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An evaluation of models for the kinematic evolution of thrust and fold belts: structural analysis of a transverse fault zone in the Front Ranges of the Canadian Rockies north of Banff, Alberta

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Abstract

The prevailing 'piggyback' conceptual model for the kinematics of 'thin-skinned' thrust and fold belts maintains that the main faults develop sequentially from the hinterland to the foreland, and from the top to the bottom of the accretionary wedge. Moreover, it presumes that when younger thrust faults originate, overlying older thrust faults become inactive and are carried forward passively. This appears to contradict the prevailing mechanical model for the evolution of 'thin-skinned' thrust and fold belts, the critical Coulomb wedge model, which requires that lateral growth of the wedge must be accompanied by vertical thickening of the wedge. Crosscutting relationships along a transverse fault zone in the Front Ranges of the Canadian Rockies north of Banff, Alberta, and patterns of overprinting of thrust-related folding on pre-existing thrust sheets, demonstrate substantial overlap in the times of displacement on four major thrust faults in this part of the Front Ranges. The presumption that displacement on one major thrust fault ends when displacement on a younger underlying thrust begins is a fallacy. There is no contradiction between the 'piggyback' conceptual kinematic model and the critical Coulomb wedge mechanical model for the evolution of 'thin-skinned' foreland thrust and fold belts. The main faults do originate sequentially from the hinterland to the foreland, and from the top to the bottom of the evolving wedge; but displacement occurs simultaneously on several major faults. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The Rocky Mountain foreland thrust and fold belt is a northeasterly tapering accretionary wedge. It consists of miogeoclinal, platformal, and foreland basin supracrustal rocks that have been scraped off the edge and flank of the under-riding North America craton and accreted to the overriding Intermontane terrane (Price, 1981, 1994). The deformation is 'thin-skinned'. That is to say, undeformed Paleoproterozoic crystalline basement extends southwestward, from beneath the Western Canada Sedimentary basin, under the thrust and fold belt, across the Canadian Rockies to beyond the Rocky Mountain trench (Shaw, 1963; Bally et al., 1966; Keating, 1966; Price and Mountjoy, 1970a; Price, 1981; Cook et al., 1988).

The structure of the accretionary wedge is dominated by listric thrust faults. The faults are concave upward in profile and generally SW-dipping. They flatten with depth and merge in a regional décollement above the undeformed crystalline basement (Bally et al., 1966). Some also flatten into higher décollement zones (Douglas, 1950; Bally et al., 1966; Dahlstrom, 1970; Price and Fermor, 1985). Displacement along the curved segments of the thrust faults involved rotation and tilting of the displaced strata (fault-bend folding) (Suppe, 1983). In the southwest where the stratigraphically thicker miogeoclinal succession is involved, the thrust faults are more widely spaced and the thrust sheets are thicker, larger, and mainly shallowly dipping. In the northeast, in the Front Ranges of the Canadian Rockies, where the thinner cratonic platform sequence and overlying foreland basin deposits are involved, the thrust faults are more closely spaced and they form an imbricate fan of steeply dipping thrust sheets (Price and Mountjoy, 1970a).

Structural analysis of relationships across thrust faults and between thrust faults and folds in the Canadian Rockies, and in many other foreland thrust and fold belts, has led to a widely held conceptual kinematic model of 'piggyback' deformation (Dahlstrom, 1970). According to this model, the main thrust faults develop sequentially from the hinterland to the foreland, and from the top to the bottom of the evolving accretionary wedge; and when new younger thrust

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faults originate, overlying older thrust faults become inactive and are carried passively by underlying younger faults. The older overlying faults commonly become folded, along with the strata beneath them, as a result of the fault-bend folding and fault-propagation folding (Suppe and Medwedeff, 1990) associated with displacement on younger underlying faults. Graphic representations of this conceptual kinematic model generally imply that displacement on one major thrust fault must end when displacement on a younger underlying thrust begins; and this has led to the use of the term 'out-of-sequence' for thrust displacements that occur above and behind the frontal thrust of an evolving accretionary prism (Morely, 1988).

The basic empirical evidence for the 'piggyback' model is the observation that the thrust faults 'always' cut upwards through the stratigraphic section in the direction of relative displacement of the hanging wall, and therefore they 'always' juxtapose older rocks over younger rocks and produce repetitions of the normal stratigraphic succession. These are the earmarks of thrust faults that have propagated through near horizontal unfaulted strata. The thrust faults 'never' cut downwards through the stratigraphic section in the direction of relative displacement of the hanging wall, and therefore they do not juxtapose younger rocks over older rocks and produce omissions of the normal stratigraphic succession, as they would if younger thrust faults had propagated through older thrust and fold structures and truncated and offset the older thrust faults and related folds.

Investigations of the dynamics of thrust and fold belt evolution that have focused on the characteristic wedge shape of the deformed and displaced mass and on the role of gravity in the evolution of the wedge (Price, 1973; Elliot, 1976; Chapple, 1978) have led to the widely accepted critical Coulomb wedge mechanical model for the dynamic evolution of the foreland fold and thrust belts (Davis et al., 1983). The critical Coulomb wedge model presumes that the accretionary wedge is mechanically homogeneous and isotropic and that an actively accreting wedge maintains a critical taper that corresponds to an internal state of stress that is everywhere on the verge of brittle shear (Coulomb) failure and to a basal shearing stress that is on the verge of frictional sliding failure (Dahlen and Barr, 1989). The critical Coulomb wedge model requires that, in general, lateral growth of an accretionary wedge must be accompanied by horizontal compression and vertical thickening of the wedge. The implication that 'out-of-sequence' thrusting should continue to occur in the interior of the wedge as it grows in width contradicts a basic presumption of the 'piggyback' kinematic model.

Structural relationships along a transverse fault in the Front Ranges of the Canadian Rockies north of Banff, Alberta, provide a special opportunity to investigate this apparent contradiction between the 'piggyback' kinematic model and the critical taper mechanical model of thrust and fold belt evolution.

2. Regional geologic structure

The transition between the cratonic platform and laterally equivalent miogeoclinal succession of the Canadian Cordillera occurs in the Front Ranges subprovince of the Canadian Rockies. In the vicinity of Banff, Alberta, the Front Ranges subprovince consists of four major NW-trending, SW-dipping thrust sheets: the McConnell, Rundle, Sulphur Mountain, and Bourgeau thrust sheets. They form a NE-verging, imbricate, thrust stack.

The structure of the imbricate stack has been etched out by erosion and is clearly expressed in the topography (Figs. 1–4). Each thrust sheet consists of erosionally resistant Paleozoic carbonate rocks that are overlain by less resistant Triassic to Middle Jurassic marine shales and siltstones, and locally by Upper Jurassic and Cretaceous non-marine foreland-basin siliciclastic deposits. The resistant SW-dipping Paleozoic carbonate rocks form conspicuous long, parallel, linear mountain ranges with steep scarps on the northeast sides and dip slopes on the southwest sides (Fig. 4B–D). Northwest–southeast-trending valleys have been carved into the intervening, much less resistant Mesozoic rocks. The generally SE-flowing Bow River, which is the main trunk stream in the area, cuts abruptly across the structural grain in the vicinity of Banff, to expose natural cross-sections through the Rundle, Sulphur Mountain, and Bourgeau thrust sheets (Figs. 1, 2, and 4A–C); but east of the Rundle thrust fault the Bow River flows southeast in a valley that has been eroded in the Mesozoic rocks of the upper part of the McConnell thrust sheet (Fig. 2a).

The thrust faults commonly are remarkably uniform along strike, having more or less the same orientation and the same stratigraphic units on either side (Fig. 2a). However, they do change along their length, and locally

Fig. 1. High-level oblique air photo looking north at the Rundle (right side), Sulphur Mountain (right-centre), and Bourgeau (centre) thrust sheets. All three thrust sheets strike 328°–330° northward to the vicinity of the Bow River valley, which extends across the centre of the photo. A transverse, NE-trending monoclinal flexure occurs in the Rundle thrust sheet at Cascade Mountain, just north of the Bow River valley (right, centre), and the Sulphur Mountain thrust sheet is folded by this transverse monocline.

the changes are relatively abrupt. The Rundle thrust fault dies out alongside a NW-plunging anticlinal fold about 30 km northwest of the Bow River valley (Figs. 2a and 4C). The Sulphur Mountain thrust sheet dies out in a SE-plunging fold structure near Lower Kananaskis Lake (McMechan, 1995), about 50 km southeast of the Bow River valley. The Bourgeau thrust fault, one of the longest thrust faults in the Canadian Rockies, extends about 500 km from latitude 52° 35′ N, at Maligne Lake in Jasper National Park, to latitude 48° 50′ N in the Flathead Valley of northern Montana (Price and Mountjoy, 1970a; Price, 1981; Wheeler and McFeely, 1991). The Sawback thrust fault (Figs. 2 and 4D) is a splay from the underlying Bourgeau thrust fault. In the vicinity of the Bow River valley, the Sawback thrust juxtaposes a thick, W-dipping panel of miogeoclinal Cambro-Ordovician and Devono-Carboniferous carbonate rocks over a steeply dipping E-facing panel of Devono-Carboniferous carbonate rocks that occurs in the hanging wall of the Bourgeau thrust fault. However, about 45 km north of the Bow River, in the Hector Lake map area, the Sawback thrust fault dies out in the core of an anticline in Lower and Middle Cambrian rocks that occupy the hanging wall of the Bourgeau thrust fault (Price and Mountjoy, 1978).

In a regional structure section that crosses these thrust sheets about 10 km southeast of Banff (Price and Fermor, 1985), the displacement on the Rundle thrust is about 10 km, the displacement on the Sulphur Mountain thrust sheet is about 6 km, and the combined displacement on Sawback and Bourgeau thrusts is about 28 km.

3. Transverse structures

An unusual transverse fault zone occurs in the Front Ranges, just north of the Bow Valley, near Banff, Alberta. It consists of a swarm of steeply dipping, NE- to ENE-striking faults, almost all of which have right-hand strike separation. The strike separation across most of the faults is less than 200 m, but the main fault in the zone has a right-hand strike separation of up to 1200 m (Fig. 2b). The cross-cutting relationships between this main transverse fault and the Sulphur Mountain and Bourgeau thrust sheets, and the spatial relationship between the fault and the structure of the underlying Rundle thrust sheet, make it possible to establish the relative timing of displacements on the Rundle, Sulphur Mountain, and Bourgeau thrust faults, and thereby to elucidate the apparent contradiction between critical taper theory and the piggyback model of thrust and fold belt development.

Other transverse faults occur locally in the Front Ranges, as for example in the Rundle, Sulphur Mountain, and Bourgeau thrust sheets in the region south of the Bow River valley (Fig. 2a). Some of these transverse faults are tear faults along which slip has been parallel to the direction of displacement on an underlying thrust fault against which they terminate (Douglas, 1958). Others evidently are older normal faults that have been transported passively in a thrust sheet (Price, 1967) because they are truncated at a high angle by an underlying thrust fault, and the slip along them has been perpendicular to the underlying thrust fault. The transverse fault zone in the Front Ranges just north of the Bow Valley is different. The main fault in this zone merges asymptotically with the underlying Sulphur Mountain thrust fault. This unusual fault is a principal focus of this paper.

4. Structural analysis

In the region south of the Bow River valley, the strata of the Rundle, Sulphur Mountain, and Bourgeau thrust sheets form three remarkably parallel, straight, steeply dipping, homoclinal panels that strike 328°–330° (Fig. 2a). This pattern is disrupted at Cascade Mountain, north of Banff, by a transverse NW-plunging monocline in the Rundle thrust sheet (Figs. 2 and 3). The monocline is most clearly outlined by the configuration of the Rocky Mountain Supergroup west of Cascade Mountain (Fig. 2b). Within the monocline, the strata strike about 030° and dip about 25° north-northwest. The monocline plunges northwest (305°) at about 25°, and is about 1 km wide. It coincides with the locus of an oblique lateral ramp along the hanging wall of the Rundle thrust fault, across which the thrust cuts abruptly upward through about 800 m of stratigraphic section. Southeast of the monocline, beneath the straight structural panel that extends through Mount Rundle (Fig. 2a), the Rundle thrust fault follows a décollement within the Middle Cambrian. Northwest of the monocline, along the northeast flank of Cascade Mountain, over an interval of about 400 m, the Rundle thrust fault follows another, higher décollement horizon just below the Upper Devonian Palliser Formation (Figs. 2b and 3b). The Rundle thrust fault is subplanar beneath the oblique hanging wall ramp, and a synclinal fold in the Jurassic Fernie Group and the Upper Jurassic–Lower Cretaceous Kootenay Group strata which occupy the footwall of this part of the Rundle thrust sheet is subparallel with the Rundle thrust fault. The transverse monocline evidently is a fault-bend fold that has developed along an oblique hanging wall ramp.

Over an interval of about 10 km beyond the transverse monocline and the décollement at the base of the Palliser Formation, the strata in the Rundle thrust sheet strike 350°, and the Rundle thrust cuts gradually upward in its hanging wall through about 800 m of stratigraphic section, from the base of the Palliser Formation to the base of the Rundle Group (Fig. 2a). At that level an essentially horizontal fault-propagation anticline appears in the hanging wall of the Rundle thrust sheet. For a distance of about 13 km, this anticline trends about 330°, subparallel with strike of the three thrust sheets south of the Bow River valley. The anticline then plunges north-northwest, and the Paleozoic rocks

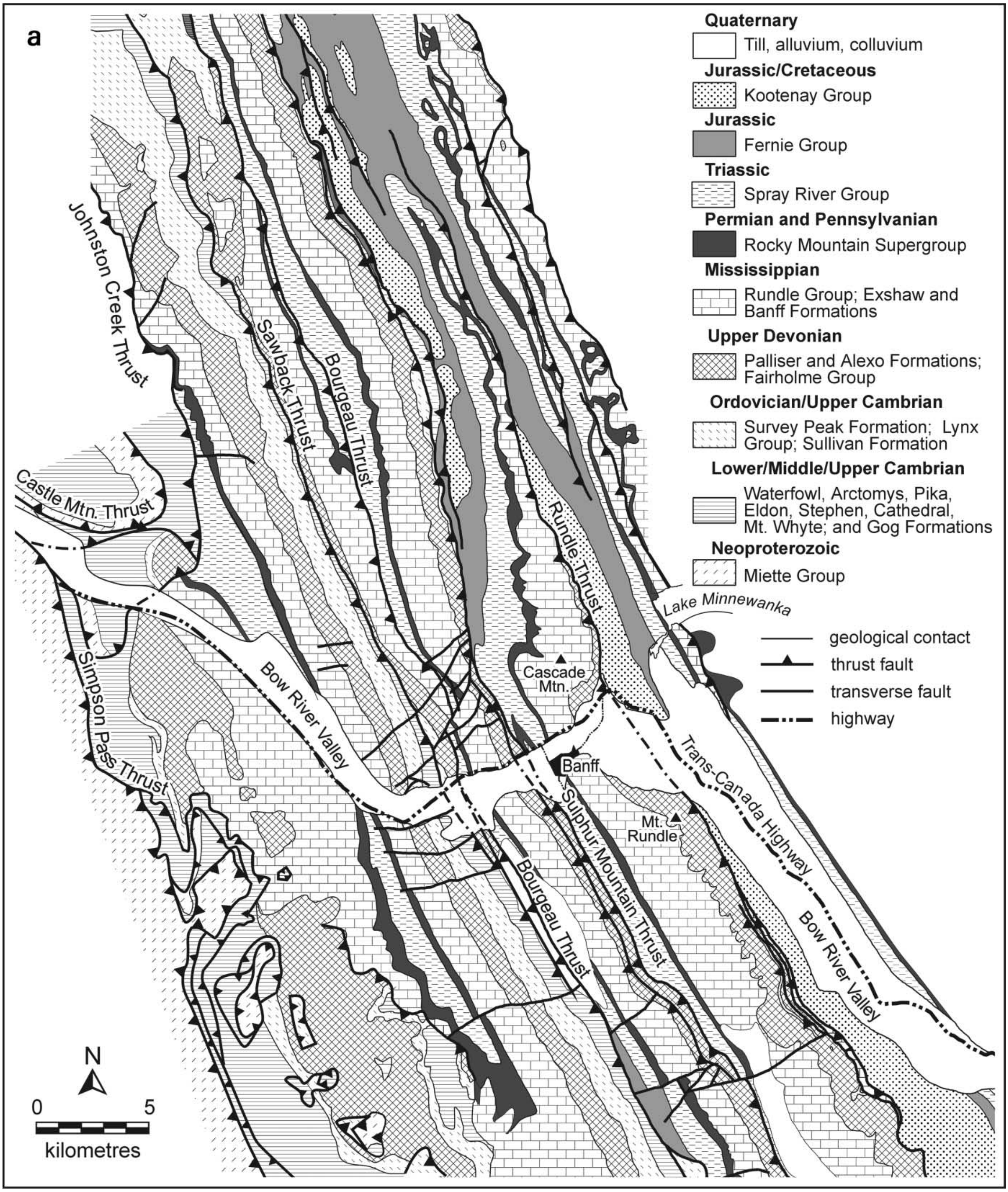


Fig. 2. (a) Geological map of the western Front Ranges of the Canadian Rockies near Banff, Alberta (after Price and Mountjoy, 1970b, 1973a–d; Price et al., 1971). (b) Enlarged view of transverse structures in the Rundle, Sulphur Mountain, and Bourgeau thrust sheets north of the Bow River near Banff, Alberta.

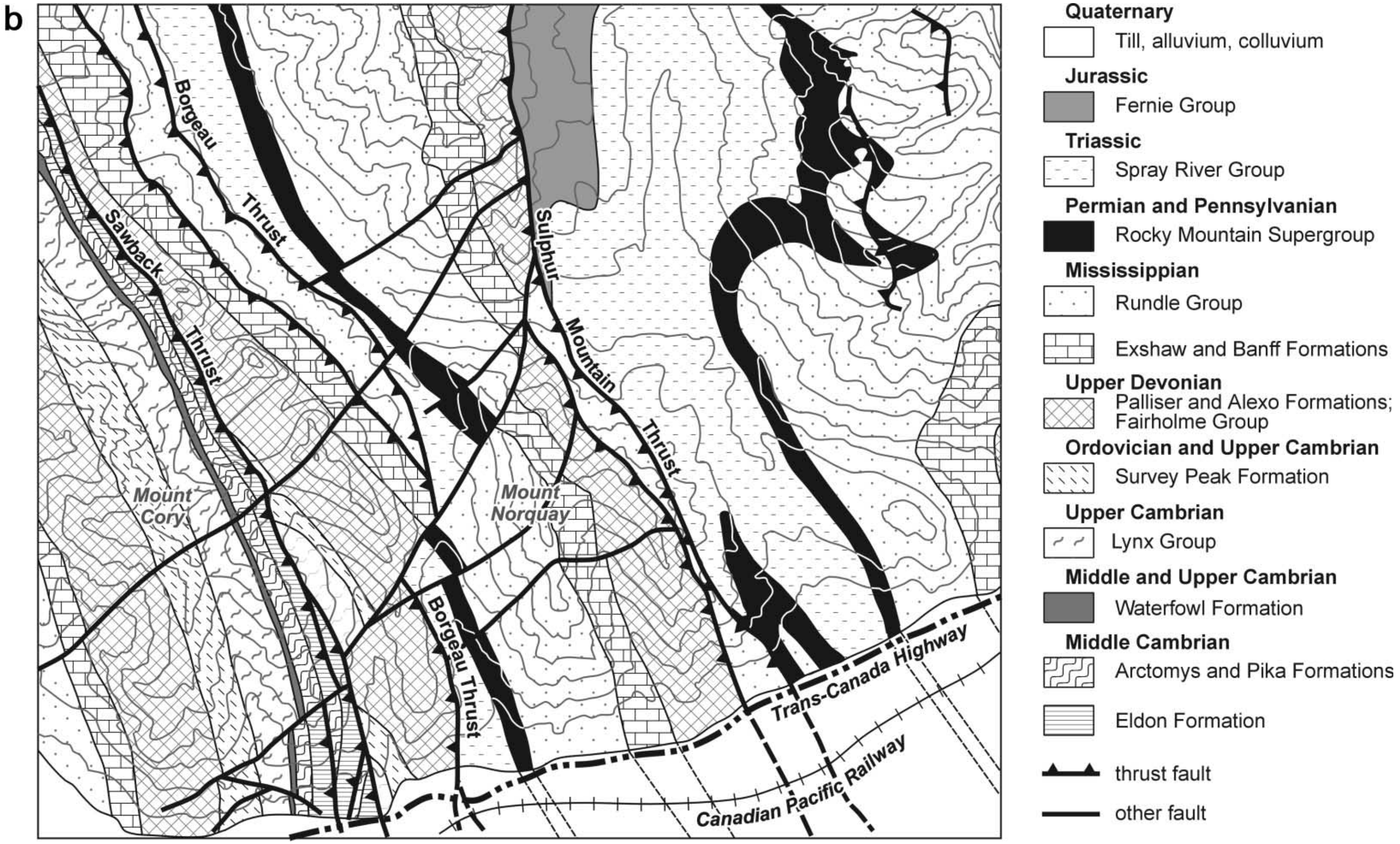
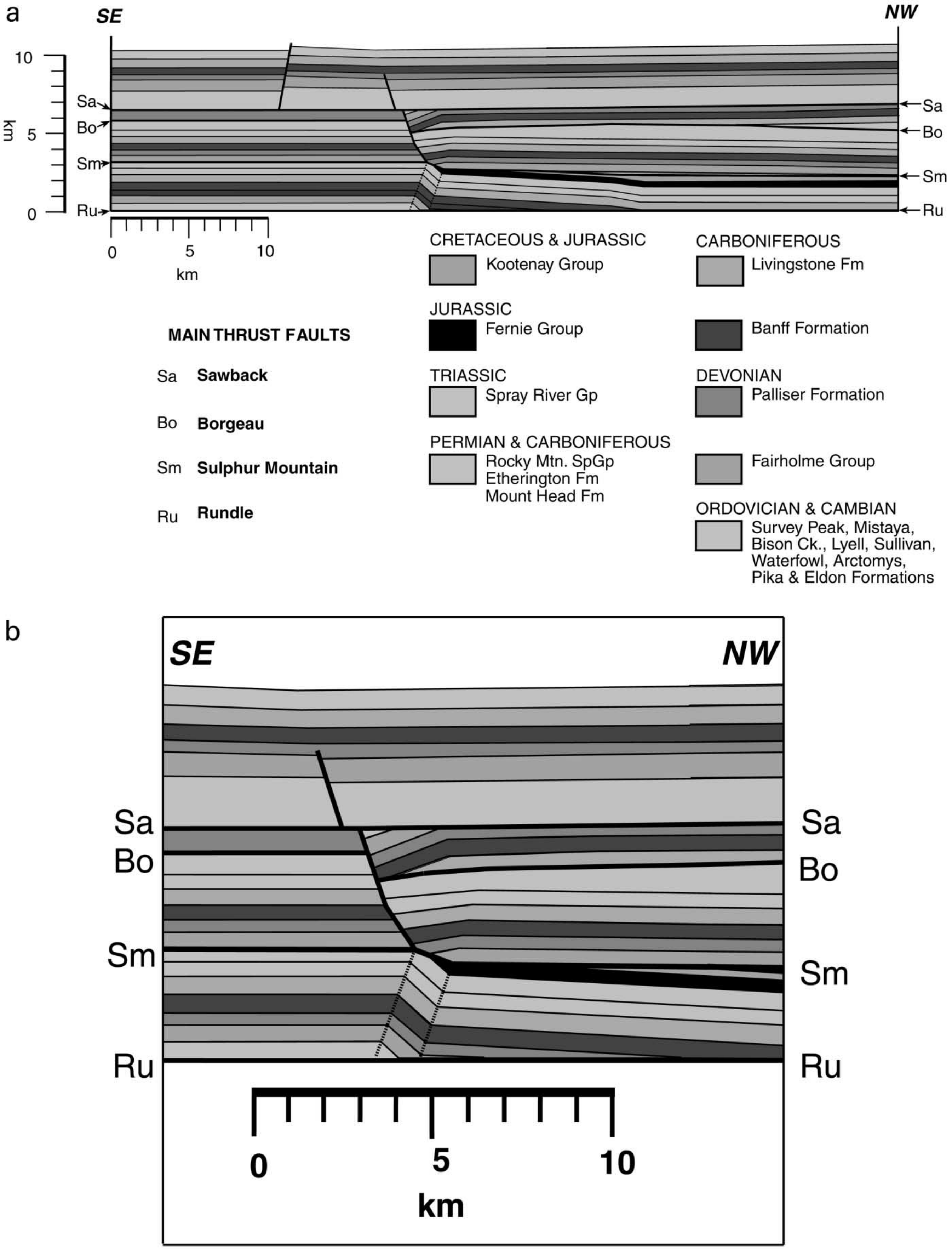


Fig. 2. (*continued*)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Kootenay Group
JURASSIC
Fernie Group
TRIASSIC
Spray River Gp
PERMIAN & CARBONIFEROUS
Rocky Mtn. SpGp
Etherington Fm
Mount Head Fm
CARBONIFEROUS
Livingstone Fm
Banff Formation
DEVONIAN
Palliser Formation
Fairholme Group
ORDOVICIAN & CAMBIAN
Survey Peak, Mistaya, Bison Ck., Lyell, Sullivan, Waterfowl, Arctomys, Pika & Eldon Formations
MAIN THRUST FAULTS
Sa Sawback
Bo Borgeau
Sm Sulphur Mountain
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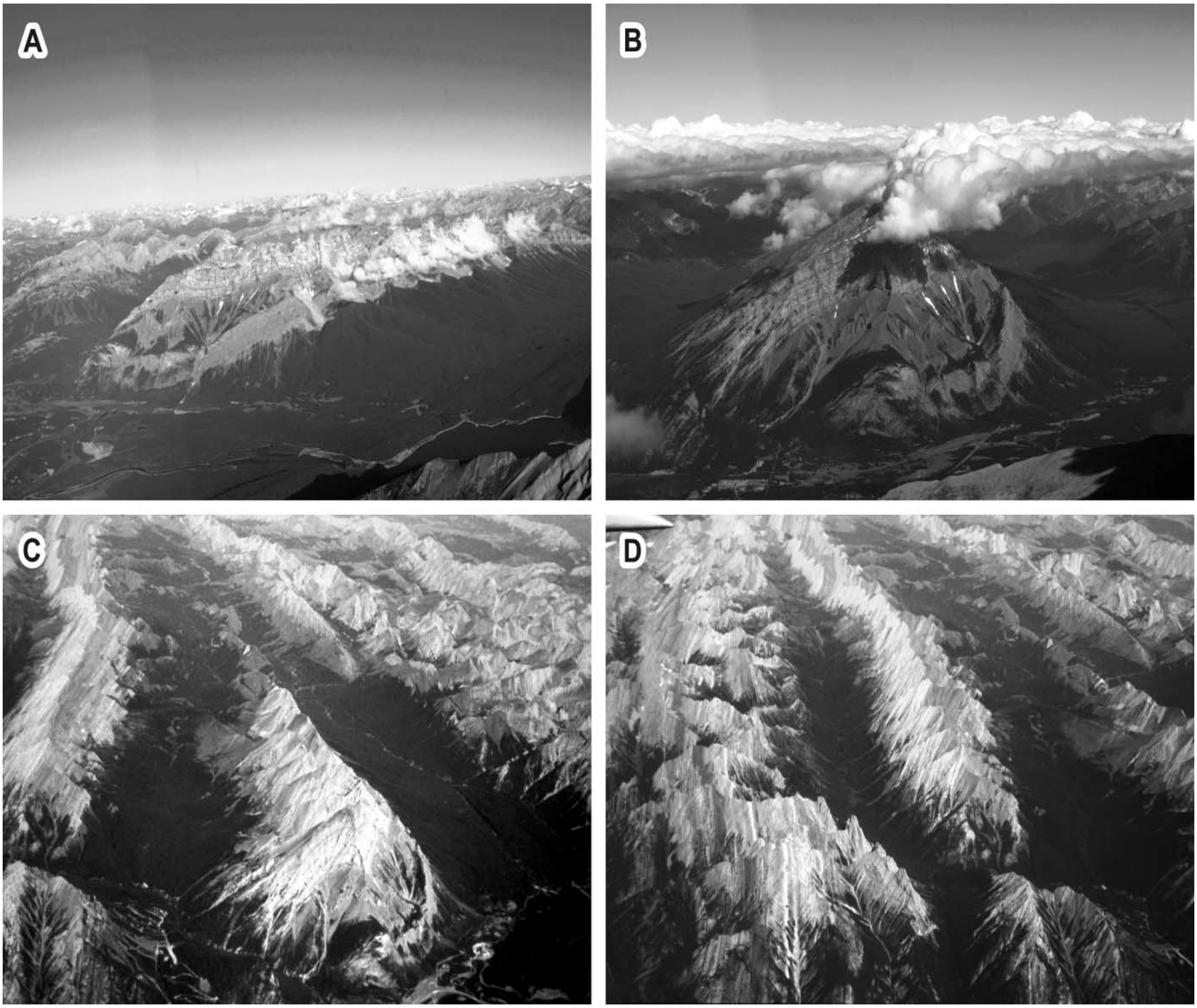

Fig. 4. (A) High-level oblique air photo looking west-northwest at the northern end of the Rundle thrust sheet. The peak at the left end of the ridge in the foreground is Cascade Mountain. The trace of the Rundle thrust fault lies just below the lower massive limestone cliff (Upper Devonian Palliser Formation), where the Palliser Formation and underlying Upper Devonian Fairholme Group are juxtaposed over the Jurassic Fernie Group and Jurassic and Lower Cretaceous Kootenay Group. The transverse monocline is outlined at the south (left) end of Cascade Mountain by the configuration of the Palliser Formation. The Sulphur Mountain thrust sheet is visible in the background, beyond Cascade Mountain. The Bow River valley is in the foreground. (B) Low-level oblique air photo looking north at a cross-section of the Rundle thrust sheet on the south slope of Cascade Mountain. The transverse monocline is outlined at the south (left) end of Cascade Mountain by the configuration of the lower massive limestone cliff (Upper Devonian Palliser Formation). The Bow River valley is in the foreground; and the town of Banff is just out of view at the lower left side of the photo. (C) High-level oblique air photo looking north at the northern end of the Rundle thrust sheet. The transverse hanging wall ramp monocline that occurs in Cascade Mountain (foreground, centre), is outlined by the configuration of the cliff-forming limestones of the Upper Devonian Palliser Formation (lower-right foreground, centre), the dark shaly rocks of the Carboniferous Banff Formation, and the overlying cliff-forming carbonate rocks of the Carboniferous Rundle Group. The same stratigraphic units (Palliser, Banff, Rundle) are easily identified by their topographic expression and colour in the Sulphur Mountain thrust sheet, which forms the linear mountain range on the left. They outline a broad, open monoclinal flexure in the Sulphur Mountain thrust sheet that conforms with some of the structure in the underling Rundle thrust sheet. The McConnell thrust sheet, which underlies the Rundle thrust sheet, is in the upper right part of the photo. The Bow River valley is in the foreground. (D) High-level oblique air photo looking north at the Bourgeau thrust sheet (left side) and Sulphur Mountain thrust sheet (centre) just north of the Bow River valley. The north end of the Rundle thrust sheet enters the photo on the right (east), and the McConnell thrust sheet is to the northeast (upper right). The Sawback thrust fault, which occurs within the Bourgeau thrust sheet, extends northwest from the central foreground of the photo, separating a NE-dipping structural panel of Devonian strata (Palliser Formation and Fairholme Group) on the east from a SW-dipping structural panel of Cambrian and Ordovician strata on the west.

Fig. 3. (a) Transverse hanging wall ramp in the Rundle thrust sheet, and related transverse extension fault in the Sulphur Mountain and Bourgeau thrust sheets, Front Ranges of the Canadian Rockies near Banff, Alberta. Schematic, oblique, longitudinal profile, looking down the dip of the thrust sheets at the present level of exposure. (GP—Group; Fm—Formation; SpGp—Super Group.) (b) Enlarged view of transverse structures.

disappear beneath the shales of the Jurassic Fernie Group. This disappearance appears to be coincident with the termination of the Rundle thrust fault, but the location of the tipline of the Rundle thrust is concealed within the shales of the Fernie Group.

If, as is presumed in the 'piggyback' model, all of the displacement on the Sulphur Mountain thrust occurred before the displacement on the Rundle thrust began, then, during the development of the transverse monocline in the underlying Rundle thrust sheet, the Sulphur Mountain thrust sheet should have been folded by exactly the same amount as the strata of the underlying Rundle thrust sheet. The reality is that the Sulphur Mountain thrust sheet is folded by the transverse monocline, but to a lesser degree than the strata in the underlying Rundle thrust sheet. This discrepancy is due to the fact that there is a transverse footwall ramp along the Sulphur Mountain thrust fault, across which the Sulphur Mountain thrust fault cuts up-section to the northwest, precisely where the Sulphur Mountain thrust sheet is folded over the transverse hanging wall ramp monocline in the underlying Rundle thrust sheet. This juxtaposition of a footwall transverse ramp along the Sulphur Mountain thrust over the hanging wall ramp along the Rundle thrust strongly suggests that the transverse monocline began developing while displacement on the Sulphur Mountain thrust was still underway. At this locality, a substantial portion of the displacement along the Rundle thrust fault probably occurred before displacement on the Sulphur Mountain thrust fault had ceased.

An unusual transverse fault occurs within the Sulphur Mountain thrust sheet exactly where it is folded over the underlying monocline in the Rundle thrust sheet (Figs. 2b and 3b). This transverse fault, when viewed obliquely, in profile, along the plane of the bedding of the Sulphur Mountain thrust sheet (Fig. 3b), has the earmarks of a listric extension fault within the Sulphur Mountain thrust sheet. It cuts the stratification within the Sulphur Mountain thrust sheet at an angle of about 60°, and it flattens and merges asymptotically with the underlying Sulphur Mountain thrust fault. It cuts down through the stratigraphic succession in the direction of relative movement of the hanging wall, juxtaposing younger rocks over older, and causing an omission in the normal stratigraphic succession. Displacement along this transverse fault has produced stretching along the strike of the Sulphur Mountain thrust sheet and shortening perpendicular to the thrust sheet. Within the Sulphur Mountain thrust sheet, the stratigraphic separation across the transverse fault, and presumably, the displacement along it, is about 1200 m. It is noteworthy that the segment of the Sulphur Mountain thrust fault with which the transverse fault merges is the segment that lies within the transverse monocline (Fig. 3b); and, in particular, that the strike-parallel extension in the Sulphur Mountain thrust sheet occurs where the thrust sheet was deformed due to the development of the underlying fault-bend transverse monocline in the Rundle thrust sheet. The sense and locus of fault displacement are kinematically congruent with the displacement and rotation that was imposed on the Sulphur Mountain thrust sheet during the development of the underlying transverse hanging wall ramp monocline in the Rundle thrust sheet.

The transverse listric extension fault obviously truncates and offsets the overlying Bourgeau thrust fault; but the amount of offset is not tightly constrained because the trace of the Bourgeau thrust is concealed by surficial deposits on the north side of the transverse fault. The stratigraphic separation along the transverse fault decreases conspicuously across the Bourgeau thrust fault, from about 1200 m in the Sulphur Mountain thrust sheet, to about 700 m in the Bourgeau thrust sheet; but this decrease is associated with a change in orientation of the bedding from SW-dipping and evidently perpendicular to the displacement on the transverse fault in the Sulphur Mountain thrust sheet, to NE-dipping and oblique to the displacement on the transverse fault in the Bourgeau thrust sheet. Thus, most, if not all of the displacement on the transverse fault occurred after displacement on the Bourgeau thrust had ended. Relationships with displacement on the overlying Sawback thrust fault are different.

The Sawback thrust offsets the transverse listric extension fault with a left-hand strike separation of about 300 m (Figs. 2b and 3b). The stratigraphic separation across the transverse listric extension fault dies out gradually southwestward at higher stratigraphic levels within the hanging wall of the Bourgeau thrust fault; but it increases conspicuously and abruptly northeastward across the Sawback thrust. It is only about 250 m where it offsets the SW-dipping Arctomys and Pika strata in the hanging wall of the Sawback thrust (Fig. 2b), but it is about 700 m where it offsets the NE-dipping Devonian strata in the footwall wall of the Sawback thrust, and about 1200 m where it offsets the SW-dipping upper Paleozoic strata in the footwall of the underlying Bourgeau thrust fault. This shows that displacement occurred on the Sawback thrust fault after displacement on the transverse extension fault had ceased; and also that some of the displacement on the transverse extension fault probably occurred after displacement on the Sawback thrust fault had begun. Considering the evidence that the formation of the transverse extension fault was due to the displacement on the Rundle thrust fault that produced the transverse hanging wall ramp anticline in the Rundle thrust sheet, these relationships between the transverse extension fault and the Sawback thrust fault demonstrate that some of the displacement on the Sawback thrust fault must have occurred after a substantial part of the displacement had occurred on the Rundle thrust fault.

Further insight on the relative timing of displacements on the Rundle, Sulphur Mountain, Bourgeau, and Sawback thrust faults can be gleaned from their mutual regional structural relationships (Figs. 1, 2, and 4C). The Sawback thrust fault and the structural panel in its hanging wall are remarkably straight and maintain a uniform strike of about 330° over the entire interval of about 60 km that is included within the map of Fig. 2(a). They are not significantly affected by the structures that have developed in the underlying thrust sheets, and therefore displacement on Sawback thrust fault is relatively young. In contrast, the Sulphur Mountain thrust sheet has been folded to conform, but to conform only partly, with the configuration of the strata in the underlying Rundle thrust sheet; therefore, it is older than the Rundle thrust fault, but a significant component of the displacement on it occurred after substantial displacement had occurred on the underlying Rundle thrust fault. The structural panel between the Bourgeau and Sawback thrust faults has not been folded to conform with the configuration of the underlying Sulphur Mountain thrust sheet; therefore, some of the displacement on the Bourgeau thrust must have occurred after the Sulphur Mountain thrust sheet had been folded in response to displacement on the underlying Rundle thrust sheet. Both the Sulphur Mountain thrust sheet and the structural panel between the Bourgeau and Sawback thrust faults have been folded in response to displacement along the transverse extension fault, but the overlying structural panel in the hanging wall of the Sawback thrust sheet has not; therefore much (or most?) of the displacement on the Sawback fault must have occurred after the development of the transverse extension fault, which occurred during displacement on the Rundle thrust fault.

5. Conclusions

Crosscutting relationships along the transverse fault, and patterns of overprinting of thrust-related folding of pre-existing thrust sheets demonstrate that, in this transect across the Rocky Mountain Front Ranges north of the Bow River valley near Banff, there was substantial overlap in the times of displacement on four main thrust faults. Displacement on the Sulphur Mountain thrust fault continued during a substantial part of the displacement on the Rundle thrust fault. Displacement on the Bourgeau thrust fault continued after the Sulphur Mountain sheet had been deformed by fault-bend folding in the underlying Rundle thrust sheet, and after the onset of displacement on the transverse extension fault that developed in the Sulphur Mountain thrust sheet because of fault-bend folding due to displacement on the underlying Rundle thrust fault. Displacement occurred on the Sawback thrust fault after the termination of displacement on the Bourgeau thrust fault, and continued after the termination of displacement on the transverse extension fault. There was significant overlap in the times of displacement on the highest (Sawback) and lowest (Rundle) thrust faults in this part of the imbricate thrust stack.

The presumption in the ‘piggyback’ kinematic model that displacement on one major thrust fault ends when displacement on a younger underlying thrust begins is incorrect. There is no contradiction between the ‘piggyback’ conceptual kinematic model and the critical Coulomb wedge mechanical model for the evolution of ‘thin-skinned’ foreland thrust and fold belts. The main faults did originate sequentially from the hinterland to the foreland, and from the top to the bottom of the evolving wedge; but the ensuing displacement occurred simultaneously on several major faults. The same kinematic relationships have been reported by Dixon and Liu (1992), on the basis of carefully monitoring the progressive development of folds and thrust faults in centrifuge analogue (plasticine and silicone putty) models of thrust and fold development.

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