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Slickenlines and the kinematics of the Crowsnest Deflection in the southern Rocky Mountains of Canada

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Abstract

In the vicinity of the Crowsnest Pass, in the southern Rocky Mountains of Canada, the strike of the structural grain deviates significantly from the regional 325° Bow Valley–northern Montana trend. This deviation is known as the Crowsnest Deflection.

The preferred azimuths for slickenlines on bedding north and south of the deflection is 056°; that is almost exactly perpendicular to the Bow Valley–northern Montana trend. Within the deflection, however, the preferred azimuth appears to be composite, ranging from 051° (Beaver Mines) to 082° (Frank, Alberta). The temporal relations of intersecting striae in the coal measures of Bow Valley would suggest, moreover, that these preferred slip directions are not sequential but may be partially or wholly concurrent.

These kinematic fabric data, in conjunction with the alignment of remanent magnetic dipoles in mid-Proterozoic (Helikian) rocks, support the hypothesis that within the Crowsnest Deflection the curviplanar shape of contraction faults in the eastern Cordillera of Canada was controlled by the ancestral shape of the Cordilleran shelf-miogeocline.

The proposed origin and tectonic significance of the Crowsnest Deflection may be similar to that of other great arcs, including the northeastward salient of the Mackenzie Mountains in the northern Cordillera of Canada, and of the northwestward salient of the central Appalachians of Pennsylvania.

1. Introduction

In the southeastern Cordillera of Canada in the vicinity of the Crowsnest Pass, the strike of the Rocky Mountains deviates significantly from the regional 325° Bow Valley–northern Montana trend. This deviation is known as the Crowsnest Deflection (Figs. 1 and 2 Norris, 1968, p. 221). It comprises the two structural salients and an intervening reentrant. Southward from Bow Valley (Fig. 2), the curvilinear shape of the orogen traces out first the Highwood salient as the structural grain deviates in arcuate fashion from a south-southeast trend to a near south trend in the neighbourhood of the Crowsnest Pass. There it swings rather abruptly to the east-southeast around the north flank of the Clark Range salient, and returns to the south-southeast (Bow Valley–northern Montana) trend in the vicinity of the International Boundary with the United States. Structural and stratigraphic continuity is maintained within each thrust sheet around the deflection.

There are a number of possible explanations for the origin of this deflection in structural grain of the southern foothills and Rocky Mountains of Canada. Hume (1933) first drew attention to the deflection in his study of the Lewis thrust fault at North Kootenay Pass (Fig. 2), some 80 km north of the border. He concluded that "This change in strike of 80° with accompanying changes in direction of dip suggests warping of the fault plane subsequent to faulting" (Hume, 1933, p. 8B).

Clow and Crockford (1951) observed changes in trend of as much as 25–30° in structurally controlled ridges in the footwall of the Lewis thrust. From truncation relationships among these (megascopic) structures they proposed that the eastward-trending structures in the Crowsnest reentrant were younger than the north-trending ones (Clow and Crockford, 1951, p. 60). Tectonic compression, therefore, was interpreted to have been first east–west and then north–south.

Recognition of the major change in trend of structures from the Flathead to the Clark Range (Fig. 2) led Norris and Black (1961, p. 935; 1962, p. 21) to investigate whether or not there could have been differential rotation between the Flathead and Clark range segments of the Lewis thrust sheet, and to reject the explanations by Hume (1933) and Clow and Crockford (1951) for the creation of this change in trend. They showed from regional geological mapping, in conjunction with measurements of the paleomagnetic fabric of selected Precambrian rock units in the sheet, that the sheet must have moved more or less unidirectionally

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Fig. 1. The Crowsnest Deflection at Crowsnest Pass, Alberta and British Columbia, where the Lewis thrust sheet changes direction from northwest-trending in the Flathead Range (FR, foreground) to north-trending in the High Rock Range (HR, background). View is to the northwest. G.S.C. neg. no. 200342. Crowsnest Mountain is the isolated mass (klippe) identified with a "K" in the middle background. Interprovincial Highway 3 is located by the number "3" and Crowsnest Lake by a "C" at the mountain front. "L" is the approximate location of the surface trace of the Lewis fault.

northeastward up and over the curviplanar ramps in its footwall as a single, coherent tectonic unit with no detectable differential rotation in the deflection. This led to the conclusion (Norris, 1968, p. 221) that the wholesale changes in structural trend of both thrust faults and folds in the deflection were inherited largely from the initial shape of the Cordilleran shelf-miogeocline.

On the basis of truncation relationships between north- and northwest-striking thrust faults and folds in the hanging wall of the Lewis thrust at the apex of the Crowsnest reentrant, Price (1962, p. 50) suggested another explanation: that "These relationships form the basis for the inference that in this part of the Lewis thrust sheet the north-trending structures are younger than the northwest-trending structures, and have been superimposed discordantly over them". A similar conclusion was reached by Benvenuto and Price (1979) in south-eastern British Columbia, at the apex of the deflection. Their conclusions with regard to the relative ages of megascopic structures with differing trends are opposite to those of Clow and Crockford.

2. Structural setting

The clastic and carbonate rocks comprising the Crowsnest Deflection are part of an eastward-tapering wedge which thickens westward from its zero edge against the Canadian Shield to approximately 4 km at the interface between the Interior Platform and the eastern edge of the Frontal Belt,[1] to about 7 km beneath the western Rockies. The wedge is well layered and distinctly anisotropic. It is composed primarily of platformal and miogeoclinal carbonates and overlying Mesozoic foreland basin clastic rocks (see Price, 1981; Fermor, 1999, p. 317), internally thickened by a family of curviplanar thrust sheets, trending regionally southeast, and overlapping one another both along and across the strike.

The thrust faults, with associated splays and folds, impart a strong northwest-trending structural grain to this segment of the Cordilleran Orogen (see Fig. 2; Wheeler and McFeely, 1991). The vertical to west-dipping axial surfaces characterising the folds, in conjunction with the dominantly east-verging thrust faults, contribute to the pronounced structural asymmetry of the wedge. Reflection seismic data (Shaw, 1963, p. 237; Bally et al., 1966, p. 357) reveal,

[1] Frontal Belt—term formally introduced (Norris, 1997, p. 22) to distinguish the fold and thrust belt of the eastern Cordillera from the contiguous foreland.

moreover, that the Precambrian crystalline basement was not involved in this Laramide contractional deformation.

Between Bow Valley and the International Boundary (Fig. 2) the net shortening arising from the Laramide faulting and folding across the Rocky Mountains and foothills decreases gradually from north to south (Fermor, pers.com., 2000) so that an increase or decrease in displacement on any one thrust fault must have accommodated concurrent, complementary changes in displacement on thrusts overlapping it (Shaw, 1963, p. 235; Bally et al., 1966, p. 357). Thus, more than one thrust was active at any given time in orogenesis. This remarkable orchestration in contractional displacements is further highlighted by the continuity of structural units around the Crowsnest Deflection. There is no penetrative set of cross faults along which differential strike-slip might have occurred during the late stages of the Laramide orogeny to produce the present curvilinear form of the eastern flank of the Cordillera.

3. Slickenlines and their tectonic significance

The supracrustal wedge in the southern foothills and Rocky Mountains of Canada contains a wide variety of fabric elements (see Price, 1967). However, some (e.g. slickenlines) were found to be more reliable kinematic indicators than others for defining the strain geometries and movement pictures within the thrust sheets comprising the Frontal Belt of the Cordilleran Orogen.

On a megascopic scale, these elements are the major thrust faults and folds which outline the curviplanar shape of the deformed belt. On a mesoscopic scale, the fabric elements consist of systematic and spurious joints in the sedimentary rocks, cleats and joints in the associated coal seams, stylolites, extension and contraction faults, transverse faults, remanent magnetic dipoles inherited from the time of deposition of the rocks, as slickenlines on bedding slip surfaces. Sets of several types of these mesoscopic fabric elements were examined across the length and breadth of the Crowsnest Deflection.

Collectively, these megascopic and mesoscopic fabric elements reveal the fundamental role played by the layered anisotropy inherent in the bedding of the sedimentary succession; the orientation of the principal compressive stresses involved in the deformation; the tectonic shortening and thickening of the supracrustal wedge; the relative timing of individual thrust sheets as the deformation front migrated from west to east across the wedge; and in the location, areal extent and timing of the tectonic depocentres as they filled with sediments, sagged under their own weight and were propelled eastward by plate convergence.

3.1. Slickenlines (slickenside striae)

Reliable data on the direction and magnitude of relative displacement on detachment surfaces, whether parallel to bedding in the form of interbed slip, or at an angle to bedding in the form of extension, contraction and wrench faults, are often difficult to obtain. They are commonly limited by the two-dimensional nature of the outcrop. Fortunately, in the Frontal Belt of the southern Canadian Cordillera some of these difficulties were overcome by extending investigations in the third dimension to underground coal mines (all now abandoned), where the coal seams were continuously and freshly exposed for several kilometres along strike and for as much as 2 km down dip.

Because sets of slickenlines were found to be the most pervasive of the mesoscopic structural fabric elements they were utilised individually or collectively for a qualitative evaluation of the kinematics and dynamics of the Crowsnest Deflection. Their pitches on bedding define at least the youngest movement picture and in turn, the orientation of the youngest kinematic *a* axis throughout the deflection. In the Crowsnest Pass region these data were supplemented with pitch measurements on bedding in abandoned coal strip mines, as well as in roadside outcrops of middle and late Paleozoic carbonate rocks (see Table 1). It was possible, therefore, to establish the movement picture between beds in a given stratigraphic succession, as well as from one thrust sheet to another within the Frontal Belt.

In all, 977 measurements of pitch of sets of striae were recorded, 683 underground, 147 in strip mines, and 147 in roadside outcrops. Of these, 878 were used in the following analysis (Table 1). Those in each coal seam were taken generally from a single bedding surface. They were deliberately spaced widely apart (100 feet; 30 m) in order to minimize duplication of measurements of sets with concomitant stacking of results in favour of the more prominent striae. The measurements on outcrops were mostly limited to one per bed although sometimes two were found. For every location the bedding was rotated into the horizontal about the local strike so that pitches of striae could be considered as azimuths of relative slip.

The possibility that the samples of pitch measurements at different locations were made up of more than one population of striae (polymodal) was tested along the length of the deflection. It was evident that the distribution of azimuths of slip was variably asymmetrical (Fig. 3) about the mean directions of relative displacement. The distributions were largely unimodal (one maximum in the middle of the histogram) outside the deflection (Canmore area) and polymodal within it (Crowsnest Pass area), suggesting the presence of a composite movement picture for the deflection.

It is noteworthy that there appears to be no correlation between the degree of shearing in the coal in any given seam and the size of the standard deviation for the pitch measurements (see Table 1). The Upper Marsh seam at Canmore, for example, has the lowest standard deviation (9°) and yet it is the most highly sheared of any of the seams studied. York Creek coal, on the other hand, is highly sheared and has the highest standard deviation (26°) for its pitch measurements. Also, the spread in the standard deviations within the same

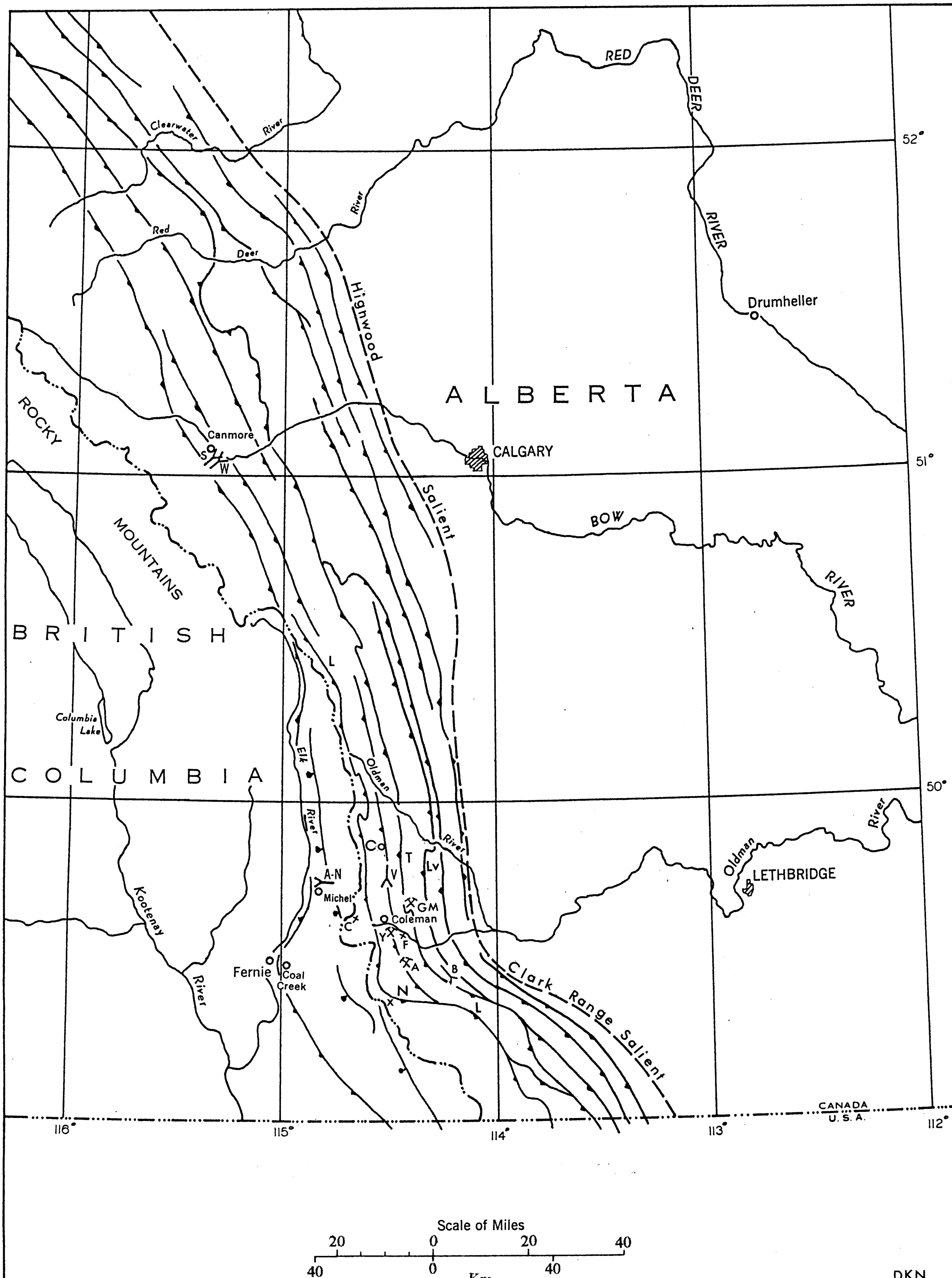

RED DEER RIVER
Clearwater River
River
Red Deer
52°
Drumheller
Highwood
ALBERTA
ROCKY MOUNTAINS
Canmore
S
W
CALGARY
51°
Salient
BOW RIVER
BRITISH COLUMBIA
L
Columbia Lake
Elk River
Oldman River
50°
Oldman River
LETHBRIDGE
Co
T
Lv
V
A-N
Michel
GM
Coleman
C
Y
F
A
B
Fernie
Coal Creek
N
X
L
Kootenay River
Clark Range Salient
CANADA
U.S.A.
116°
115°
114°
113°
112°
Scale of Miles
20 0 20 40
40 0 40
Km.
DKN

Table 1
Fabric data for slickenlines on bedding. (Bedding dips are to the southwest unles otherwise designated)

Location	Stratigraphic unit	No. of observations	A.M. Az. of slip (degrees)	Std. Dev. (degrees)	Bedding dip/strike (degrees)	Div.[a] (degrees)
Canmore	Kootenay (Stewart)	91	059	18	45/320	9
Canmore	Kootenay (Upper Marsh)	140	056	9	23/323	3
Canmore	Kootenay (Wilson)	129	055	13	16/333	8
Michel	Kootenay (A seam)	73	079	20	16/295	54
Crowsnest Lake	Paleozoic (middle and upper)	75	079	23	51/357	8
Vicary Creek	Kootenay (#2 seam)	93	073	22	30W/000	18
Grassy Mtn.	Kootenay (#2 seam)	90	081	–	47NW/003	12
York Creek	Kootenay	28	075	26	40/353	8
Frank (Blairmore Range)	Carnarvon (north side)	12	078	–	53/353	5
Frank (Blairmore Range)	Liv. and Mt. Head (south side)	60	082	14	68/355	2
Adanac	Kootenay (#2 seam)	29	070	14	36/336	4
Beaver Mines	Kootenay	58	051	14	33/293	28

[a] Divergence (Div., new term): acute angle between counterdip direction and arithmetic mean azimuth of slip in the plane of the bedding.

thrust sheet, as at Canmore (9°), is comparable with that from one thrust sheet to another within the deflection as, for example, in the Crowsnest Pass (12°).

Pitch measurements of slickenlines on both roof and floor were made in three coal seams at Canmore: Stewart, Upper Marsh and Wilson seams (Table 1). They were reduced to a common reference surface by rotation into the horizontal about the local strike of the bedding and statistical tests were performed to evaluate their usefulness in the kinematic analysis (see Norris and Barron, 1969, pp. 145–146).

The mutual independence of adjacent measurements of the kinematic *a* direction was established for the Upper Marsh seam. The arithmetic means and standard deviations were then calculated for the kinematic *a* directions for the roof and floor of the seam and statistical tests were performed to demonstrate with reasonable assurance that roof and floor samples of pitch measurements of slickenside striae were from the same normally distributed population of striae (Fig. 3a). Altogether, 140 measurements were made of the pitch of striae on the roof and floor of the Upper Marsh seam. They were normally distributed, with a mean azimuth of the kinematic *ac* plane of 056°, practically the same as that for the adjacent Stewart (059°) and Wilson (055°) seams.

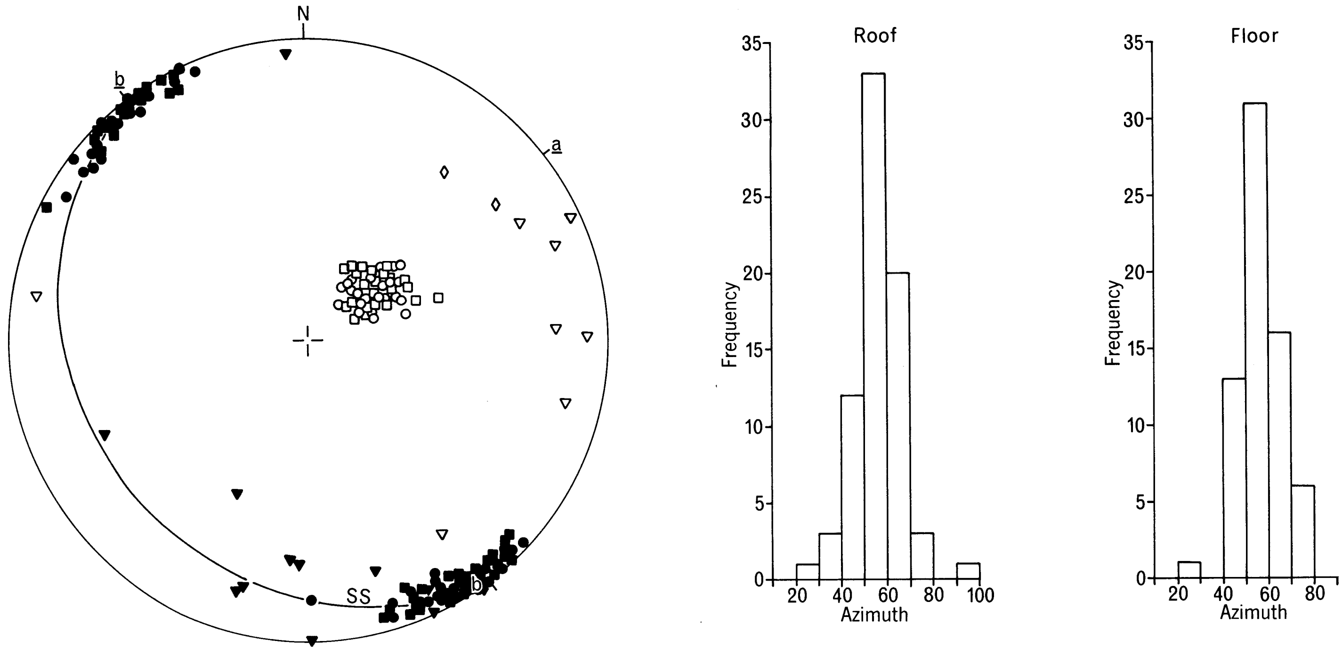
Furthermore, a sample of 40 relatively older and 36 relatively younger intersecting striae on the roof and floor of the Upper Marsh seam reconfirmed the assumption that interbed slip adjacent to the seam was represented by a single movement picture (Norris and Barron, 1969, p. 145). The mean kinematic *ac* plane for the relatively older striae was 056° and that for the relatively younger 054°.

The samples of both non-intersecting and intersecting striae, therefore, included a very large number of discrete, temporally distinct, randomly used slip directions with a circular normal distribution representing at least in part the latest kinematic activity on the bedding surfaces. The kinematic *ac* planes for all three seams were subparallel to the mean counterdip direction (055°), in near coincidence with the presumed direction of relative transport of the thrust plates north and south of the Crowsnest Deflection. There are no data from the Canmore area to support the hypothesis of a second movement picture overprinting the first.

Farther south and structurally higher in the orogen on the north-trending arm of the Crowsnest Deflection, 73 measurements were made of the pitch of slickenlines on bedding in the A seam (A-North coal mine; point "A-N", Figs. 2 and 3b), approximately 120 m below the top of the Jurassic and Lower Cretaceous Kootenay Group. The mine was located in the Lewis thrust sheet in southeastern British Columbia (Norris, 1965a, p. l). There, the frequency distribution of azimuths of striae departs from a normal density

Fig. 2. Location map of control points for structural fabric data on the Crowsnest Deflection in the Frontal Belt of the Cordilleran orogen, southwestern Alberta and southeastern British Columbia. The traces of selected thrust faults are used to reveal the curvilinear form of this segment of the orogen embracing the Crowsnest Deflection. Outcrops studied are shown by an "x"; portals to underground mines by , and abandoned strip mines by . Control points are identified alphabetically as follows: A, Adanac; A-N, A-North Mine; B, Beaver Mines; C, Crowsnest Lake; Co, Coleman thrust; F, Frank; GM, Grassy Mountain; L, Lewis thrust; Lv, Livingstone thrust; N, North Kootenay Pass; S, Stewart Seam; T, Turtle Mountain fault; V, Vicary Creek Mine; W, Wilson Seam; Y, York Creek Mine. The location of the Upper Marsh Seam is not shown. It lies between the Wilson and Stewart Seams at Canmore. Fabric data relating to it are included in Table 1. The approximate eastern limit of the southern Canadian Cordillera is shown in Figs. 2 and 3 by the curvilinear dashed line extending from the International Boundary with the United States to a little north of the Clearwater River. Bedrock geology is modified after Wheeler and McFeely (1991). Bow Valley is occupied by Bow River and Crowsnest Pass by Crowsnest Lake.


APPROXIMATE EASTERN LIMIT OF CORDILLERA
RED DEER RIVER
Clearwater River
River
Red Deer
ALBERTA
Drumheller
ROCKY MOUNTAINS
Canmore
91
129
CALGARY
BOW RIVER
BRITISH COLUMBIA
Columbia Lake
Elk River
Oldman River
Kootenay River
93
73
Michel
90
Coleman
75
28
60
29
58
Fernie
Coal Creek
Oldman River
LETHBRIDGE
52°
51°
50°
116°
115°
114°
113°
112°
CANADA
U. S. A.
Scale of Miles
20 0 20 40
40 0 40
Km.
DKN



Upper Marsh Seam

Roof		Floor		Extension Faults		Contraction Faults	
poles ○	b axes ●	poles □	b axes ■	poles ▽	b axes ▼	poles ◊	b axes ♦
71	73	63	67	8	10	2	1

Preferred orientation of bedding: SS
Preferred orientation of fabric axes: a, b,
Mean Azimuth of Bedding Striae (roof): 56°
Standard Deviation of Mean (roof): ±10
Mean Azimuth of Bedding Striae (floor): 56°
Standard Deviation of Mean (floor): ±9°

Fig. 3. (*continued*)

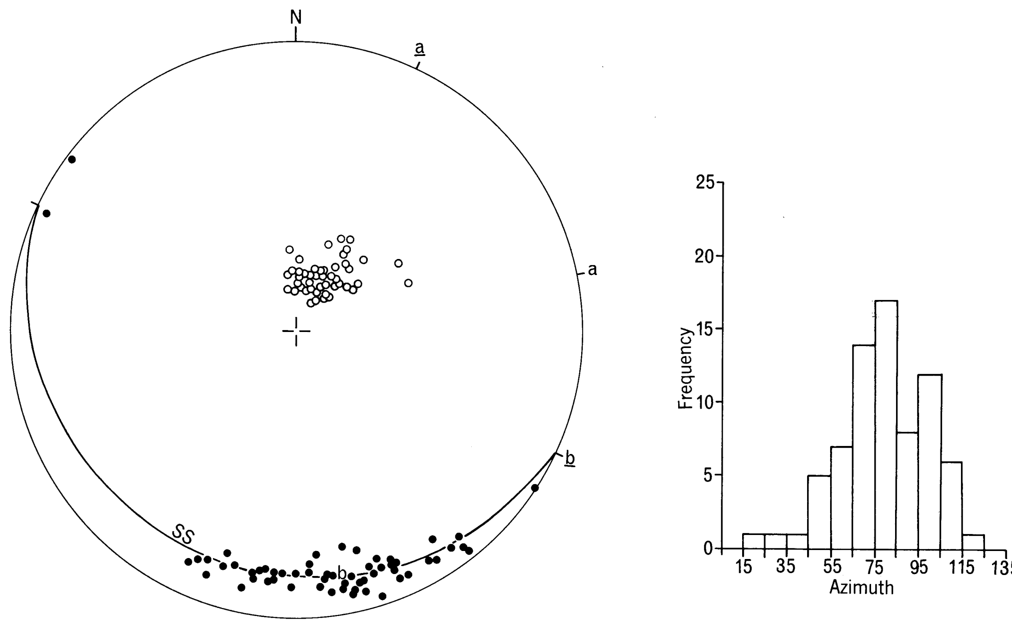
function, possibly representing at least two populations, one with a mean azimuth of 079° (Table 1) and one with a mean azimuth of approximately 110° (est.).

Farther east and somewhat lower in the section, 75 measurements of the pitch of slickenlines on bedding were made in an extensive outcrop of middle and upper Paleozoic rocks exposed along Highway 3 beside Crowsnest Lake (point "C", Figs. 2 and 3c), in the immediate hanging-wall of the Lewis thrust. Here also, the azimuths of striae appear to conform to a normal density function across the stratigraphic succession, with a mean value of 079° (Table 1), in good agreement with a prefered azimuth of striae between 080° and 090° determined by McClay and Insley (1986, p. 911) in the same outcrop and, with that esablished at the A-North mine much higher in the section.

Well-preserved striae on bedding occur throughout the succession at Crowsnest Lake but, intersecting striae are sparse. Seven sets were found, mostly in the Lower Carboniferous Banff Formation but, of these, just two could be used to determine the relative ages. If the intersecting relationships demonstrated for 40 sets of slickenlines in the Upper Marsh seam at Canmore hold true here, these two sets are merely integral parts of a statistically well defined movement picture.

Still farther east, in the Coleman thrust sheet in the Frontal Belt of the Canadian Cordillera, the pitch of

Fig. 3. Kinematic synthesis for thrust sheets in Phanerozoic rocks in and adjacent to the Crowsnest Deflection. Fat arrows indicate mean azimuths of slickenlines on bedding after the beds containing them have been rotated into the horizontal. The number of measurements shown at each control point is taken from Table 1. Representative fabric diagrams are as follows: (a) Upper Marsh Seam (140); (b) A-North Mine (73); (c) Crowsnest Lake (75); (d) Vicary Creek (93); (e) Blairmore Range at Frank (60); (f) Adanac Mine (29); (g) Beaver Mines (58). As in Fig. 2, the location of the Upper Marsh Seam at Canmore is not shown. It lies between the Wilson (below) and Stewart (above) seams. Schmidt equal area projections from the lower hemisphere. Data on extension and contraction faults in fabric diagrams are included for completeness but are not required for the kinematic analysis.



A-North Mine

Bedding		Extension Faults		Contraction Faults		Wrench Faults	
poles ○	b axes ●	poles ▽	b axes ▼	poles □	b axes ■	poles ◊	b axes ♦
53	73	0	0	0	0	0	0

Preferred orientation of bedding: SS
Preferred orientation of fabric axes: a, b
Mean Azimuth of Bedding Striae: 079°
Standard Deviation of Mean: ±20°

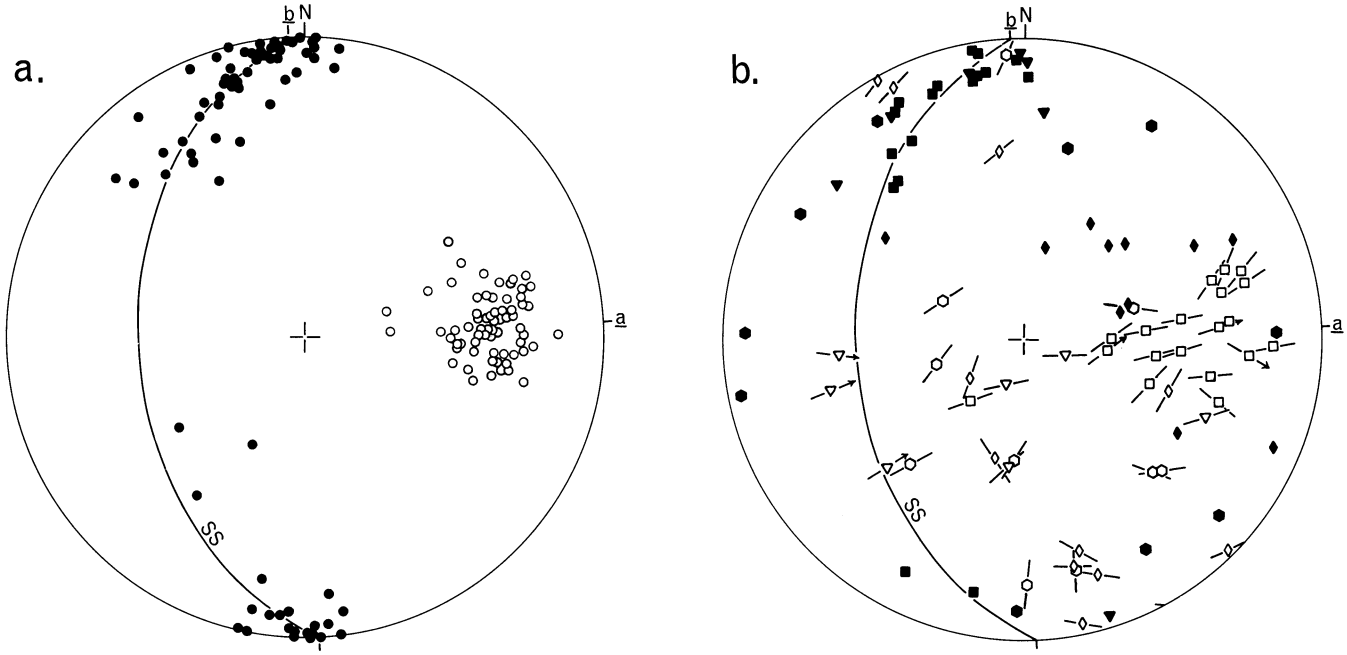
Fig. 3. (*continued*)

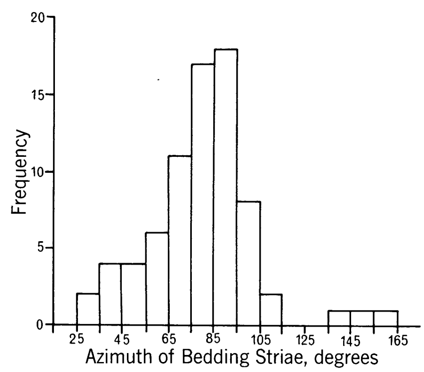
slickenside striae was measured over a strike length of 3.2 km (10,500 feet) in the Number 2 seam of the Kootenay Group at the Vicary Creek mine (point "V", Figs. 2 and 3d) (Norris, 1966, p. 196; Bustin, 1982). There, the strike of the coal measures averages due north and dips 30° west. The mean azimuth of slickenlines for the workings accessible at the time of the survey (mid 1960s), was 073° for horizontal bedding, with a standard deviation of 22° (Table 1).

On Grassy Mountain, in the footwall of the Coleman thrust fault (point "GM", Fig. 2), 90 measurements of pitch of slickenlines on the floor of No. 2 seam of the Kootenay Group have a mean azimuth of transport of 081° (Norris, 1994, p. 31), just two degrees different from the average slip direction in the Devonian and Lower Carboniferous section at Crowsnest Lake (079°; see above). Moreover, in an abandoned strip pit on York Creek in the immediate hanging wall of the Coleman fault, the average of 28 measurements of the pitch of slickenlines on the floor of the No. 2 seam is 075°; that is closely parallel to the mean azimuth of transport at Crowsnest Lake and Grassy Mountain. The large standard deviation (26°) for this sample of measurements at York Creek (point "Y", Fig. 2) is readily attributable to the irregular nature of the floor of the pit and possibly to the small size of the sample (28 measurements).

On the south side of Highway 3 at Frank (point "F", Figs. 2 and 3e) 60 measurements were made of the pitch of slickenlines in the Lower Carboniferous carbonate rocks in the hangingwall of the Turtle Mountain fault. Again, the sample of measurements conformed to a normal density function, with a mean value of the azimuth of slip of 082°, closely parallel to that at Crowsnest Lake and Grassy Mountain. At 14 km along strike to the south, a careful search of the floor of the Number 2 coal seam exposed in the abandoned Adanac open pit mine (point "A", Figs. 2 and 3f) yielded 29 sets of slickenlines. Their mean azimuth of slip for horizontal bedding was determined to be 070°; that is subparallel to determinations cited above for the Crowsnest Pass area (see Table 1).

By far the most tectonically revealing measurements of relative slip directions were made underground in the Kootenay Group at Beaver Mines, 16 km east of Adanac, in the immediate hanging wall of the Livingstone thrust fault (point "B", Figs. 2 and 3g). There, 58 measurements were made of the pitch of slickenside striae on the roof of the coal seam. They had a normal distribution with a mean azimuth of slip of 051°, markedly askew from the counter-dip direction (023°) of the seam but sub-parallel to the mean slip direction of the Wilson, Stewart and Upper Marsh





Crowsnest Lake

	Bedding		Extension Faults		Contraction Faults		Wrench Faults		Faults indet.	
	poles ○	b axes ●	poles ▽	b axes ▼	poles □	b axes ■	poles ◊	b axes ♦	poles ⬡	b axes ⬢
a.	75	75	—	—	—	—	—	—	—	—
b.	—	—	7	7	19	17	11	11	10	10

Preferred orientation of bedding: SS
Preferred orientation of fabric axes: a, b
Mean Azimuth of Bedding Striae: 079°
Standard Deviation of Mean: ± 23°

Fig. 3. (*continued*)

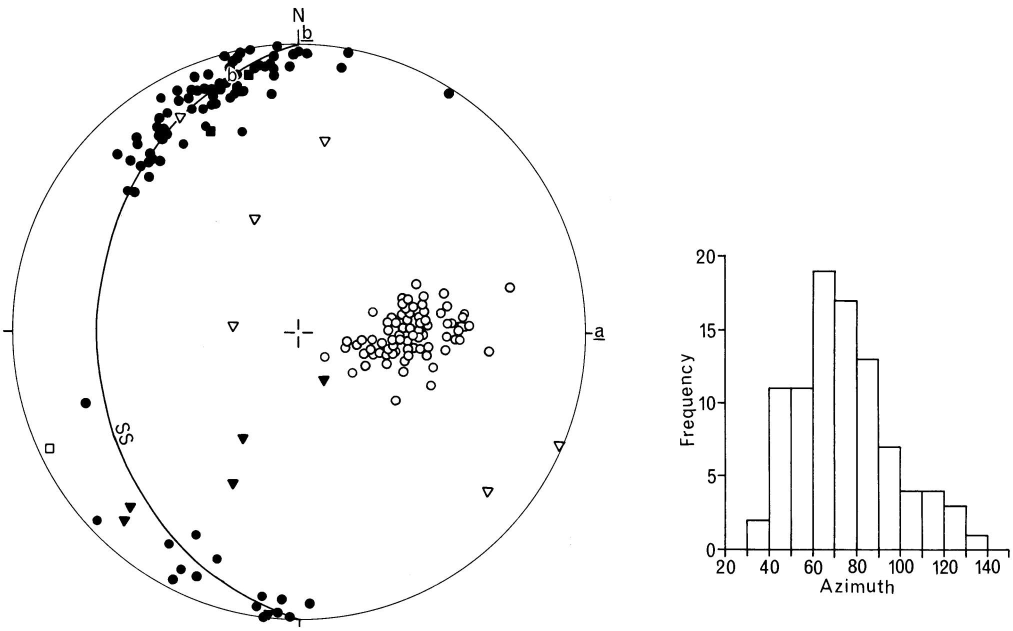
seams (055, 059 and 056°, respectively) at Canmore on the other side of the Crowsnest Deflection.

4. Origin and evolution of the Crowsnest Deflection

A meaningful interpretation of the origin and evolution of the Crowsnest Deflection, and for that matter of any similar, curvilinear, megascopic feature in the eastern Cordillera, can only be made if: (1) structural continuity or discontinuity within individual thrust sheets can be established, (2) actual directions of relative displacements along thrust faults can be measured, (3) segments of the orogen can be demonstrated to have or have not undergone external rotation or bending about vertical axes, and (4) the interpretation is consistent with the structural geometry and origin of the mechanical units involved in the deformation.

Whatever the deflection mechanism, continuity of structural units throughout the deflection is readily demonstrated. There is no penetrative system of cross faults which might be called upon during the late stages of the Laramide orogeny, to produce the current arcuate form of the Frontal Belt of the Canadian Cordillera.

The distributions of mean azimuths for slickenside striae on bedding on the north flank of the Highwood salient in the Canmore area appear to be normal with a preferred direction of 056°, that is closely perpendicular to the Bow Valley–northern Montana trend (Fig. 3). This is close to the mean azimuth of striae at Beaver Mines (051°) within the deflection. The fact that the mean direction of slip at most other locations in the Crowsnest Pass area tends to be perpendicular to the local strike (small divergences; see Table 1) suggests that the overall movement picture for the compressional collapse of the Frontal Belt may not have been entirely unidirectional. Moreover, the asymmetry in the movement pictures of the A-North seam (Fig. 3b) and the Vicary Creek coal seam (Fig. 3d), for example, would suggest the presence of more than one population of striae,



Vicary Creek Seam

Bedding		Extension Faults		Contraction Faults		Wrench Faults	
poles ○	b axes ●	poles ▽	b axes ▼	poles □	b axes ■	poles ◊	b axes ♦
92	93	6	6	2	2	0	0

Preferred orientation of bedding: SS
Preferred orientation of fabric axes: a, b
Mean Azimuth of Bedding Striae: 073°
Standard Deviation of Mean: ±22°

Fig. 3. (*continued*)

perhaps the result of localised external rotation within the arms of the deflection. Underlying, pre-existing structural controls (Montania?, Norris and Price, 1966, p. 399; Vulcan Low?, Clowes et al., 1997, p. 16) may have added to the complexities. Moreover, the changes in the thickness and facies of the sedimentary rocks across such basement features may well have influenced the structural style superimposed upon them by the Laramide orogeny (Price, 1994, p. 316).

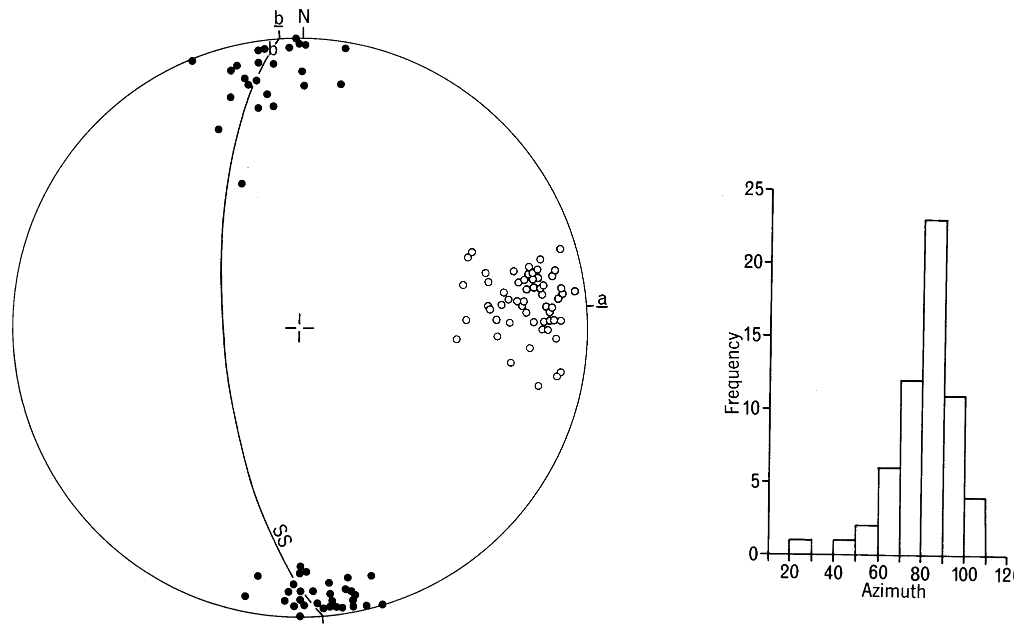
These kinematic data in conjunction with the paleomagnetic measurements support the hypothesis that while the Frontal Belt underwent west-to-east, differential contraction during the Laramide orogeny, structural continuity along the strike was maintained. Moreover, there was no differential rotation of the Frontal Belt about vertical axes and, correspondingly, no significant folding about these axes that would require either synkinematic longitudinal contraction and buckling of the orogen or stretching of the supracrustal wedge in and around the Crowsnest Deflection. The curviplanar form of the shelf-miogeocline would appear to have been controlled by the initial and fundamental shape of the Archaean? crystalline basement surface upon which the supracrustal wedge was deposited (Norris, 1968, p. 221).

Should this have been the case, the formations comprising the deflection initially must also have had this curviplanar form. Some examples that tend to support this conjecture[2] are the mid-Proterozoic Belt–Purcell Basin (McMechan, 1981, p. 617), isopach maps of the Upper Cretaceous Cardium Formation in the region of the deflection (Norris, regional mapping; unpublished data), the Upper Carboniferous Misty Formation (Norris, 1965b, p. 27) and the Lower Carboniferous Mount Head Formation (Brandley et al., 1996, Fig. 2).

Three mechanisms for the origin of the Crowsnest Deflection (Fig. 4) need consideration:

1. Differential rotation of parts of the orogen about vertical axes.
2. Differential shear on two sets of near vertical, northeast-trending, strike- or oblique slip faults.
3. Uniform translation in a common direction regardless of position in the deflection.

[2] Tippett (pers. com., Dec. 1997) has advised me that "top Cambrian Cathedral Fm. does not appear to show a trough or ridge through the Crowsnest Pass and hence if there is topography on the top of the Precambrian it was deeply buried and compensated for by Cambrian time".



Blairmore Range

Bedding		Extension Faults		Contraction Faults		Wrench Faults	
poles ○	b axes ●	poles ▽	b axes ▼	poles □	b axes ■	poles ◊	b axes ♦
60	60	0	0	0	0	0	0

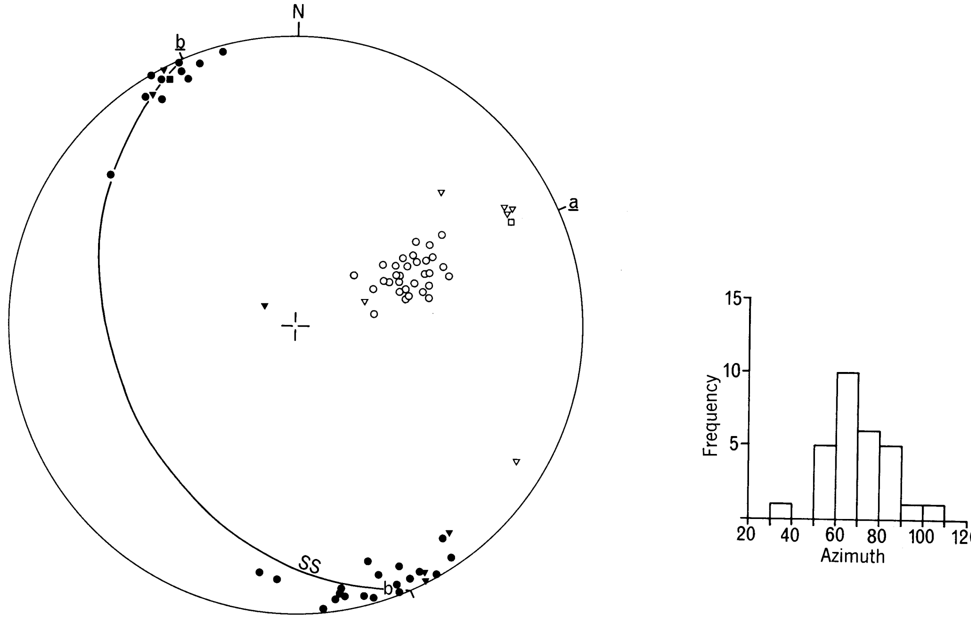
Preferred orientation of bedding: SS
Preferred orientation of fabric axes: a, b
Mean Azimuth of Bedding Striae: 082°
Standard Deviation of Mean: ±14°

Fig. 3. (*continued*)

Differential rotation may have been a viable mechanism within the deflection where there was incomplete transfer of displacement from one thrust sheet to another. It may, indeed, have been responsible for the tendency for slickenlines within the deflection to orient themselves perpendicular to the local strike (see Table 1), thereby minimizing their structural divergence. Moreover, passive rotation of sheets during shortening may have reoriented the fold axes so that they do not necessarily reflect their orientations at the time of thrusting (Fermor, pers. com., 2000). However, folding of the orogen about vertical axes requires longitudinal stretching if there is no synkinematic, longitudinal convergence or buckling. In the case of the Crowsnest Deflection this would require about 10 km of extension along strike. There is no field evidence for this either in the form of northeast-trending extension faults, or in extension distributed throughout a set of northeast-trending joints. In addition, the remanent magnetic dipoles in the mid-Proterozoic sedimentary rocks remain aligned and subparallel to one another from the Clark Range at least to the southern extremity of the Highwood salient, thereby eliminating the possibility of major rotation about vertical axes.

Differential shear on sets of northeast-trending wrench faults, in the manner of slip folding, also is not considered a viable alternative because of the conspicuous absence of vertical cross faults with the appropriate reversals in sense of shear as the structural grain swings to the right or left in the deflection. Multidirectional translation of the dismembering, layered mass is the favoured alternative because there need be neither synkinematic longitudinal stretching nor buckling, nor differential transverse shear, nor significant differential rotation. Rather, there would be a preferred azimuth for tectonic transport common to both sides of the deflection, and a tendency for striae to reorient parallel to the local counterdip direction within the deflection, with corresponding adjustments to the structural divergence.

The imprint of the deflection on both the pre- and post-Laramide sedimentary record, moreover, provides additional support for the hypothesis that the eastern flank of the Cordilleran shelf-miogeocline was curved somewhat in the manner of the Crowsnest Deflection, perhaps in response to basement fault control (Norris, 1968, p. 221), and for the hypothesis that this persistent shape dictated to some considerable degree the thinning of the sedimentary prism at the deflection since mid-Proterozoic time (McMechan, 1981, p. 616). Should the initial structural geometry and the layered anisotropy of the supracrustal



Adanac Strip Mine

Bedding		Extension Faults		Contraction Faults		Wrench Faults	
poles ○	b axes ●	poles ▽	b axes ▼	poles □	b axes ■	poles ◊	b axes ♦
32	29	6	6	1	1	0	0

Preferred orientation of bedding: SS
Preferred orientation of fabric axes: a, b
Mean Azimuth of Bedding Striae: 070°
Standard Deviation of Mean: ±14°

Fig. 3. (*continued*)

wedge have controlled the orientation and shape of failure surfaces within the wedge, then they must have been the underlying control for the orientation and shape of both the set of contraction (thrust) faults comprising the Frontal Belt of the eastern Cordillera and of the migrating, Laramide exogeocline. The parts of the Lewis sheet comprising the Clark Range and Highwood salients were always structurally farther east than their continuations in the Crowsnest reentrant. The present curviplanar form of successive thrust sheets is, therefore, primarily related to the geometry of the sheets established at initial shear failure rather than to later, wholesale tectonic bending of the orogen.

5. Conclusions

Slickenlines on bedding in the southern Rocky Mountains provide a comprehensive insight into the tectonic development of the Crowsnest Deflection. They reveal that both within the deflection and beyond it there was a strong tendency for interbed slip to be parallel to the local counterdip direction. Moreover, the curviplanar shape of the deflection in the mid-Proterozoic through early Tertiary sedimentary formations comprising the supracrustal wedge in southwestern Alberta and southeastern British Columbia appears to have been inherited from the ancient and persistent shape of the crystalline basement surface extending westward from the Canadian Shield and, in turn, of the shape of the overlying Cordilleran shelf-miogeocline. The deflection would appear to be similar in orogenesis to the great northeastward salient of the Mackenzie Mountains in Northwest Territories (Norris, 1972, p. 642) and to the northwestward salient of the central Appalachians in Pennsylvania, interpreted from paleomagnetic evidence by Roy et al. (1967, p. 5085) to indicate that the curvature of the Appalachians follows closely that of the original geosyncline.

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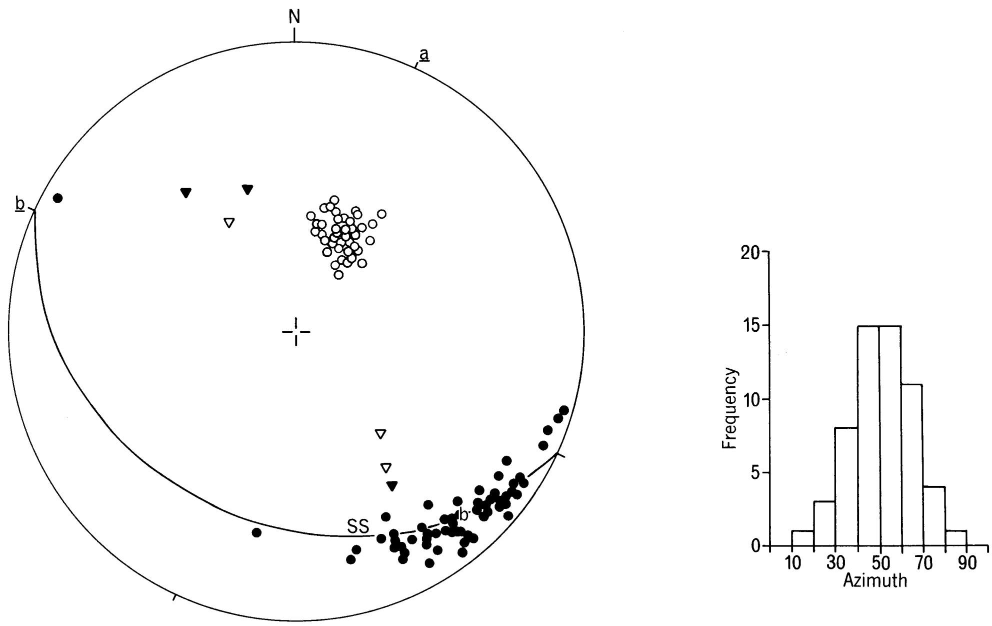

Beaver Mines Seam

Bedding		Extension Faults		Contraction Faults		Wrench Faults	
poles ○	b axes ●	poles ▽	b axes ▼	poles □	b axes ■	poles ◊	b axes ♦
62	58	3	3	0	0	0	0

Preferred orientation of bedding: SS
Preferred orientation of fabric axes: a, b
Mean Azimuth of Bedding Striae: 051°
Standard Deviation of Mean: ±14°

Fig. 3. (*continued*)

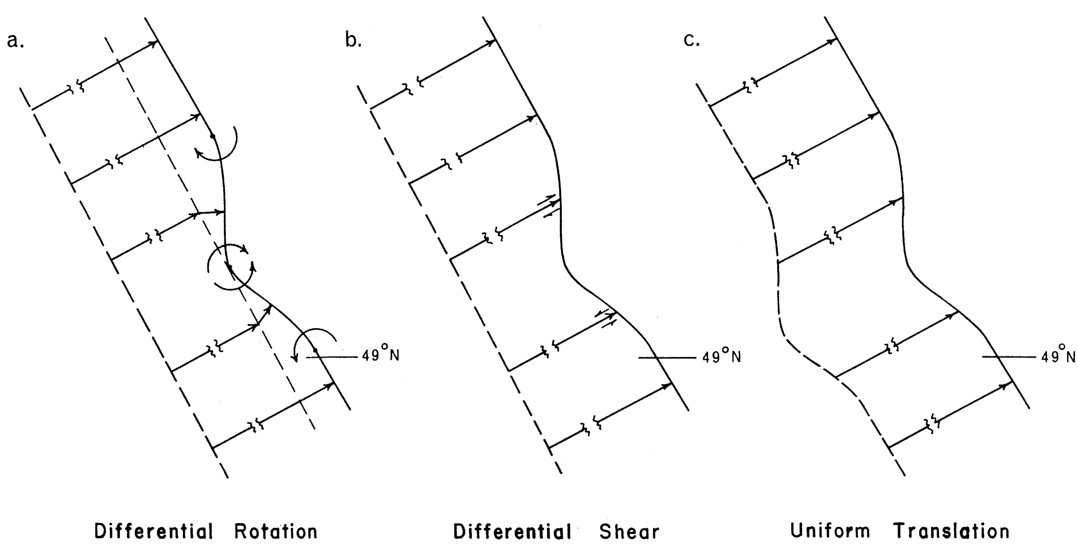

Fig. 4. Three possible mechanisms for the development of the Crowsnest Deflection: (a) differential rotation of parts of the orogen about vertical axes above a regional detachment surface on crystalline basement, (b) differential shear on near-vertical, strike- or oblique-slip faults in the manner of slip-folding; and (c) uniform translation in a common direction regardless of position in the deflection (following Norris and Black, 1962). Curvilinearity of orogen is shown schematically by the dashed line to the left of each mechanism.

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