two-thirds of British Columbia and adjacent parts of Washington and Alaska (a region which later was referred to as *Baja British Columbia* (Irving 1985)) had been displaced from the south in latest Cretaceous and Palaeocene time. The concept of Baja British Columbia, (or Baja B.C.) was developed from the work of Packer & Stone (1974), and from Atwater's study of the northward motion of Baja California (Atwater 1970). However, the term 'Baja B.C.' is meant to imply only that the region formerly had a lower or more southerly position, and that the motions which brought it into its present position was predominantly in a coastwise sense, like that of Baja California today, but no specific mechanism of transport is implied.

The third theme concerns data from older sequences (Permian, Triassic, Jurassic) which have yielded apparent displacements that are very much less than those obtained from Cretaceous rocks. Initially, these data indicated motions from the south in excess of 1000 km (Symons 1971*b*; Irving & Yole 1972, 1980; Hillhouse 1977), but revisions of the timescale (for example by Harland *et al.* 1982) have forced a recalibration of the apparent polar wander path for cratonic North America, causing a decrease in estimates of displacement to the point that many of them may not be significant (Gordon *et al.* 1984; May & Butler 1986). These discoveries of large net displacements from younger rocks and small net displacements from older rocks has led to two divergent discussions in the palaeomagnetic literature. In one, workers have entertained the possibility that the terranes of the Pacific Northwest sector of the Cordillera first moved south *en bloc* by 1000 km or more, and then north by as much as 2000 km (Irving *et al.* 1985; Beck 1990; Irving & Wynne 1990). In the second discussion, the small or negligible net displacements estimated from older rocks is deemed the more important discovery, and the larger displacements determined from younger rocks are explained by appealing to systematic tilt, thus denying large latitudinal displacements (May & Butler 1986; Butler *et al.* 1989) From the latter has emerged a conservative 'fixist' view of the tectonics of the Cordillera by which terranes of the Pacific Northwest are believed to have formed essentially where they are now, and to have moved no more than small distances in a latitudinal sense.

The fourth theme concerns the attenuation and dispersal of crustal elements in the Cordillera. This was first noted in Wrangellia, when localities now 1500 km apart yielded similar palaeolatitudes (Hillhouse 1977; Yole & Irving 1980) indicating that localities, once close together, have since been pulled apart. Other instances have been discussed for tectonic units situated inboard of Wrangellia (Irving *et al.* 1985; Irving & Monger 1987; Umhoefer 1987).

Some difficulties

Although the principle is the same as that used in the 1950s to test Wegener's hypothesis of continental drift, the practice is more difficult for several reasons. Firstly, the apparent relative displacements are 2–5 times less than those among continents so that some studies have been made at the limits of resolution of the method. Secondly, in orogenic regions it is difficult to obtain accurate, well-dated records of the palaeofield, because thermal, structural and diagenetic histories of rocks which control their magnetization, are complex and only partly understood; magnetic overprinting often occurs at times that are ill defined relative to deformation, making the separation of pre-, syn- and post-tilting magnetizations an ever-present and sometimes insoluble problem. The third difficulty concerns the interpretation of data from plutonic rocks in orogenic belts. In stable cratons, plutons generally have not undergone post-emplacement tilting and serve as excellent recorders of the palaeofield, but in orogenic zones it is generally difficult to determine post-emplacement tilt, so the interpretation of palaeomagnetic data from them can be ambiguous. Hence, discordant data from plutons indicate either displacement or post-emplacement tilt, or some combination of the two (Beck *et al.* 1981). However, sufficient detailed studies have now been made to allow these problems to be addressed although not yet settled.

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Table 1. Craton reference palaeopoles

		T (Ma) craton	T (Ma) cordillera	lat.° N, long.° E (A_{95})	rel.	
A	Eocene	54–48	55–48	83, 176 (3)	H	KE, KA, SP, FL
B	Palaeocene	67–62	Palaeocene (66–58)	81, 185 (6)	L	CA
C	latest Cretaceous and Palaeocene	73–63	70	78, 186 (8)	L	CK
D	mid-Cretaceous	136–85	120–95	71, 196 (5)	H	SC, SS, SA, AX, SB, CK, CS, SP, PP, MS
E	early Jurassic	195–191	Sinemurian–Toarcian (204–187)	65, 082 (4)	M	HZ, BZ
F	late Triassic	Norian–Carnian (230–208)	late Ladinian–early Norian (332–323)	53, 098 (7)	M	ST, KX, NI
G	early Permian	285–255	late Sakmarian–early Artinskian (270–265)	46, 119 (4)	H	AS

Notes for table 1. First column gives ages for which data are available from both craton and cordillera. Age spans of respective data are given in the second and third columns, in numbers if determined radiometrically, and by geological stages if determined stratigraphically followed by numerical ages estimated from the timescale of Palmer (1983). Palaeopoles and errors ($P = 0.05$) are followed by an estimate of reliability (H, high; M, moderate; L, low). The last column gives the cordilleran rock-units for which displacements and rotations have been calculated in table 2. The derivation of palaeopoles E and F is detailed below. A, B, C, D, and G have been given elsewhere, A, Irving & Brandon (1990); B, Jacobsen *et al.* (1980); C, Marquis & Globerman (1988); D, Globerman & Irving (1988); E, derived from following Newark Supergroup rocks that have been unaffected by Middle Jurassic overprints: North Mountain basalts, Nova Scotia, 191 Ma, 66.4° N, 71.9° E, $A_{95} = 11°$ (Hodych & Hayatsu 1988); Connecticut Valley rocks, 193 Ma, 65° N, 87° E, $A_{95} = 10°$ (de Boer & Snider 1979); prefolding magnetization of intrusive rocks Connecticut and Maryland, 91 Ma, 63.1° N, 82.5° E, $A_{95} = 2.8°$ (Smith & Noltimier 1979); Piedmont dykes, 195 Ma, 66.1° N, 83.9° E, $A_{95} = 7.5°$ (Dooley & Smith 1982); F, is the mean of following three data: Middle Carnian to early Norian rocks (Stockton, Lochatong and Passiac formations) of Newark Supergroup 53.6° N, 101.6° E, $A_{95} = 4.8°$ (Witte & Kent 1989); Popo Aige Formation, Norian and Carnian of Wyoming 55.5° N, 95.5° E, $A_{95} = 8°$ (Grubbs & van der Voo 1976); the Abbott (228 Ma) and Agamenticus (221 Ma) plutons of Maine, mean of 16 sites in Wu & van der Voo (1988) is 188.7°, −4.9°, $k = 241$, $\alpha_{95} = 2.4°$ with palaeopole 48.3° N, 96.0° E, $A_{95} = 1.9°$; G, mean of 9 palaeopoles in Irving & Irving (1982).

Table 2. Cordilleran data

rock-unit	ref.	lat.° N, long.° W	$D°$, $I°$	$\alpha_{95}°$	lat.° N, long.° E	$A_{95}°$	$\lambda_p°$	RPD°	RR°
			Palaeogene						
KE, Kelowna volcanics (52 Ma) IMB	pc	49.9, 119.7	352, 69	6	85, 197	10	53±08	00±08	−02±14
KA, Kamloops Group, volcanics (49 Ma) IMB	tc	51.0, 121.3	355, 73	7	81, 222	12	59±10	−05±10	−06±19
SV, Sanpoil volcanics (53–48 Ma) Wa., IMB	tc	48.5, 118.5	016, 69	4	79, 305	6	52±04	−01±05	−26±08
FL, Flores volcanics (51 Ma) INB	tc	49.0, 125.5	350, 69	7	81, 188	10	53±08	00±08	00±14
CA, Cantwell Formation, volcanics (61 Ma) Alaska	tc	63.6, 148.8	143, −85	5	70, 195	11	81±10	−09±09	—
			Cretaceous						
			Pacific Northwest (British Columbia, Yukon Territory and Washington)						
SC, Skelly Creek batholith (95 Ma) OB	nc	49.3, 116.5	349, 74	6	78, 216	10	60±08	−01±08	−17±17
SS, Summit Stock (104 Ma) OB	tc	49.1, 117.1	318, 74	3	64, 194	5	60±04	−01±06	14±11
SY, Permian limestone, overprint, OB	nc	59.4, 129.9	328, 77	4	76, 172	9	65±06	08±07	−05±20
AX1, Axelgold intrusion, gabbro (120–90 Ma) IMB	nc	56.2, 126.1	032, 60	4	64, 348	6	41±05	27±06	−65±12
AX2, Axelgold intrusion, gabbro (120–90 Ma) IMB	tc	56.2, 126.1	025, 69	5	76, 327	8	53±06	16±07	−58±15
SB, Spences Bridge Group, volcanics (104 Ma) IMB	tc	49.9, 121.0	039, 64	5	64, 321	7	46±06	16±07	−66±12
CK, Carmacks Group (70 Ma), volcanics Yukon, IMB	tc	61.2, 135.5	167, −71	5	82, 109	8	55±06	14±09	−09±21
CS1, Captains Cove pluton (109 Ma) CB	nc	53.2, 129.4	021, 61	7	72, 351	10	42±08	25±09	−49±14
CS2, Stephens Island pluton (102 Ma) CB	nc	54.1, 130.6	013, 53	5	67, 021	9	34±07	34±08	−41±13
CS3, Gil Island pluton (136 Ma) CB	nc	53.2, 129.2	029, 50	17	59, 356	19	31±15	36±16	−57±21
CS, Three coast pluton combined, CB	nc	53.5, 129.7	022, 56	6	67, 360	8	37±06	30±07	−50±13
SP, Spuzzum pluton (104 Ma) CB	nc	49.4, 121.5	031, 57	6	65, 017	7	38±06	23±07	−58±11
PT, Porteau pluton (100 Ma) CB	nc	49.5, 123.2	031, 54	9	63, 345	11	35±09	27±09	−58±13
MS, Mount Stuart batholith (100 Ma) Wa. CB	nc	47.5, 121.0	010, 45	5	68, 035	5	27±04	32±06	−36±09
			Klamath Mountains–Sierra Nevada						
KM, Great Valley sequence, Ca. sst.	tc	40.3, 122.7	338, 65	6	73, 177	8	47±07	06±09	01±14
SN, Sierra Nevada plutons, Ca.	nc	37.5, 119.0	—	—	72, 175	6	43±04	06±06	03±09
MD, Mina deflection, plutons, Nv.	nc	38.5, 118.3	356, 64	11	81, 226	16	47±15	03±15	−18±23
BV, Bear Valley Springs pluton, Ca.	nc	35.2, 118.3	022, 56	6	72, 322	7	37±06	10±08	−42±10
			Baja California (Mexico and U.S.A.)						
SA, Ladd and Williams Fms seds, Ca.	tc	34.5, 117.0	324, 45	7	58, 149	7	27±06	19±07	16±09
AL, Alisitos Fm, Baja Ca.	tc	31.5, 116.5	010, 50	8	81, 336	9	31±08	12±09	−29±11
LB, La Bocana Roja Fm, Baja Ca.	tc	30.0, 116.0	012, 52	6	80, 317	6	33±05	−09±07	10±09
PR, Peninsular Ranges batholith, Ca. and Baja Ca.	nc	30.0, 115.0	006, 48	3	85, 346	3	29±03	12±06	−25±07
VF, Valle Fm, turbidites, Baja Ca.	tc	27.5, 114.5	006, 40	4	83, 013	4	23±03	16±06	−25±07
ER, El Rosario Formation, Baja Ca.	tc	31.3, 116.3	005, 45	3	83, 021	2	26±01	16±04	−24±06
			Western California						
LL, Laytonville Limestone age, Albian–Cenomanian	tc	39.5, 123.6	—	—	—	—	−14±05	66±07	—
PP, Pigeon Point Fm, Upper Cretaceous turbidites	tc	37.2, 122.5	, 37	5	—	—	21±04	29±06	—
CL, Calera Limestone, mid-Cretaceous	tc	37.5, 122.3	—	—	—	—	24±04	27±06	—
FT, Figueroa Mt, Upper Cretaceous turbidites	tc	35.0, 120.0	023, 12	11	54, 019	8	06±06	41±08	−43±09
JA, Jalama Fm, Upper Cretaceous turbidites	tc	34.0, 120.4	024, 44	3	68, 345	3	26±02	11±05	−01±07
MC, Marin County basalt, Valinginian	tc	38.0, 122.8	078, 47	8	26, 309	9	28±07	23±10	[illegible] 13

			Jurassic (British Columbia and Washington)						
HZ1, Hazelton Group, Jl (ST)	tc	56.5, 126.8	114, −52	25	40, 144	30	33±24	01±25	52±29
HZ2, Hazelton Group, Jl (ST)	tc	55.8, 126.6	242, 56	19	17, 185	22	37±18	−04±19	105±22
HZ3, Hazelton Group, Jl (ST)	tc	55.6, 126.4	359, 55	16	70, 057	19	36±16	−03±17	−12±19
HZ, Hazelton Group, volcanics, Jl (ST)	tc	56.0, 126.6	—, 54	—	—	—	35±16	−01±16	—
BV, Bonanza Group, volcanics, Jl (WT)	tc	50.5, 128.1	276, 42	6	22, 154	8	25±06	04±07	71±07
JI, James Island Fm, turbidites, Ju, Wa. (DT)	tc	48.5, 122.8	344, −01	18	39, 078	14	01±01	37±12	−19±12
			Triassic (British Columbia and Alaska)						
ST1, Stuhinni Group, Tru (ST)	tc	56.7, 126.4	300, 44	6	38, 133	10	26±08	−01±09	32±10
ST2, Stuhinni Group, Tru (ST)	tc	56.6, 126.5	281, 38	7	24, 146	9	21±07	03±09	51±09
ST, Stuhinni Group, volcanics combined, Tru (ST)	tc	56.7, 126.5	—, 41	—	—	—	23±07	02±09	—
KX1, Karmutsen Formation, lavas, sills, Tru (WT)	tc	49.9, 125.6	337, −24	9	24, 080	8	13±06	06±08	177±08
KX2, Karmutsen Formation, Tru (WT)	tc	49.9, 125.6	013, −34	5	20, 042	5	19±04	00±06	141±07
KX, Karmutsen Formation combined, Tru (WT)	tc	49.9, 125.6	003, −33	6	23, 052	6	18±05	01±07	−29±07
NIA, Nicolai volcanics 1–3 combined, Ak., Tru (WT)	tc	61.6, 142.3	074, −20	6	02, 146	5	10±03	23±08	−133±09
NI1, Nicolai volcanics, Ak. (WT)	tc	61.7, 142.4	077, −23	3	−05, 325	2	12±02	22±05	64±06
NI2, Nicolai volcanics, Ak. (WT)	tc	61.6, 142.9	065, −18	8	03, 333	7	09±02	25±07	105±08
NI3, Nicolai volcanics, Ak. (WT)	tc	61.5, 142.8	095, −15	17	−10, 306	14	08±11	26±12	45±13
NIB, Nicolai volcanics, 4–9 combined, Ak. (WT)	tc	—	—	—	—	—	14±04	22±07	—
NI4, Nicolai volcanics, Ak. (WT)	tc	63.1, 147.4	060, −33	9	−04, 338	9	18±08	18±08	103±10
NI5, Nicolai volcanics, Ak. (WT)	tc	63.1, 147.1	138, −32	11	−37, 265	8	18±06	19±08	01±09
NI6, Nicolai volcanics, Ak. (WT)	tc	63.2, 146.3	084, −20	12	−07, 313	8	10±06	26±08	53±09
NI7, Nicolai volcanics, Ak. (WT)	tc	63.3, 145.9	095, −07	7	−05, 302	6	03±05	33±07	43±08
NI8, Nicolai volcanics, Ak. (WT)	tc	63.1, 144.4	105, −30	13	−22, 300	10	16±08	19±10	34±11
NI9, Nicolai volcanics, Ak. (WT)	tc	63.1, 144.3	119, −27	25	−30, 288	24	15±19	21±20	20±21
			Permian (British Columbia)						
AS, Asitka Group, basalts, Pl (ST)	tc	56.7, 126.6	129, −40	8	40, 123	5	23±04	04±05	06±06

Notes for table 2. First column gives the rock-unit name, age, province or state of origin (those undesignated are from British Columbia), and, when in Canada, the tectonic belt or terrane (bracketed) as follows. IMB Intermontane, OB Omineca, and CB Coast belts; ST Stikine, DT Decatur and WT Wrangel terranes. Second column gives the attitudinal corrections applied, tc total correction, pc partial correction, nc no corrections. Column three gives the sampling location. $D°$, $I°$ are the declination and inclination of the mean direction of remanent magnetization, α_{95}° is the radius of the circle of confidence ($P = 0.05$). Column six contains the palaeopole and A_{95}° is its radius of the circle of confidence. λ_{p}° is the palaeolatitude of the sampling locality. RPD is the relative palaeolatitudinal displacement (positive if the motion is northward), and RR the rotation (negative if clockwise), both relative to the reference palaeopoles of table 1 for the northern option. Values for southern option are not listed, but can be readily calculated from table 1. The references are as follows: KE, Bardoux & Irving (1989); KA, Symons & Welling (1989); SP, Fox & Beck (1985); FL, Irving & Brandon (1990); CA, Hillhouse & Grommé (1982); SC and SS, Irving & Archibald (1990); SY, Butler *et al.* (1988); AX, Monger & Irving (1980), Armstrong *et al.* (1985); CS, Symons (1977); SB, Irving & Thorkelson (1990); SP, Irving *et al.* (1985); PT, Porteau pluton based on high unblocking temperature (755 °C) high coercive force (greater than 80 mT) magnetizations from five sites which fulfill the most stringent (AI) criteria in Irving *et al.* (1985), data of Irving *et al.* (1985) and unpublished data of Irving & Yorath; TS, Beck (1975); MS, Beck *et al.* (1981); KM, Mankinen & Irwin (1982); JM, Russell *et al.* (1982); SN, Frei *et al.* (1984), Grommé & Merrill (1965), Frei (1986) mean of four plutons; MD, Geissman *et al.* (1984); BV, Kanter & McWilliams (1982); SA, Fry *et al.* (1985); AL, LB, and VF, Hagstrum *et al.* (1985); PR, Teissere & Beck (1973), Hagstrum *et al.* (1985); ER, Filmer & Kirschvink (1989); LL, Alvarez *et al.* (1980), Tarduno *et al.* (1986); PP, Champion *et al.* (1984); CL, Courtillot *et al.* (1985), Tarduno *et al.* (1985); FT, McWilliams & Howell (1982); JA, Champion *et al.* (1986); MC, Grommé (1984); HZ, Monger & Irving (1980); BV, Irving & Yole (1987); ST, formerly Takla Group, Monger & Irving (1980); KX, KX1 NW group, KX2 NNE group calculated from Yole & Irving (1980) and Schwarz *et al.* (1980) sites unit weight; NIA McCarthy Quadrangle, Hillhouse (1977) three localities; NIB Mt, Hayes & Healey Quadrangle, Hillhouse & Grommé (1984) six localities; AS, Irving & Monger (1987).

We consider only data from rocks that are well dated, and for which there are good reasons to assume that they record the palaeofield at, or soon after, deposition. With one exception (SY of table 2), we do not consider magnetizations that could be overprints because they generally lack an adequate time basis for tectonic discussions. Finally, only data from rock-units that may be expected to have averaged out palaeosecular variation are included. Data that has not been accepted are listed in the appendix. Data available in abstract are noted, but are not integrated into the analysis.

2. Cratonic reference palaeopoles

Data from the Pacific Northwest fall into four main (Eocene, mid-Cretaceous, early Jurassic, late Triassic) and three subordinate (Palaeocene, latest Cretaceous, Permian) groups. Reference palaeopoles have been obtained by selecting data from the craton which span each of these seven time intervals (table 1). In this way errors in time correlation between craton and cordillera are minimized. The rationale for using this, rather than other procedures (see, for example, Gordon *et al.* 1984) has been given by Irving & Yole (1987). Only the reference palaeopoles for the Eocene, mid-Cretaceous and early Permian can be regarded as of high reliability. Others are based on fewer, often less well-based data.

3. Tertiary

Many studies of Neogene rock-units have yield palaeopoles that agree with the present geographic pole and with palaeopoles from the craton (reviewed Irving & Wynne 1990). Three studies of Eocene rocks from British Columbia (FL, KA, KE) yielded results that are concordant with the craton (figure 3). Data from eastern Washington (SV) gave a concordant palaeolatitude, but a clockwise rotation. Data from the Cantwell Formation (CA) give very high palaeolatitudes with a mean displacement of 9°, which is marginally significant. Note, however, that the reference palaeopole for the Palaeocene is based on only a single

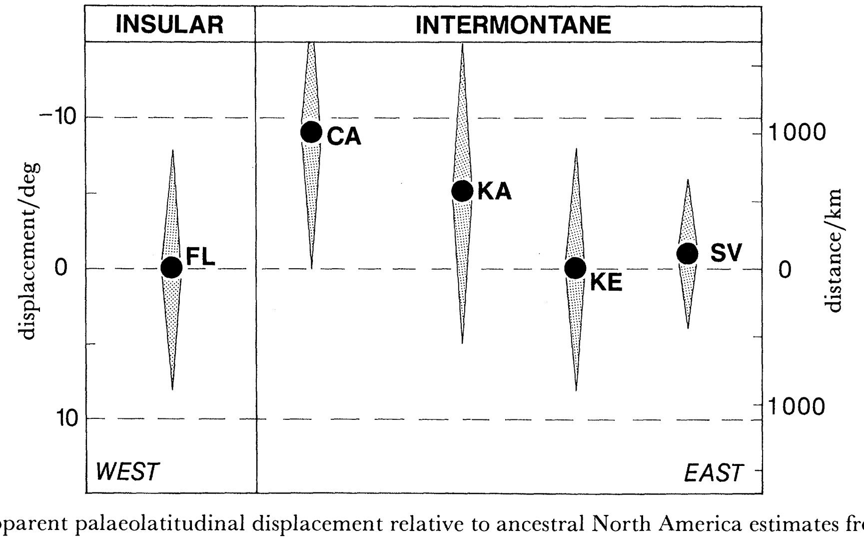

FIGURE 3. Apparent palaeolatitudinal displacement relative to ancestral North America estimates from Palaeocene and Eocene rocks. Labelled as in table 2 and figure 1. Recent data from Eocene rocks of central Intermontane Belt similarly yield no palaeolatitudinal displacement (Vandall & Palmer 1988).

determination (table 1). In these and other analyses of table 2 and figures 4, 7 and 8, 95% errors are given, so that if departures are found they must be regarded as statistically significant. It is important to note that these errors are not ranges but are probability distributions. The probability is highest at, or close to, the mean and diminishes away from it. For this reason 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 data of figure 3 show that the major elements of the Pacific Northwest sector of the Cordillera were essentially in place by 50 Ma.

4. Cretaceous data from the Pacific Northwest

Apparent displacements estimated from Cretaceous rocks of British Columbia and Washington are shown in figure 4. Data are grouped according to the degree of attitudinal control. Apparent displacements increase from east to west, and rotations are predominantly clockwise (figure 5).

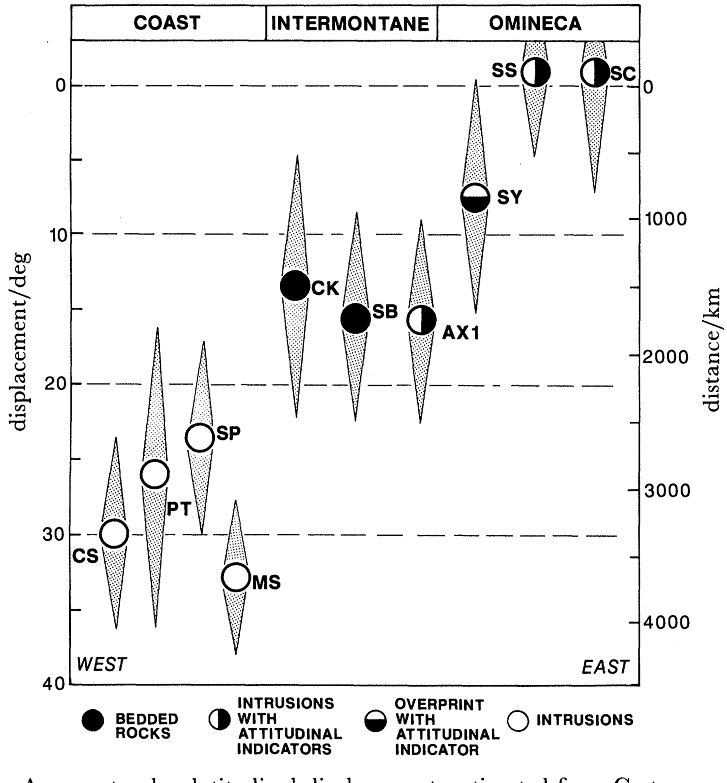

Figure 4. Apparent palaeolatitudinal displacements estimated from Cretaceous rocks. Labelled as in table 2 and figure 1.

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. These data are from plutons, but corrections for tilts have been made using bathozonal information (Irving & Archibald 1990). Evidently this region has remained nearly 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

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Mountain Trench fault, has yielded an apparent displacement of 800 ± 850 km (SY, figure 1 and table 2). This is marginally significant, but is, nevertheless, consistent with geologically based estimates of displacement of at least 750 km on the Tintina and northern Rocky Mountain Trench and associated faults, which are located to the east of the sampling locality (Gabrielse 1985). SY is derived from an overprint observed in Permian limestones of the Slide Mountain Terrane. This magnetization is presumed to be contemporaneous with that of the nearby mid-Cretaceous Cassiar batholith, and the sub-horizontal thrust that underlies the sampling area indicates that post-intrusion tilting has been negligible. This datum is, therefore, accepted as a reasonable indicator of modest displacement.

Displacements estimated from the Spences Bridge and Carmacks Groups, both stratified volcanic units in the Intermontane Belt, are significant, and are in mutual agreement. It should be noted, however, that the Carmacks Group was laid down in the latest Cretaceous (70 Ma) at a time when the cratonic reference field is not well known and may have been changing rapidly (table 1). Both studies include data from beds which yield a positive tilt test, indicating that the magnetization was acquired before deformation. The Spences Bridge has rotated clockwise. The young Carmacks has not undergone significant rotation. Displacements obtained from bedded sequences also are in good agreement with that estimated for the Axelgold intrusion after correction to its prominent planes of layering (Monger & Irving 1980). If Axelgold magnetizations are considered to have been acquired after the layers were tilted, then the estimated displacement approaches 3000 km (table 2).

All data from the Coast Belt are from plutonic rocks. Mount Stuart, in the northern Cascade Mountains of Washington, has the largest apparent displacement, exceeding 3500 km. Alternatively, it may have been tilted down by about 33 at 210° E (figure 1). Three coastal plutons in the Prince Rupert area, detailed separately in figure 1 and table 2, have a mean apparent displacements of over 3000 km, or a mean apparent tilt of down 28° at 223°. The Spuzzum and Porteau plutons in the southern Coast Ranges give displacements of about 2600 km, or mean apparent downward tilts of 29° at 238° E and 32° at 240° E respectively. All apparent displacements exceed those observed from the Intermontane Belt, and all apparent rotations are about 60° clockwise (table 2 and figure 5). The question is, have the plutons been tilted or have they been displaced latitudinally?

Irving & Thorkelson (1990) have attempted an answer by comparing data from the bedded volcanics of the Spences Bridge Group of the Intermontane Belt, and the nearby Spuzzum pluton of the Coast Belt. The apparent displacement of the former is just significantly less than that of the latter (figure 4). The two mid-Cretaceous units are separated by a series of dextral strike–slip faults, which delineate the belt boundary, and which were active in late Cretaceous and early Tertiary times. Monger (1990) and Umhoefer *et al.* (1989*a*) have estimated a total displacement of between 300 and 400 km along them. Adding 350 km to the displacement of 1750 ± 800 km estimated for the Spences Bridge Group, produces a total expected displacement of the Spuzzum pluton of about 2100 ± 800 km. This is not significantly different from the displacement estimated from the untilted pluton itself (2600 ± 700 km, table 2). Hence, it appears that most but not necessarily all of the apparent displacement observed from the Spuzzum pluton is a real latitudinal offset, and is unlikely to have been caused entirely by 30° tilting to the southwest as depicted in figure 1.

Displacements estimated for the Prince Rupert and Mount Stuart intrusions are larger (about 3000 km). Hence, the total offset elsewhere on faults between the Coast and

Intermontane belts either has been larger than estimated, or these intrusions have been tilted relative to Spuzzum as well as translated. The tilting about a horizontal axis required to bring the palaeodirection from the Coast (CS) plutons into accord with that from Spuzzum is $6° \pm 6°$ at 157°, that for the Porteau Pluton is negligible, and that for Mount Stuart is $18° \pm 7°$ at 142°.

Alternatively one may argue that all differences between apparent displacements from the Intermontane and Coast belts are caused by tilting 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: coastal plutons (CS) down 12° at 168, Porteau plutons (PT) 8° at 194°, Spuzzum pluton (SP) 08° at 176°, Mount Stuart batholith (MS) down 25° at 154°.

We may summarize now the three possible explanations of the Cretaceous data of figure 4: (*a*) regional tilting to the west and southwest by about 30° (figure 1); (*b*) real displacements increasing westward to over 2000 km; (*c*) real displacement of about 1500 km, the additional aberrancies of the Coast Belt being caused by variable tilt of plutons to the south and southeast. Data presently available from bedded rocks of the Spences Bridge group are inconsistent with (*a*). It should be possible to test the validity of (*a*) or (*c*) using geological studies because the required tilts are in directions approximately 90° apart.

If hypothesis (*b*) is correct, then there must have been not one but many fault systems along which transcurrent motion occurred. Moreover, the clockwise rotations commonly observed (table 2 and figure 5) show that some of the apparent strain may have been accommodated by block rotation. Therefore, to make quantitative geological tests of palaeomagnetically estimated displacements, it is necessary to determine displacements on all late Cretaceous and Palaeocene faults and all the associated block rotations that have occurred to the west of the Rocky Mountain Trench in the north, and west of the boundary between the Omineca and Intermontane belts in the south. It is not a sufficient test to analyse a few fault systems, as Price & Carmichael (1986) have done. It is noteworthy that where such comparisons have been made in juxtaposition to palaeomagnetically estimated displacements, notably along the Northern Rocky Mountain and the Fraser–Yalakom fault systems, the displacements obtained are broadly consistent with the palaeomagnetic data, as described above.

4. Cretaceous results, California and Baja California

It should be possible to integrate the data of figure 4 with that from mid-Cretaceous rocks elsewhere in the Cordillera, and an attempt at integration might help to distinguish among the three possibilities identified above. We now attempt to do this by reviewing data from California and Baja California (table 2). For space reasons, Cretaceous data from terranes north and west of Wrangellia are not considered.

In figure 5, the data are arranged in four regional groups, the Pacific Northwest (just described), the Klamath Mountains and Sierra Nevada, Baja California, comprising Baja California and the adajacent Peninsular Ranges batholith of southern California, and Western California, comprising California west of the Great Valley sequence. Palaeolatitudes are plotted against the modern west coast of North America whch runs approximately north–south on the mid-Cretaceous cratonic reference grid. Rotations are shown in insets. All magnetizations, like those further north, have positive inclinations and can be ascribed to the

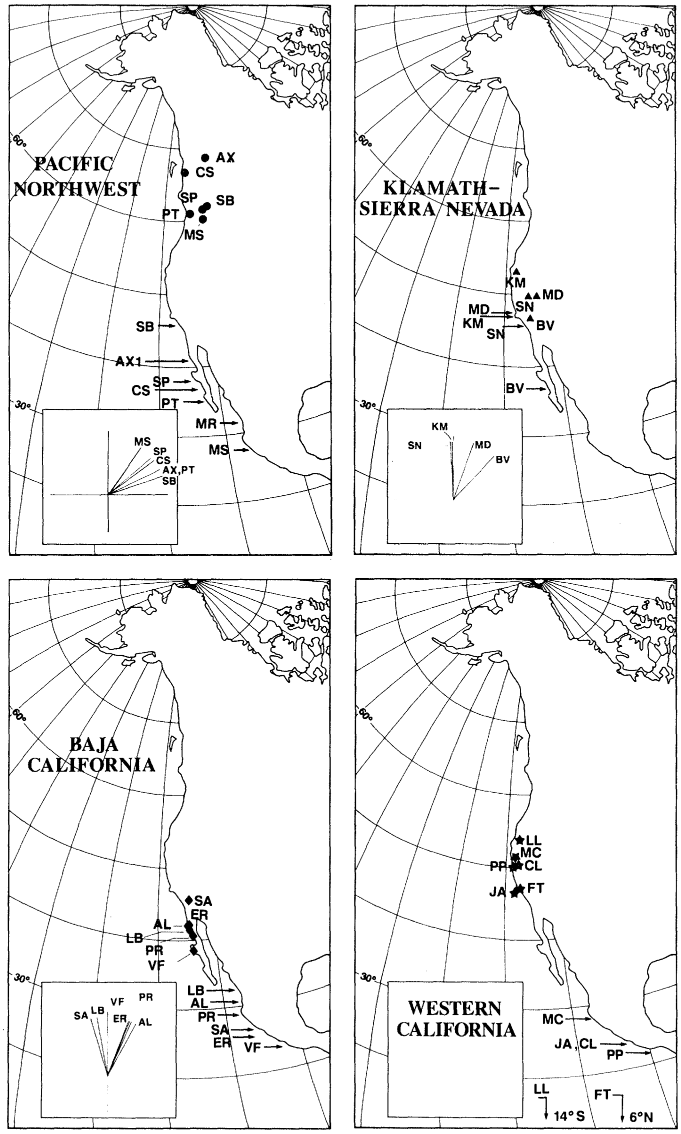

FIGURE 5. Mid-Cretaceous rocks of the Cordillera grouped by region of derivation. Alaskan data not included. Dots (Pacific Northwest), triangles (Klamath–Sierra Nevada), diamonds (Baja California) and stars (Western California) are sampling localities labelled as in table 2. Arrows are the corresponding estimated palaeolatitudes. The grid is drawn relative to the mid-Cretaceous cratonic palaeopole of table 1. Rotations relative to cratonic North America are shown in insets, the convention being that if rotation were zero the line would be along the vertical axis.

Cretaceous Normal Superchron (Harland *et al.* 1982). Consequently, all regions, except possibly parts of Western California, were in northern palaeolatitudes in the Cretaceous. Palaeolongitude is indeterminate, so localities marked in figure 5 could have lain anywhere to the west within the palaeolatitudinal belts indicated.

Klamath Mountains–Sierra Nevada

One datum (KM) is from bedded rocks and attitude corrections have been applied. Three data are from intrusive rocks and no corrections have not been made. Except for BV, which is from the southern end of the Sierra Nevada, they all are in good agreement, and all displacements are small (table 2, figure 5). Rotations are negligible or small and clockwise. BV shows the largest displacement, although barely significant at the 95% confidence level; Kanter & McWilliams (1982) ascribe the 45° apparent rotation to bending of the southern end of the Sierra Nevada in response to dextral shear along the proto-San Andreas transform. Tilting to the southwest also could have been responsible for part of the divergence of BV.

Baja California

All apparent displacements of about 15° are from the south and are in good agreement. Rotations are variable. Of the six determinations, five are from bedded sequences and attitude corrections have been applied. The sixth, is based on extensive studies of the Peninsular Range batholith.

Western California

Data from the Franciscan Complex and 'Salinia' block of western California yield very large and generally variable displacements from the south. One, from the Laytonville Limestone (LL of figure 5 and table 2), in which age, top-direction, and bedding attitudes are well known, and whose magnetization has been subject to detailed study, implies a displacement exceeding 60°. Northward displacement of about 24° is inferred from studies of the Calera Limestone (CL) which, like the Laytonville Limestone, is a knocker in the Franciscan Complex. Apparently the Laytonville Limestone was deposited in the Southern Hemisphere, and the Calera in the Northern Hemisphere. According to the palaeomagnetic evidence the Franciscan Complex and Western California generally, is unlike the other three regions, and, contains rocks that have come from very different places. Some rock-units are from Cretaceous oceanic assemblages (e.g. Laytonville Limestone, Pigeon Point Formation) that may have been transported on oceanic plates from considerable distances. It is noteworthy that very recently data has been obtained from the Jurassic James Island Formation of the Deatur Terrane of the San Juan Islands, which indicate net displacement from the south in excess of 20° (Bogue *et al.* 1989). Although situated much further north at present, the Decatur Terrane (the San Juan Islands are just southeast of Vancouver Island) is an oceanic assemblage with many resemblances to the Franciscan Complex.

5. Reconstructing the mid-Cretaceous Cordillera

A major uncertainty in the interpretation of data from the western Cordillera is in the determination of the horizontal plane at the time of remanence acquisition (Beck *et al.* 1981; Irving *et al.* 1985). In the Sierra Nevada and Klamath region and Baja California, there is good agreement among data from intrusive and bedded sedimentary rocks (table 2, figure 5). In the Pacific Northwest, when due account is taken of transcurrent motions along faults separating palaeomagnetically studied bedded rocks and intrusions, there is also a fair measure of agreement. It could be argued that these agreements are fortuitous. For example the plutons could have been tilted and the inclinations in the bedded sedimentary sequences could have been flattened at deposition (the inclination error of King (1955)) or by later compaction, yielding palaeolatitudes that are too low in both rock types. This is unlikely in the Pacific Northwest where the bedded sequences studied are for the most part massive lava flows

(Marquis & Globerman 1988; Irving & Thorkelson 1990). Hence, the agreements between different rock-types, constitute good evidence that the estimates of palaeolatitude are correct within the errors stated.

Data from western California indicate large and internally variable displacements. In contrast, data from the other three regions of the western Cordillera yield post-mid-Cretaceous displacements that differ from region to region, but within each region they are generally in good internal agreement (figure 5). Cretaceous intrusions from these three regions are subduction related, and the sedimentary and volcanigenic rocks are all of shallow-water or terrestrial origin. It is unlikely, therefore, that these assemblages were formed far from the margin of cratonic North America. Hence it would seem that the terranes into which they were intruded or upon which they were deposited, had by then been accreted to North America, but not, according to the evidence of figure 5, in their present relative positions. It is as if the three regions were not formed in their present order. Instead, during the early Cretaceous, the Pacific Northwest was interposed between the Klamath Mountains–Sierra Nevada and Baja California blocks. In latest Cretaceous and earliest Tertiary time, the southerly elements of the margin moved north, not as a whole, but differentially, the Pacific Northwest, or Baja British Columbia as we may now call it, being carried outboard of the Klamath Mountains and southern Sierra Nevada to achieve its present position by Eocene time, and Baja California moving northwards to abut against the southern Sierra Nevada. During the mid-Tertiary, western and northern elements of Baja B.C. were displaced northwards forming the present Wrangel block (block 1A of figure 6).

Umhoefer (1987) and Umhoefer *et al.* (1989*b*) have developed a model that reconciles the above evidence with the motions of oceanic plates to the west (figure 6). Their model is based on the suggestion by Beck *et al.* (1981) that terranes were moved northwards by the short-lived Kula Plate (Atwater 1970). They assume that between 85 and 66 Ma that Baja B.C. was

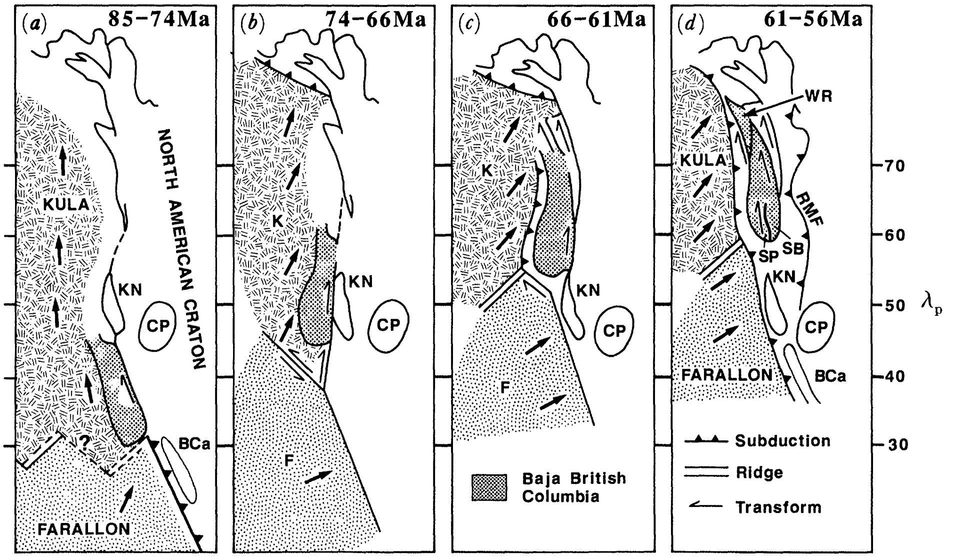

FIGURE 6. Plate model of Umhoefer (1987) and Umhoefer *et al.* (1989*b*) for evolution of the Cordillera in the interval 85–56 Ma. KN is the Klamath–Sierra Nevada; CP, Colorado Plateau; BCa, Baja California; WR, Wrangel Block; SP and SB, Spuzzum and Spences Bridge localities separated by transcurrent faults (Irving & Thorkelson 1990); RMF, Rocky Mountain Fault.

coupled to the Kula Plate. Plate reorganization at 66 Ma resulted in dextral oblique convergence between the Kula and North America plates west of Baja B.C. In the interval 66–55 Ma, Baja B.C. became detached from the Kula Plate continued to move northward relative to cratonic North America along inboard dextral faults. It was finally coupled to North America by 55 Ma.

6. Permian, Triassic, Jurassic

Determinations from bedded, palaeontologically well-dated, early Permian, late Triassic and early Jurassic rocks from Wrangellia and Stikinia are listed in table 2. In Triassic and Jurassic rocks, reversals occur, and their frequency is such that polarity zones cannot be related to the global timescale. Hence, from a palaeomagnetic datum it is not possible to determine whether the rock-unit was north or south of the palaeoequator. However, there are several reasons for believing that the palaeolatitudes, like those for Cretaceous rocks, are all northern. Firstly, Jurassic ammonite forms of the Canadian cordillera are boreal in character (Tipper 1981, 1984; Taylor *et al.* 1984; Cameron & Tipper 1985). Secondly, the Lower Permian Asitka Group (AS of table 2) has predominantly negative inclinations, the polarity expected for Northern Hemisphere localities in a geomagnetic field of reversed polarity, such as existed in the early Permian (Irving & Monger 1987). The third argument makes use of the fact that, with the exception of data from the Nicolai volcanics which have probably been moved northward during Tertiary coastwise motion (see below), the net displacements for the northern option are in excellent agreement with one another, differing by no more than 5°, which is not significant (figure 7). For the southern option they differ by as much as 30°. The Triassic and Jurassic rock-units from both Wrangellia and Stikinia are in stratigraphic sequence one above the other. That rock-units in stratigraphic continuity should have been separated by such large distances is most unlikely. Hence, the northern is the favoured option.

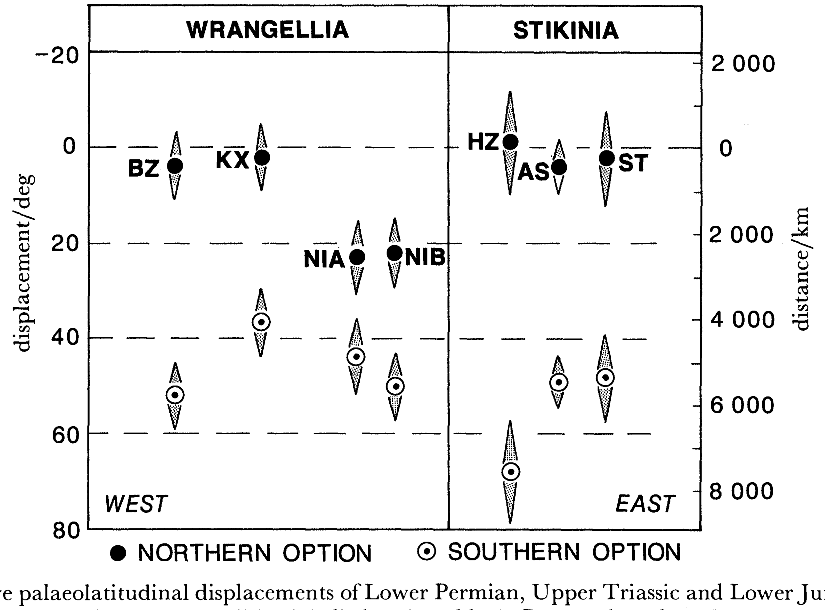

Figure 7. Relative palaeolatitudinal displacements of Lower Permian, Upper Triassic and Lower Jurassic localities from Wrangellia and Stikinia. Localities labelled as in table 2. Recent data from Lower Jurassic of central Stikinia confirms the displacements given here (Vandall *et al.* 1989).

Excluding data from the Nicolai, the net displacements do not differ significantly from zero. Apparently Stikinia and Wrangellia were close together in the late Triassic and early Jurassic, and were near their present latitudes relative to ancestral North America. However, palaeolongitude is indeterminate and positions westward in the Pacific are permissible.

The results of figure 7, although they agree in broad terms with other recent studies (Gordon *et al.* 1984; May & Butler 1986; Irving & Yole 1987; Irving & Wynne 1990; Beck 1990), differ from them in detail, as these studies do from one another. This arises because of the present unsatisfactory state of knowledge of the details Triassic and Jurassic APW path. Displacement estimates have not stabilized because data-selection and analytical procedures, adopted by different authors to establish cratonic reference data, differ substantially. Until choices are limited by more and better cratonic data, this somewhat unsatisfactory situation will persist. Nevertheless there seems little doubt that displacements are small, just how small remains to be seen. Changes are most likely to affect the displacement scale of figure 7*b*, whereas the relative positions of points probably will not be grossly affected. In other words, the good agreement now found amongst palaeolatitude estimates for Lower Permian, Upper Triassic and Lower Jurassic rocks from Stikinia and the Vancouver Island segment of Wrangellia, is less vulnerable to future revisions than the net displacement values themselves.

We now must ask, how this good agreement was preserved while the later apparent displacements of figure 4 were occurring. Because of the uncertainty in the estimates of the early Mesozoic cratonic reference field, it is perhaps premature to attempt to answer, but one solution is to assume that the difference between the apparent displacements of the Coast and Intermontane belts was caused by variable tilting of plutons in the former (hypothesis (*c*) above).

Consider now the displacement of the Nicolai volcanics of Alaska which is about 20° (figure 7). They are essentially coeval with the Karmutsen Formation of Vancouver Island which yields zero net displacement. Palaeolatitudinally the two, however, are in close accord (figure 8). The corresponding rotations are very large (almost 180° in the case of Vancouver Island) and variable. Evidently, in the late Triassic, Wrangellia was a compact terrane that was later fragmented and the Alaskan element moved north along the western margin of North America.

The rotations required are large, variable and well documented. The geometrical relationship of locality and APW path is such that estimates of rotations are essentially independent of selections used to derive cratonic reference palaeopoles. It is important to note that although the net rotations are well established, the magnitude and, to a degree, the sense of post-depositional pre-mid-Cretaceous rotations estimated are much less certain, because they depend on the amount of the post-mid-Cretaceous dextral rotation assumed for the localities in question. It has not yet proved possible, and may never be possible because of the structural complexity of Western Cordillera, to measure both the early sinistral and later dextral rotation in the same uninterrupted sequence.

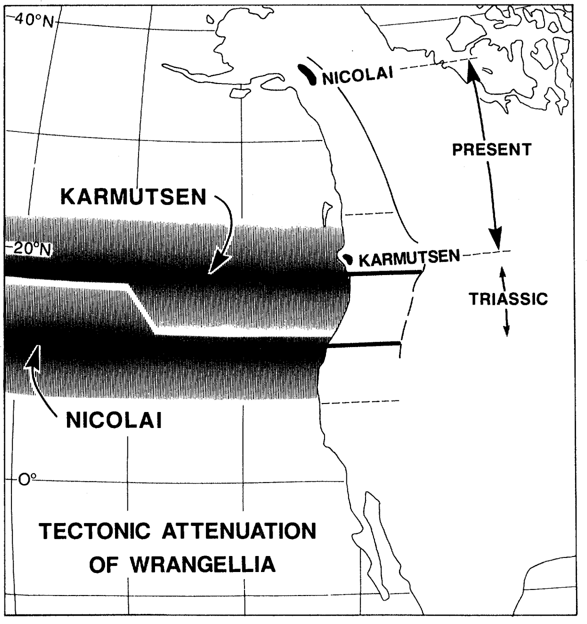

FIGURE 8. Palaeolatitudes from Upper Triassic rocks of Wrangellia compared. Details in table 2. Note that the error zones are shaded densely near the mean and with the density diminishing outwards to the limit ($P = 0.05$).

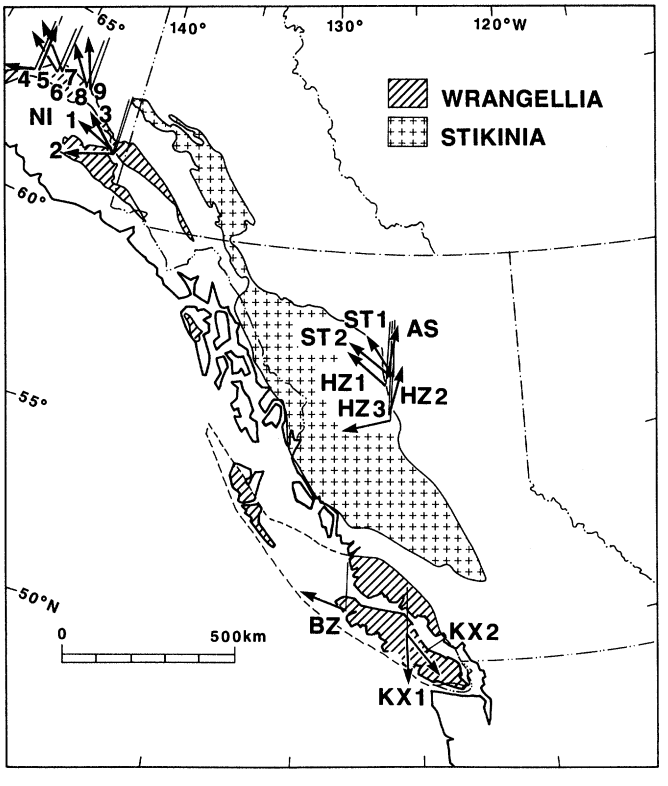

FIGURE 9. Apparent rotations of Lower Permian, Upper Triassic and Lower Jurassic localities, Northern Hemisphere option. Localities labelled as in table 2. Large anticlockwise rotations have recently been reported from Lower Jurassic rocks of central Stikinia (Vandall *et al.* 1989).

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7. Conclusions

Consider again the three processes invoked to explain data from Cretaceous rocks of the Pacific Northwest: (*a*) general 30° tilt to the southwest, (*b*) displacement from the south increasing from east to west, greater than 2000 km in the west, and (*c*) lesser (1000–2000 km) displacement from the south, and within the Coast Belt, lesser tilts to the south and southeast. The displacement estimates obtained from a wide variety of bedded rocks of Permian through Jurassic age are in full agreement with hypothesis (*a*), and together they indicate that the Cordillera of the Pacific Northwest was formed initially more or less where it is now. Data from bedded volcanics of the Intermontane Belt are inconsistent with hypothesis (*a*), but provide support for hypotheses (*b*) and (*c*). Strong support for the process of coast-wise displacement in general is provided by Cretaceous palaeomagnetic data from Baja California (figure 5) and, of course, by the present motions of western and Baja California relative to North America; although these have no direct bearing on the tilt-displacement problem in the Pacific Northwest, they do show that coast-wise displacements of the margins of North America are not isolated phenomenon.

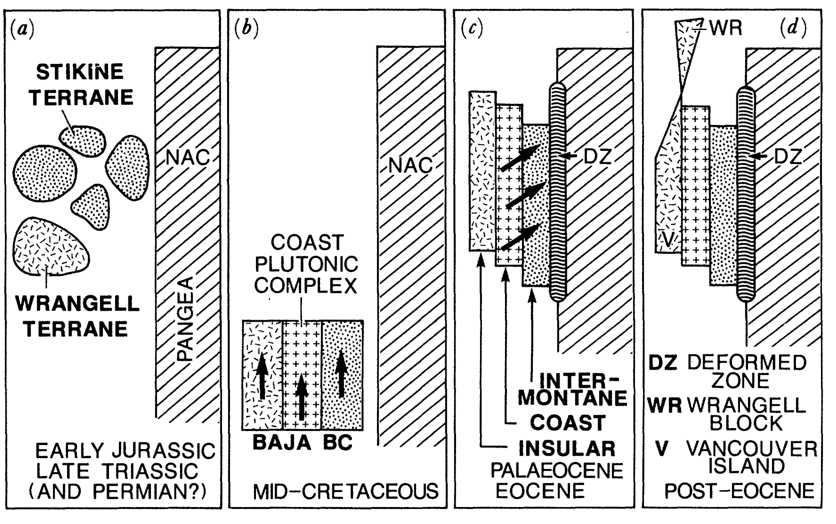

Figure 10. Speculative scheme for evolution of the allochthonous terranes of Western Canada. NAC is the North American craton. DZ is the deformed zone consisting of Omineca and Foreland belts with the possibility that there may have been some involvement of the inner part of the Intermontane Belt. The heavy arrows in the centre two panels represent diagrammatically the directions of palaeonorth that were systemmatically rotated during attenuation and differential northward movement. The northward slivering of the Wrangel block in the right-hand panel is meant to represent the final attenuation of the Insular Belt in the Tertiary (see figure 9).

Hypothesis (*a*) is summarized in figure 10. The various terranes that now constitute the Insular, Coast and Intermontane belts were originally situated close together, and not far from where they are at present relative to ancestral North America. This choice is arbitrary to a degree, because the indeterminacy of longitude allows positioning farther west. Uncertainties in the cratonic reference field are such that they could have been situated several hundred kilometres to the north or south. Presumably Wrangellia and Stikinia in the late Triassic and early Jurassic were, in large part, a succession of island-arcs, seamounts, etc. They moved southward together, became amalgamated and attached temporarily to North America in

Jurassic through early Cretaceous time. Large rotations, predominantly anticlockwise, occurred. In mid-Cretaceous time they were intruded by the Coast Plutonic Complex and Baja B.C. was formed. In the latest Cretaceous and earliest Tertiary (90–50 Ma), Baja B.C. moved northward along the margin of North America to its present position and clockwise rotations commonly occurred. Finally the Wrangel block was displaced as a sliver 20° northward.

The displacement hypothesis of figure 10 depends, perhaps to a disproportionate degree, on the systematic nature of the westerly increase in apparent displacements estimated from mid-Cretaceous (120–102 Ma) plutons, and the displacement estimated from the stratified mid-Cretaceous (104 Ma) Spences Bridge Group (figure 4). Clearly very much more data are required from this time interval before the thesis of figure 10 can be considered as other than tentative. The displacement estimate from the latest Cretaceous (70 Ma) Carmacks Group (Marquis & Globerman 1988) also is consistent with this thesis, but as already noted, is based on an as yet uncertain reference field. However, the Carmacks datum is not critical, because the northward movement of Baja B.C. may have been partly or even largely accomplished by this time.

Appendix

Data from Mesozoic rocks, other than those listed in table 2, are available from the Pacific Northwest but have not been included in our analysis for reasons given below.

The Cretaceous plutons of Howe Sound (Symons 1973*a*) have been shown to contain substantial Tertiary overprints (Irving *et al.* 1985; E. Irving & C. J. Yorath, unpublished work). Cretaceous rocks of the Methow–Pasayten trough have syn-deformational magnetizations that cannot be related confidently to palaeohorizontal (Granirer *et al.* 1986). Late Cretaceous sedimentary rocks of McColl Ridge (Panuska 1985) of the Wrangel Block, although providing a positive tilt test from two localities, are based on only a few sedimentary rock samples which may have been affected by inclination error (Coe *et al.* 1985). Data from the Topley intrusions (Symons 1973*b*, 1983*a*) of Stikinia are affected by early Tertiary overprinting (Monger & Irving 1980) in our opinion. Despite their shortcomings, these data, if accepted at their face-value, would all yield southerly displacements, broadly consistent with interpretation given above.

Data from the Albian Crowsnest Formation are not considered because the unit probably represents a single eruption insufficient to average the palaeosecular variation (Irving *et al.* 1986).

The Triassic Hound Island volcanics (Hillhouse & Grommé 1980) from the Alexander terrane have been restudied by Haeuseller *et al.* (1989), who report that the earlier determination was affected by Cretaceous overprinting, and that detailed demagnetization yields magnetizations with inclinations concordant with the contemporaneous Nicolai volcanics.

Upper Triassic volcanics and Lower Jurassic intrusions of south central British Columbia (Quesnellia) have yielded magnetizations directed towards the northeast (GBT, GBA, CMT, CMA, NA of figure 11) with positive inclination. Similar palaeodirections, known to be overprints, have been observed in nearby Norian to Hettangian volcaniclastics (QL). On Vancouver Island, comparable palaeodirections have been observed from the Jurassic West Coast Complex and Island Intrusions (WI), and as overprints from the Karmutsen Formation

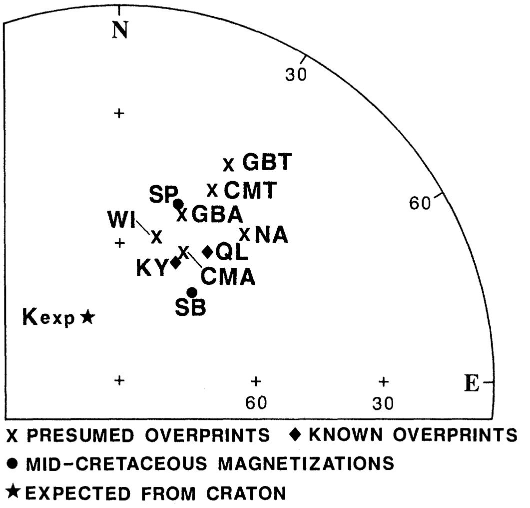

FIGURE 11. Examples of magnetizations in Triassic and Jurassic rock-units that are interpreted as entirely or in part of mid-Cretaceous age. Directions plotted on stereogram are recalculated to the town of Kamloops (50.6° N, 120.4° W) for comparison. All directions with respect to present horizontal except SB. WI, West Coast Complex and Island intrusions (Symons 1984*a*); CMT (Symons & Litalien 1984), CMA (Symons 1973*a*), Copper Mountain intrusion derived from thermal and alternating field demagnetization studies; GBA (Symons 1971*a*), GBT (Symons 1983*b*), Guichon Batholith derived from alternating field and thermal studies; KY, Karmutsen Formation (Yole & Irving 1980); NA, Nicola volcanics (Symons 1984*b*); QL, Quesnel lake volcaniclastics overprint (Rees *et al.* 1985); SP and SB, Spuzzum pluton and Spences Bridge Group from table 2. Expected mid-Cretaceous palaeodirection (K_{exp}) calculated from data of table 1.

(KY). All are broadly similar to known Cretaceous palaeodirections (SB, SP). The sampling area in south-central British Columbia has been the focus of extensive mid-Cretaceous volcanism and intrusion. Although statistically significant differences occur among the palaeodirections of figure 11, the overall agreement is such that we feel justified in concluding that these rock-units have been partly or completely remagnetized in mid-Cretaceous time, and hence, cannot be used confidently for earlier tectonic reconstructions. Note, however, that all are markedly different in direction from the expected Cretaceous palaeofield.

REFERENCES

Alvarez, W., Kent, D. V., Premoli, S. I., Schweichert, R. A. & Larson, R. L. 1980 *Bull. Geol. Soc. Am.* **91**, 476–484.
Armstrong, R. L., Monger, J. W. H. & Irving, E. 1985 *Can. J. Earth Sci.* **22**, 1217–1222.
Atwater, T. 1970 *Bull. Geol. Soc. Am.* **81**, 3513–3536.
Bardoux, M. & Irving, E. 1989 *Can. J. Earth Sci.* **22**, 829–844.
Beck, M. E. Jr 1975 *Earth planet. Sci. Lett.* **26**, 263–268.
Beck, M. E. Jr 1976 *Am. J. Sci.* **276**, 694–712.
Beck, M. E. Jr 1980 *J. geophys. Res.* **85**, 7115–7131.
Beck, M. E. Jr 1990 In *Geophysical framework of the Continental United States* (ed. L. C. Pakiser & W. D. Mooney). *Geol. Soc. Am. Mem.* **172**. (In the press.)
Beck, M. E., Burmester, R. F. & Schoonover, R. 1981 *Earth planet. Sci. Lett.* **56**, 336–342.
Beck, M. E. & Noson, L. 1972 *Nature, Lond.* **235**, 11–13.
Bogue, S. W., Cowan, D. S. & Garver, J. I. 1989 *J. geophys. Res.* **94**, 10415–10427.
Butler, R. F., Harms, T. A. & Gabrielse, H. 1988 *Can. J. Earth Sci.* **25**, 1316–1322.
Butler, R. F., Gehrels, G. E., McClelland, W. C., May, S. R. & Klepacki, D. 1989 *Geology* **17**, 691–694.
Cameron, B. E. B. & Tipper, H. W. 1985 *Bull. Geol. Surv. Can.* **365**, 1–49.
Champion, D. E., Howell, D. G. & Grommé, C. S. 1984 *J. geophys. Res.* **89**, 7736–7752.
Champion, D. E., Howell, D. G. & Marshall, M. 1986 *J. geophys. Res.* **91**, 11557–11570.

Coe, R. S., Globerman, B. R., Plumley, P. W. & Thrupp, G. A. 1985 In *Tectonostratigraphic terranes of the Circum-Pacific region* (ed. D. G. Howell), Circum-Pacific Council for Energy and Mineral Resources, pp. 85–108. Houston, Texas.

Courtillot, V., Feinberg, M., Ragaru, J. P., Kerguelen, R., McWilliams, M. & Cox, A. 1985 *Geology* **13**, 107–110.

Cox, A. V. 1957 *Nature, Lond.* **179**, 685–686.

Cox, A. V. 1980 *Geol. Ass. Can., Spec. Pap.* **20**, 305–321.

de Boer, J. & Snider, F. G. 1979 *Bull. Geol. Soc. Am.* **90**, 185–198.

Dooley, R. E. & Smith, W. A. 1982 *Tectonophysics* **90**, 283–307.

Filmer, P. E. & Kirschvink, J. L. 1989 *J. geophys. Res.* **94**, 7332–7342.

Fox, K. F. & Beck, M. E. 1985 *Tectonics* **4**, 323–341.

Frei, L. S., Magill, J. R. & Cox, A. 1984 *Tectonics* **3**, 157–177.

Frei, L. S. 1986 *Bull. Geol. Soc. Am.* **97**, 840–849.

Fry, J. G., Bottjer, D. J. & Lund, S. P. 1985 *Geology* **13**, 648–651.

Gabrielse, H. 1985 *Bull. Geol. Soc. Am.* **96**, 1–14.

Geissman, J. W., Collins, J. T., Oldow, J. S. & Humphries, S. R. 1984 *Tectonics* **3**, 179–200.

Globerman, B. R. & Irving, E. 1988 *J. geophys. Res.* **93**, 11721–11733.

Gordon, R. G., Cox, A. & O'Hare, S. 1984 *Tectonics* **3**, 499–537.

Granirer, J. L., Burmester, R. F. & Beck, M. E. Jr 1986 *Geophys. Res. Lett.* **13**, 733–736.

Grommé, S. 1984 *Pacific Section S.E.P.M.* **43**, 113–119.

Grommé, C. S. & Merrill, R. T. 1965 *J. geophys. Res.* **70**, 3407–4320.

Grubbs, K. L. & van der Voo, R. 1976 *Tectonophysics* **33**, 321–336.

Hagstrum, J. T., McWilliams, M., Howell, D. G. & Grommé, S. 1985 *Bull. Geol. Soc. Am.* **96**, 1077–1090.

Harland, W. B., Cox, A. V., Hewellyn, P. G., Pickton, C. A. G., Smith, A. G. & Walters, R. 1982 *A geological time scale*. Cambridge University Press. (131 pages.)

Hillhouse, J. W. 1977 *Can. J. Earth Sci.* **14**, 2578–2592.

Hillhouse, J. W. & Grommé, C. S. 1980 *J. geophys. Res.* **85**, 2594–2602.

Hillhouse, J. W. & Grommé, C. S. 1982 *Geology* **10**, 552–556.

Hillhouse, J. W. & Grommé, C. S. 1984 *J. geophys. Res.* **89**, 4461–4477.

Hodych, J. & Hayatsu, A. 1988 *Can. J. Earth Sci.* **25**, 1972–1989.

Haeussller, P. J., Coe, R. S. & Onstott, T. C. 1986 *Eos, Wash.* **70**, 1068.

Irving, E. 1985 *Nature, Lond.* **314**, 673–674.

Irving, E. & Archibald, D. A. 1990 *J. geophys. Res.* (In the press.)

Irving, E. & Brandon, M. T. 1990 *Can. J. Earth Sci.* (In the press.)

Irving, E. & Irving, G. A. 1982 *Geophys. Surv.* **5**, 141–188.

Irving, E. & Monger, J. W. H. 1987 *Can. J. Earth Sci.* **24**, 1490–1494.

Irving, E., Monger, J. W. H. & Yole, R. W. 1980 *Geol. Ass. Can. Spec. Pap.* **20**, 441–456.

Irving, E. & Thorkelson, D. K. 1990 *J. geophys. Res.* (Submitted.)

Irving, E., Woodsworth, G. H., Wynne, P. J. & Morrison, A. 1985 *Can. J. Earth Sci.* **22**, 584–598.

Irving, E. & Wynne, P. J. 1990 In *The Cordilleran Orogen in Canada* (ed. H. Gabrielse & C. J. Yorath). DNAG contribution. (In the press.)

Irving, E., Wynne, P. J., Evans, M. E. & Gough, W. 1986 *Can. J. Earth Sci.* **23**, 591–598.

Irving, E. & Yole, R. W. 1972 *Pub. Earth Phys. Branch* **42**, 87–95.

Irving, E. & Yole, R. W. 1987 *Geophys. Jl R. astron. Soc.* **91**, 1025–1048.

Jacobson, D., Beck, M. E., Diehl, J. K. & Hearn, B. C. 1980 *Geophys. Res. Lett.* **7**, 549–552.

Kanter, L. R. & McWilliams, M. O. 1982 *J. geophys. Res.* **87**, 3819–3830.

King, R. F. 1955 *Mon. Not. R. astr. Soc. geophys. Suppl.* **7**, 115–134.

Mankinen, E. A. & Irwin, W. P. 1982 *Geology* **10**, 82–87.

Marquis, G. & Globerman, B. R. 1988 *Can. J. Earth Sci.* **25**, 2005–2016.

May, S. R. & Butler, R. F. 1986 *J. geophys. Res.* **91**, 11519–11544.

McWilliams, M. O. & Howell, D. G. 1982 *Nature, Lond.* **297**, 215–217.

Monger, J. W. H. 1990 In *The Cordillera in Canada* (ed. H. Gabrielse & C. J. Yorath). DNAG. (In the press.)

Monger, J. W. H. & Irving, E. 1980 *Nature, Lond.* **285**, 289–294.

Monger, J. W. H., Price, R. A. & Tempelman-Kluit, D. J. 1982 *Geology* **10**, 70–75.

Packer, D. R. & Stone, D. B. 1974 *Can. J. Earth Sci.* **11**, 976–997.

Palmer, A. R. 1983 *Geology* **11**, 503–504.

Panuska, B. C. 1985 *Geology* **13**, 80–883.

Price, R. A. & Carmichael, D. M. 1986 *Geology* **14**, 468–471.

Rees, C. J., Irving, E. & Brown, R. L. 1985 *Geophys. Res. Lett.* **12**, 498–501.

Russell, B. J., Beck, M. E. Jr, Burmester, R. F. & Speed, R. C. 1982 *Geology* **10**, 423–428.

Schwarz, E. J., Muller, J. E. & Clark, K. R. 1980 *Can. J. Earth Sci.* **17**, 389–399.

Smith, T. E. & Noltimier, H. C. 1979 *Am. J. Sci.* **279**, 778–807.

Symons, D. T. A. 1971*a* *Can. J. Earth Sci.* **8**, 1388–1396.

Symons, D. T. A. 1971*b* *Geol. Surv. Can. Pap.* **71–24**, 9–24.

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Symons, D. T. A. 1973*a* *Nature, Lond.* **241**, 59–61.
Symons, D. T. A. 1973*b* *Can. J. Earth Sci.* **10**, 1099–1108.
Symons, D. T. A. 1977 *Can. J. Earth Sci.* **14**, 2127–2139.
Symons, D. T. A. 1983*a* *Geophys. Res. Lett.* **10**, 1065–1068.
Symons, D. T. A. 1983*b* *Can. J. Earth Sci.* **20**, 1340–1344.
Symons, D. T. A. 1984*a* *J. Geodyn.* **2**, 229–244.
Symons, D. T. A. 1984*b* *J. Geodyn.* **2**, 211–228.
Symons, D. T. A. & Litalien, C. R. 1984 *Geophys. Res. Lett.* **11**, 685–688.
Symons, D. T. A. & Wellings, M. R. 1989 *Can. J. Earth Sci.* **26**, 821–828.
Tarduno, J. A., McWilliams, M., Debiche, M. G., Sliter, W. V. & Blake, M. C. 1985 *Nature, Lond.* **317**, 345–347.
Tarduno, J. A., McWilliams, M., Sliter, W. V., Cook, H. E., Blake, M. C. Jr & Premoli-Silva, I. 1986 *Science, Wash.* **231**, 1425–1428.
Taylor, D. G., Callonon, J. H., Hall, R., Smith, P. L., Tipper, H. W. & Westermann, G. E. G. 1984 *Geol. Ass. Can. Spec. Pap.* **27**, 121–141.
Teissere, R. F. & Beck, M. E. Jr 1973 *Earth planet. Sci. Lett.* **18**, 296–300.
Tipper, H. W. 1981 *Can. J. Earth Sci.* **18**, 1788–1792.
Tipper, H. W. 1984 *Geol. Ass. Can. Spec. Pap.* **27**, 113–120.
Umhoefer, P. J. 1987 *Tectonics* **6**, 377–394.
Umhoefer, P. J., Granier, J. I., Schiarizza, P. & Glover, J. K. 1989*a* *Geol. Soc. Am. Cordilleran Meeting* (abst.), p. 92.
Umhoefer, P. J., Dragovich, J., Cary, J. & Engebretson, D. C. 1989*b* *Geophys. Monog. Am. Geophys. Union* **50** (ed. J. W. Hillhouse), pp. 101–111.
Vandall, T. & Palmer, H. C. 1988 *Eos, Wash.* **69**, 1165.
Vandall, T., Palmer, H. C. & Woodsworth, G. J. 1989 *Abst. Geophys. Union 16th A. Mtg* (*Abst.*), no. 77.
Witte, W. K. & Kent, D. V. 1989 *Bull. Geol. Soc. Am.* **101**, 1118–1126.
Wu, F. & Van der Voo, R. 1988 *Tectonophysics* **156**, 51–58.
Yole, R. W. & Irving, E. 1980 *Can. J. Earth Sci.* **17**, 1210–1228.

Discussion

P. F. Hoffman (*Geological Survey of Canada, Ottawa*). Granitic rocks deform by dislocation creep at temperatures well below the Curie temperature. How, then, does one determine the local palaeohorizontal for palaeomagnetic purposes?

E. Irving, F.R.S. Within the regional groups of figure 5, the remanence directions in plutons are in good agreement with one another and with those of bedded rocks where available. We argue that this consistency observed between rocks of very different origins rules out local processes, such as dislocation creep or tilting, as major causes of the aberrances observed in figure 4. Under favourable circumstances, local palaeohorizontal for individual plutons can be obtained by estimating the tilt of bathozones in their vicinity, as noted in the text.

A. Trench (*Department of Earth Sciences, University of Oxford, U.K.*). Professor Irving demonstrated that palaeomagnetic anomalies in both inclination and declination exist between the terranes of the Western Canadian Cordillera and coeval strata on the North American craton. Clockwise declination anomalies are linked to dextral movements in the plate boundary zone whereas anti-clockwise anomalies are found to accompany sinistral movements. To what extent do intra-terrane declination variations exist within the Cordillera? If present, do these record temporal evolution of rotation or do they result from local tectonic rotations within a given terrane?

A. H. F. Robertson (*Grant Institute of Geology, Edinburgh, U.K.*). Is there any evidence of small-scale block rotations within the transported terranes, especially near the bounding strike–slip faults, or do they behave as relatively coherent units?

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E. Irving, F.R.S. Apparent dextral rotations of 40–70° observed in Cretaceous rocks are always associated with apparent northward displacement (figure 5). The hypothesized northward movement of Baja B.C. attached to the Kula Plate would produce an *en bloc* dextral rotation relative to North America of about 20°. Additional rotations could have been caused by local block rotations (Umhoefer 1987), but the structures defining these have not been identified.

Variable but predominantly sinistral net rotations occur in Upper Triassic and Lower Jurassic rocks. Because these have all been observed from bedded rocks, they are the best established and in some ways the most intriguing palaeomagnetic results from the Cordillera. Their common occurrence indicates that they are present throughout the terranes involved, and are not just a marginal phenomenon (figure 9). For example, in Stikinia the bunching of observations near the eastern margin appears to be a sampling artifact, because recently Vandall *et al.* (1989) have reported, in abstract, variable net sinistral rotations of 20 to 110° from Lower Jurassic rocks of central Stikinia. The timing of rotations observed from Triassic and Jurassic rocks, is poorly constrained but they are so widespread that I am inclined to believe that they occurred soon after deposition as a consequence of rifting in a transcurrent or transpressive environment.

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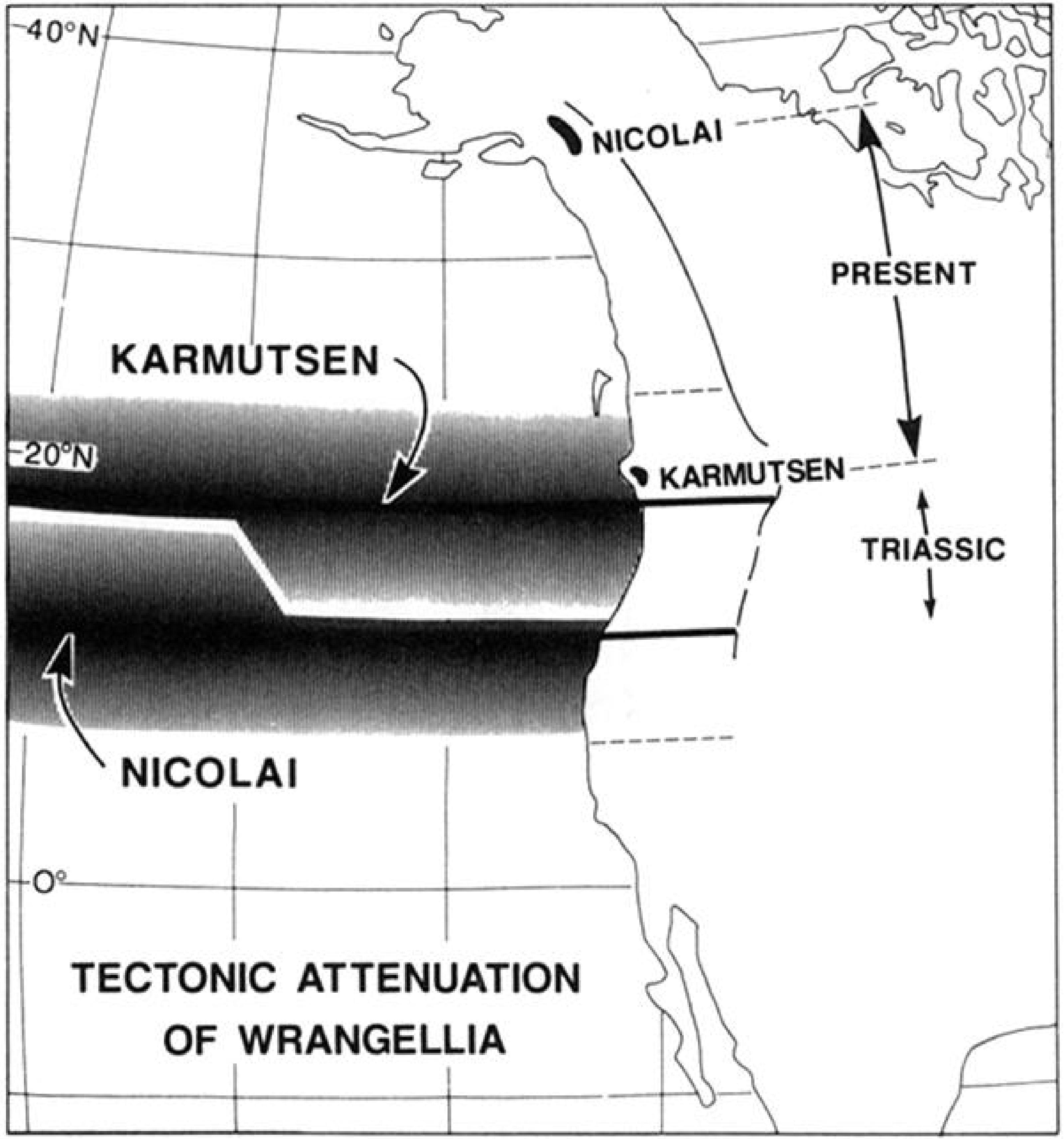

IGURE 8. Palaeolatitudes from Upper Triassic rocks of Wrangellia compared. Details in table 2. Note that the error zones are shaded densely near the mean and with the density diminishing outwards to the limit ($P = 0.05$).