PERGAMON

Journal of Structural Geology 24 (2002) 689–707

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jstrugeo

Role of transverse faulting in along-strike termination of Limestone Mountain Culmination, Rocky Mountain thrust-and-fold belt, Alberta, Canada

Normand J. Bégin[a], Deborah A. Spratt[b,*]

[a]Talisman Energy Inc., Suite 3400, 888-3rd Street SW, Calgary, AB, Canada T2P 5C5
[b]Department of Geology and Geophysics, University of Calgary, Calgary AB, Canada T2N 1N4

Received 2 August 2000; revised 3 January 2001; accepted 19 May 2001

Abstract

Surface geology, well data, and ~100 km of 2D seismic reflection data delineate the 3D geometry of Limestone Mountain Culmination (LMC). The lower lithotectonic package of the culmination is a SE-plunging antiformal stack of four thrust sheets of Paleozoic platform carbonates that is detached from and folds the upper package of NE-verging thrust sheets of Mesozoic siliciclastics, tilting these imbricates toward the foreland. LMC abruptly loses 1.5 km of structural relief along strike in less than 2 km across a NE-striking blind transverse fault that changes from a NW-dipping lateral ramp in the southwest to a steep tear fault in the northeast. It soles into the Brazeau Thrust and merges upward into the roof thrust of LMC. An extension fault that soles into the steepest portion of the transverse fault cuts moderately SW-dipping Mesozoic rocks that drape over the tear fault, thereby juxtaposing Mesozoic siliciclastics against Paleozoic carbonates of the Brazeau sheet. Synchronous thrusting is suggested by preferential imbrication over the forelimb of the antiformal stack, by offset of the roof thrust, and by folded and unfolded thrust segments in the stack. A Precambrian basement structure beneath this transverse fault may have acted as a buttress during the Laramide Orogeny. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Thrust faults; Western Canada; Rocky Mountains; Structural traps; Seismic profiles; Duplex

1. Introduction

The structural architecture in the thin-skinned thrust-and-fold belt of the southern Canadian Rocky Mountains has long been defined by the pioneering work of Douglas (1950, 1951), Bally et al. (1966), Dahlstrom (1970), Price (1981, 1986), Price and Fermor (1985), and Norris (1993a,b). Common structural elements in the southern Alberta Foothills include (Fig. 1): west-dipping thrusts, folded thrusts, concentric folds, transfer zones between individual thrusts, broad synclines in the footwalls of major faults, and a triangle zone at the leading edge of the thrust-and-fold belt. In addition to the Mesozoic–Cenozoic foreland basin rocks exposed at the surface throughout the Foothills Belt, Paleozoic strata of the underlying continental platform outcrop in the cores of prominent structural culminations (e.g. the Limestone Mountain, Marble Mountain, Panther River, and Moose Mountain areas; Fig. 1). Several of these culminations have been large hydrocarbon producers from Devonian- and Mississippian-age carbonates in subsurface structures. High-quality petroleum industry seismic data and detailed bedrock mapping over the last decade have provided key new insights into the geometrical evolution of Foothills structures in the foreland basin (Sanderson and Spratt, 1992; Skuce et al., 1992; Lawton et al., 1994, 1996; MacKay et al., 1994; McMechan, 1995; Spratt et al., 1995; Bégin et al., 1996; Lebel et al., 1996; Soule and Spratt, 1996; Stockmal et al., 1996; Fermor, 1999). Moreover, such work has contributed to a better understanding of along-strike variations and closure of structures common to the Foothills Belt.

Several of the structural culminations are located along strike of and adjacent to broad synclines cored by relatively young rocks of Upper Cretaceous and Tertiary age (Fig. 1). For example, the Limestone Mountain Culmination terminates southward against the Williams Creek Syncline, and the Moose Mountain Culmination abuts against the Burnt Timber and Dyson Creek Synclines, respectively, to the north and south (Fig. 1); both produce folded thrusts over and around these culminations. Although the map patterns of these structures are very similar, Fermor (1999) has shown that their subsurface geometries are quite different. Most of the thrusts that he studied cut up-section and lose

---

* Corresponding author. Tel.: +1-403-220-6446; fax: +1-403-284-0074.
E-mail address: spratt@geo.ucalgary.ca (D.A. Spratt).

0191-8141/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0191-8141(01)00119-5

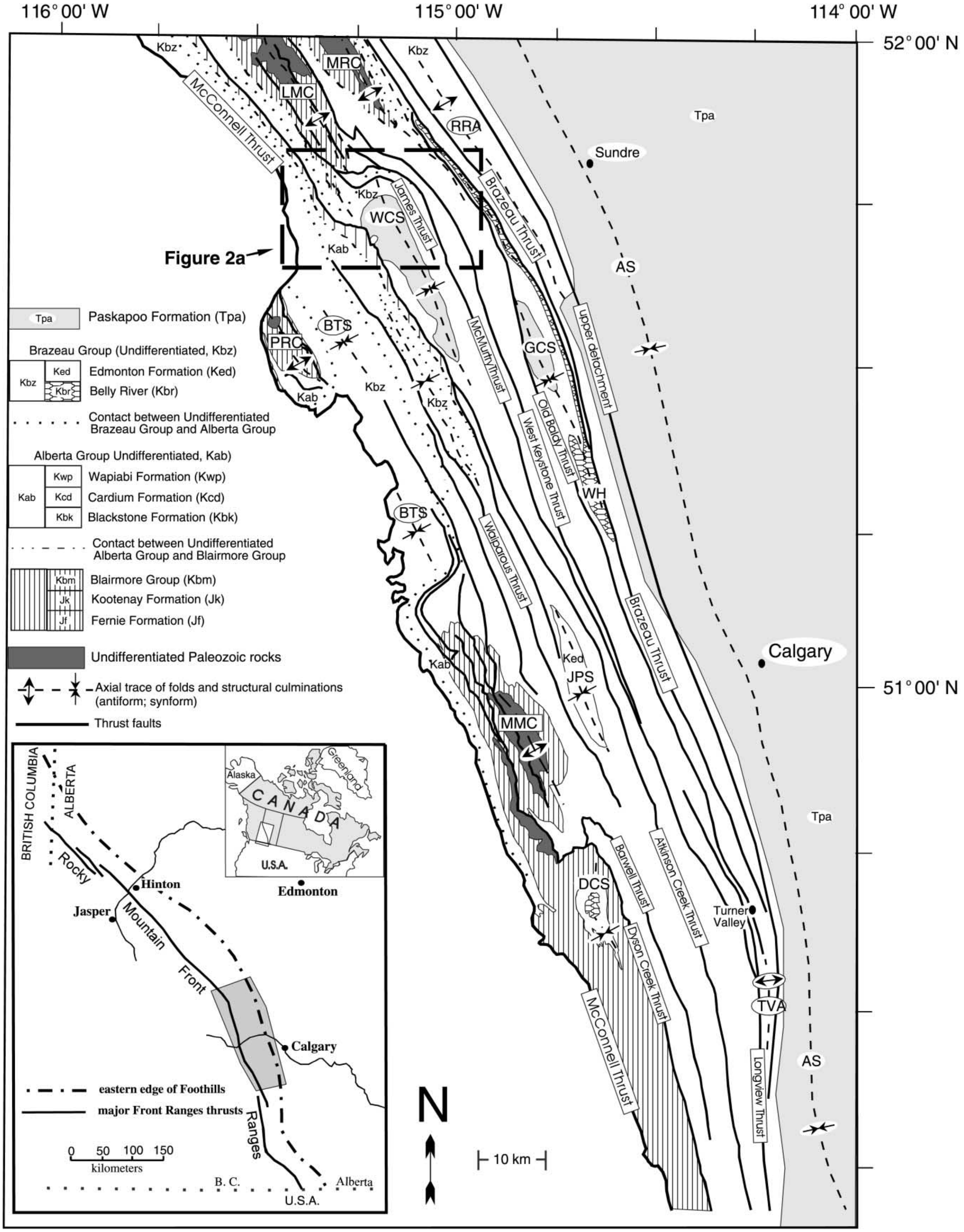

Fig. 1. Regional geological map of the southern Alberta Foothills (modified from Ollerenshaw, 1976) outlining the major structural elements. Structural culminations comprising Paleozoic rocks in front of the McConnell Thrust are labelled as the Limestone Mountain (LMC), Marble Mountain (MRC), Panther River (PRC) and Moose Mountain (MMC) culminations. Open synclines are marked as the Williams Creek (WCS), Grease Creek (GCS), Burnt Timber (BTS), Jumping Pound (JPS) and Dyson Creek (DCS) synclines. Other abbreviations are Raven River Anticline (RRA), Turner Valley Anticline (TVA), Wildcat Hills (WH) and Alberta Syncline (AS). Dashed box shows the outline of Fig. 2a.

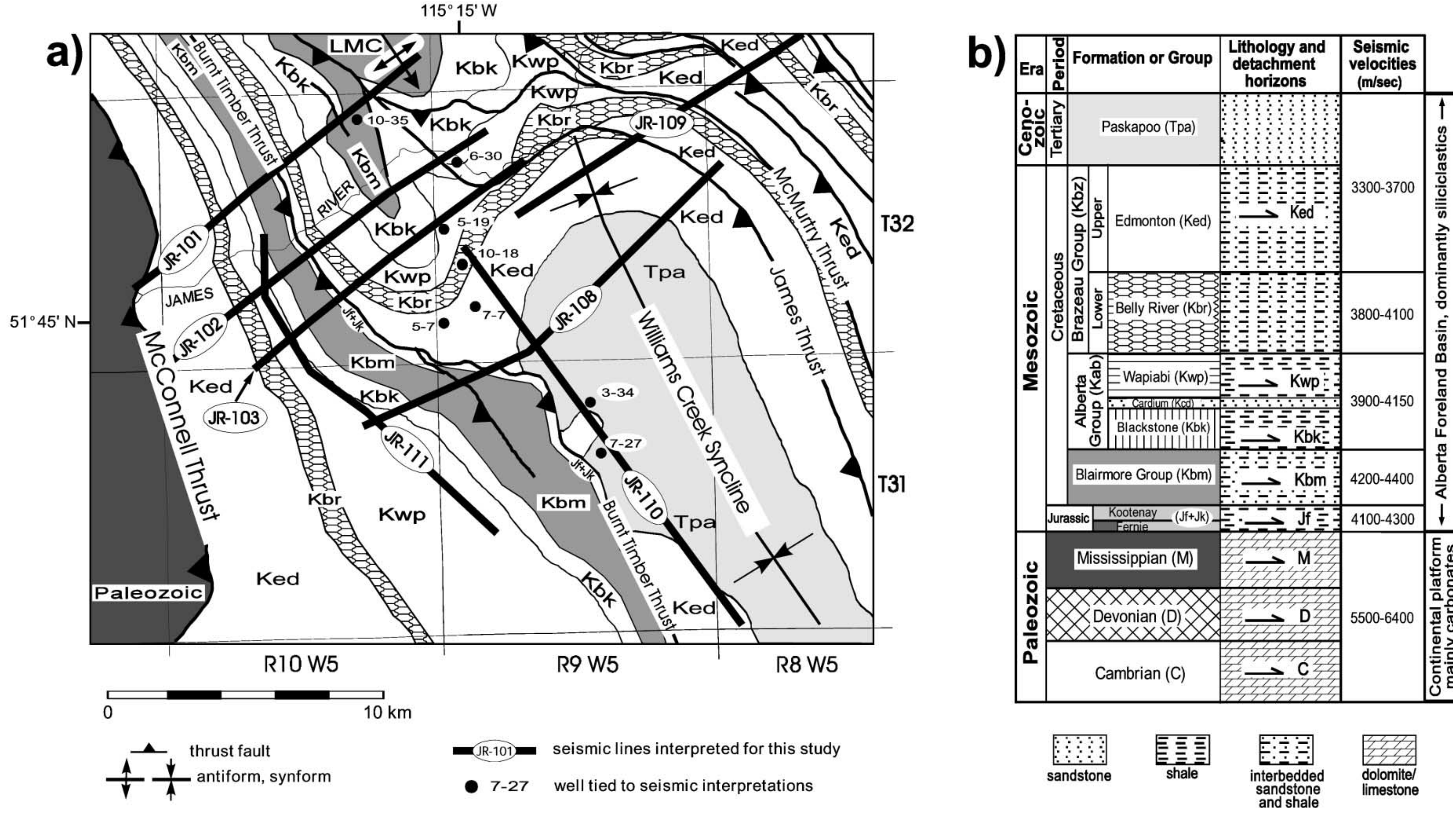

Fig. 2. (a) Geological map of the Alberta Foothills in the vicinity of James River (modified from Ollerenshaw, 1976). Thick straight lines, labelled JR-101 to JR-111, show positions of 2D seismic lines interpreted in this study. Bottom-hole locations of wells tied to the seismic sections are shown as solid dots. (b) Stratigraphic column and legend for (a). Positions of the main detachment horizons in the Foothills Belt, as identified in the map and seismic interpretations, are marked with arrows.

displacement gradually along strike, but the southern termination of the Limestone Mountain Culmination is abrupt and anomalous.

In this paper we present a detailed investigation of the transition from the Limestone Mountain Culmination to the Williams Creek Syncline (Figs. 1 and 2) based on interpretation of modern 2D seismic dip and strike lines provided by industry sponsors of the Fold–Fault Research Project at the University of Calgary. These data have been tied to wells and to new surface geological mapping to constrain the along-strike extent and geometry of individual thrust sheets in the vicinity of James River (Fig. 2a) where, in map view, the Limestone Mountain Culmination terminates abruptly against the Williams Creek Syncline (Fig. 1). Douglas (1950, 1951), Price (1967), Dahlstrom (1970), Moffat and Spang (1984), and Fermor (1999) have previously documented transverse faults in the Alberta Foothills; the majority are minor faults in the regional sense, and the largest ones are found primarily in the subsurface. Dahlstrom (1970) and Fermor (1999), after earlier work by F.R. Frey (unpublished), have documented and discussed the configuration of the lateral termination at the southern end of the Limestone Mountain Culmination, which they informally refer to as the Marble Mountain 'swingback' (of the Brazeau Thrust sheet). Fermor (1999) interpreted the transverse termination of the structure as a south-side-down normal fault, possibly emerging at the current erosion level, based on these earlier works and examination of a proprietary sparse 3D seismic data set in the vicinity of James River. However, their models do not fully address the detailed 3D geometry of the transverse structure or how it developed and how it corresponds to the surface geology. The model we present in this paper suggests that the normal fault discussed by Fermor (1999) was not the primary mechanism to explain the abrupt termination of the Limestone Mountain Culmination. By integrating the surface and subsurface data, we propose that the Limestone Mountain Culmination is a duplex, which terminates to the south at a blind transverse fault and which detaches from the overlying Upper Cretaceous strata that are passively folded over and around it. We interpret the normal fault of Fermor (1999) to be a minor gravitational (extensional) feature related to mechanical instability of the hanging wall rocks above the steepest segment of the transverse fault. We also suggest a mechanism for the origin and localization of this transverse feature during the Laramide orogeny.

2. Geological setting

The study area is located in the thrust-and-fold belt of the southern Alberta Foothills in Canada (Fig. 1). It is east of the McConnell Thrust and centered around James River in Ranges 8W5 to 10W5 and Townships 31 to 32 (Fig. 2a). The stratigraphic column (Fig. 2b) shows the dominant lithologies of Cambrian through Tertiary strata of Alberta, their seismic velocities, formation and group names and abbreviations used in the maps and sections. Here we describe the stratigraphy and depositional setting briefly, as the primary concerns are which packages of rock behave as coherent beams and which stratigraphic levels serve as detachment horizons. More complete descriptions of the stratigraphy can be found in Bally et al. (1966) and Price (1981). All detachment levels identified in this study are marked by arrows in Fig. 2b.

Two major lithotectonic packages are recognized in the area. The lower package consists of a westward-thickening supracrustal wedge of Paleozoic continental platform carbonates deposited directly on top of the gently southwest-dipping Hudsonian crystalline basement surface of the North American craton and telescoped by thrusting during the Laramide orogeny (Bally et al., 1966; Dahlstrom, 1970; Price, 1981). These carbonates are well-exposed in the Front Ranges west of the McConnell Thrust, but are only exposed in the Foothills Belt in the cores of structural culminations such as the Limestone Mountain and Marble Mountain Culminations (Fig. 1). The upper package consists of Jurassic to Tertiary siliciclastics deposited during the Columbian and Laramide orogenies. Large amounts of sediment were shed eastward from the active orogen and deposited in a foreland basin that was subsiding due to loading of the continental crust. Sedimentation occurred first in an epeiric sea and later in a continental–lacustrine setting (Price, 1981). These rocks outcrop over most of the Foothills Belt and occur in west-dipping thrust sheets that commonly sole into a detachment in shales of the Jurassic Fernie Formation.

The foreland edge of the Foothills is within the triangle zone where a wedge of imbricates has been driven beneath the Alberta Syncline (Bégin et al., 1996; Jones, 1996; Lawton et al., 1996; MacKay, 1996; Soule and Spratt, 1996). A major east-dipping thrust, the upper detachment of the triangle zone (Figs. 1 and 2) along the west flank of the Alberta Syncline, represents the uppermost boundary between east- and west-verging structures at the present-day erosion surface. The lower detachment of the triangle zone is within Upper Cretaceous shales (Kbr, Fig. 2b) and is connected to the basal thrust of the Foothills Belt by a series of ramps and flats. Major flats occur in Cambrian shales, which have been decoupled and transported northeastward over the crystalline basement, and in Jurassic shales above the underlying platform carbonates (Bally et al., 1966; Dahlstrom, 1970; Price, 1981). Other detachment horizons in the Foothills Belt occur within Paleozoic shales and Mesozoic shales and coals (Fig. 2b; Spratt and Lawton, 1996); they link frontal and lateral ramps in competent Paleozoic limestones and dolostones and in Mesozoic sandstones and conglomerates.

Fig. 3 shows the entire study area with the digital topography shaded from the northeast to emphasize the northeast–southwest-trending ridges in the thrust belt.

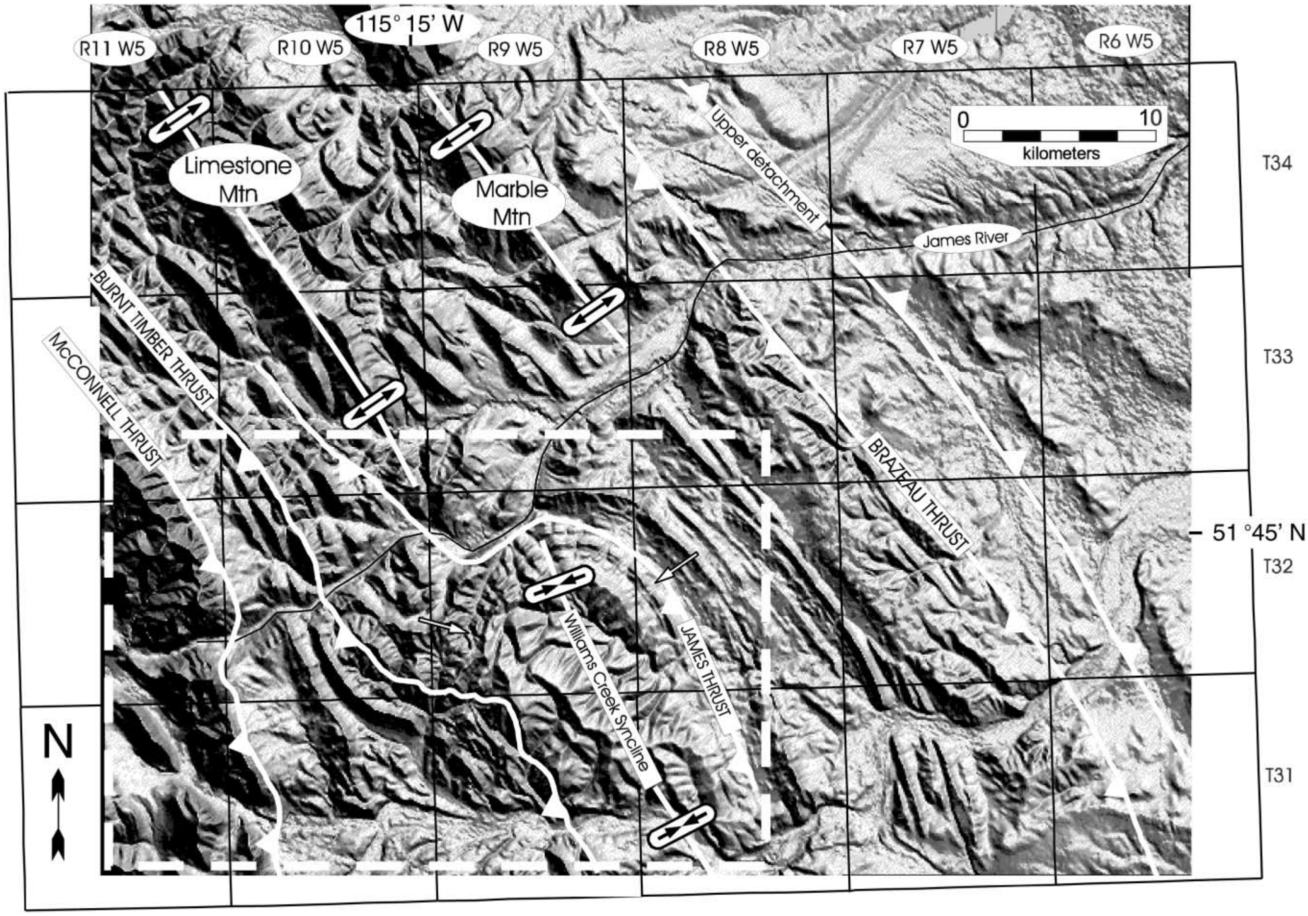

Fig. 3. Digital shaded topography of the study area. The main regional thrusts interpreted in the seismic profiles are traced, as are the axes of the Limestone Mountain culmination, Marble Mountain culmination and Williams Creek Syncline. The two small white arrows along the northern end of the WCS delineate a drainage pattern radiating outward. White dashed area is the extent of Fig. 2a.

This image highlights several major structural features pertinent to the current study. The Limestone Mountain and Marble Mountain Culminations appear as rougher and higher topography than the Foothills ridges to the south. The Limestone Mountain Culmination loses elevation as it reaches the James River, north of the Williams Creek Syncline. The Williams Creek Syncline is very well outlined by curved, thin ridges near its northern closure where field data indicate a southerly plunge. There is also a radiating drainage pattern in the northern hinge zone of the syncline, indicated by the two arrows on Fig. 3. These gullies may represent a series of extensional fractures related to the development of the Williams Creek Syncline, as they are parallel to decimeter-scale extension fractures seen in outcrops. The James Thrust wraps around the Williams Creek Syncline and cuts up-section from north to south, as documented on the geological maps of Ollerenshaw (1965, 1968, 1969, 1976) (Fig. 2a). The western limb of the Williams Creek Syncline is truncated by the Burnt Timber Thrust. Finally, the McConnell Thrust sheet outlines the eastern edge of the Front Ranges, where Paleozoic carbonates are thrusted to the surface, producing some of the highest relief ridges in the area (Fig. 3).

3. Seismic database

To investigate the subsurface structural geometry and transition between the Limestone Mountain Culmination and Williams Creek Syncline, we interpreted seven 2D seismic lines (pre-stack, time-migrated) with a total line-length of approximately 100 km. The data set consists of five dip lines and two strike lines with several intersections that provide critical ties (Fig. 2a). Interpreted sections are shown in time for easy comparison to the seismic data and because examination of pull-up gradients provides key constraints on the location and geometry of overlying ramps. Surface geology and well data (converted to time) were projected into the seismic profiles parallel to the trends of the structures. All sections are displayed at the same scale to allow comparison.

4. Seismic interpretation

4.1. Dip lines

The five lines that are at a high angle to the regional

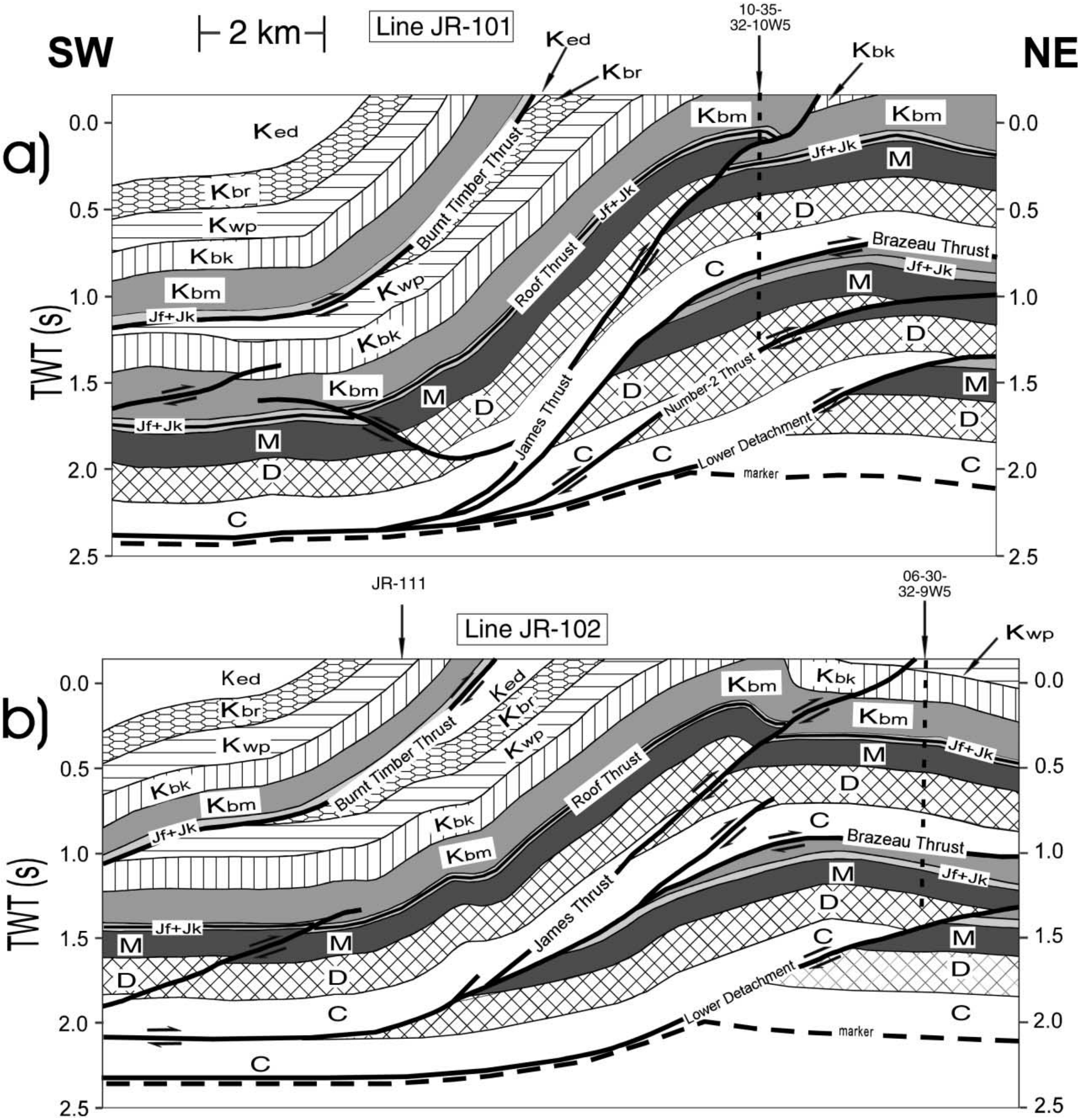

Fig. 4. Interpreted cross-sections from seismic profiles of the northernmost dip lines in the southern part of the Limestone Mountain Culmination. (a) Section JR-101 tied with well 10-35-32-10W5. (b) Section JR-102 tied with well 6-30-32-9W5. Abbreviations: Cambrian (C), Devonian (D), Mississippian (M), Jurassic Fernie and Kootenay (Jf + Jk), Cretaceous Blairmore (Kbm), Blackstone (Kbk), Wapiabi (Kwp), Belly River (Kbr), and Edmonton (Ked). The dashed marker in the regional Cambrian, at approximately 2.1 s TWT, represents the detachment level in the Cambrian.

structural trend are described in order from north to south (JR-101, JR-102, JR-103/JR-109 and JR-108; Figs. 2 and 4–6). Together, they represent an array of cross-sections from the southern end of the Limestone Mountain Culmination to the northern termination of the Williams Creek Syncline. The major faults interpreted on these lines, above the Lower Detachment, are the Brazeau, James and Burnt Timber Thrusts (Fig. 2a). Key relationships between all of these faults are illustrated in the longest line (Fig. 5), which shows that the overall geometry of the Limestone Mountain Culmination is a duplex, floored by the 'Lower Detachment' and capped by the 'Roof Thrust'. The Lower Detachment sheet is locally known as the Burnt Timber–Limestone Structure and its basic geometrical features and regional extent are illustrated and discussed in Fermor (1999). So that the reader will not confuse it with the Burnt Timber Thrust sheet or the Limestone Mountain Culmination, we have chosen to label the basal thrust and the previously unrecognized roof thrust using the simpler names Lower Detachment and Roof Thrust. The Roof

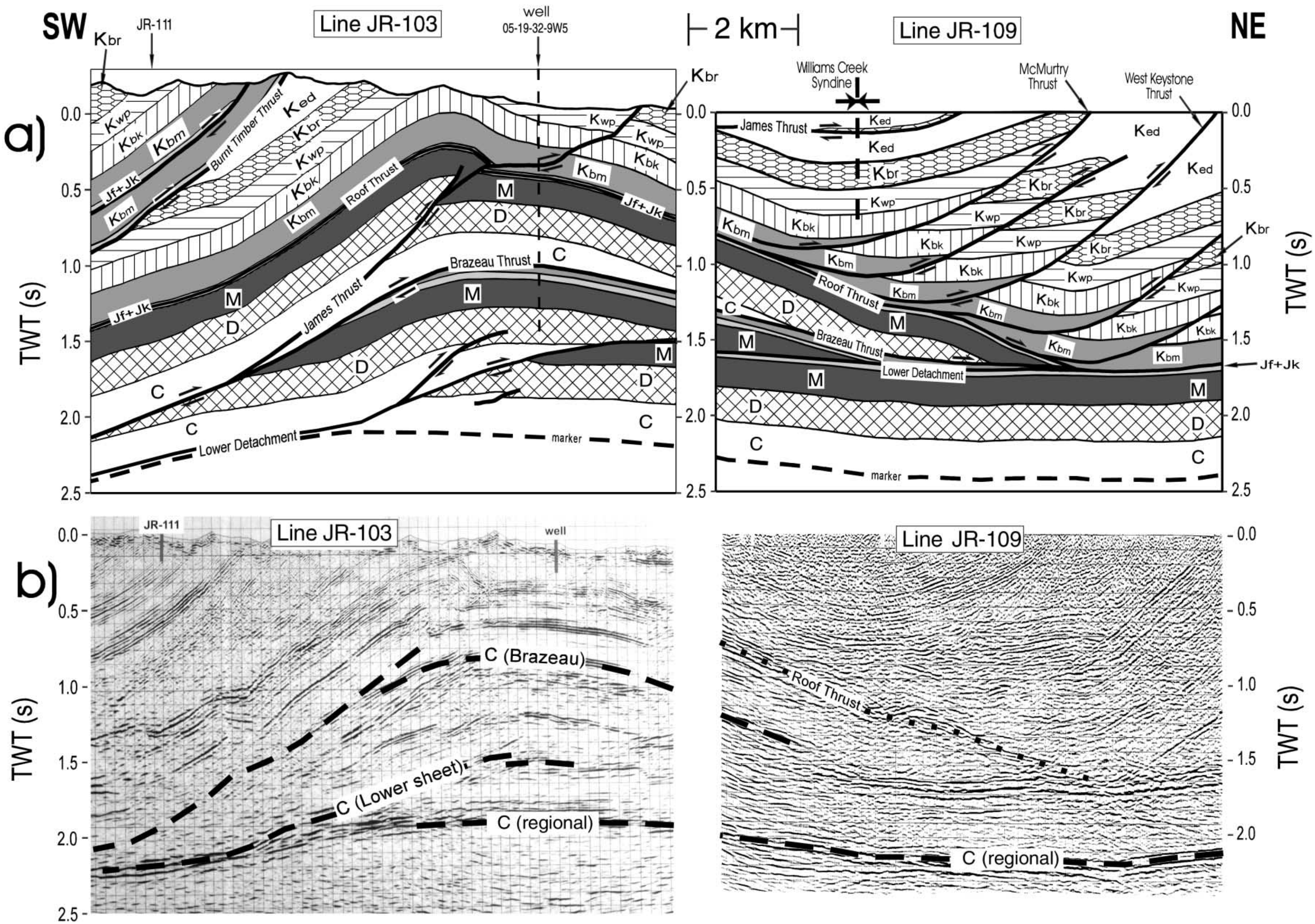

Fig. 5. (a) Combined interpreted cross-sections from seismic profiles of dip lines JR-103 (tied with well 5-19-32-9W5) and JR-109. JR-109 is projected 1.5 km into the line of section. (b) Pre-stack, time-migrated seismic profiles for lines JR-103 and JR-109. Positions of the Roof Thrust and top Cambrian seismic markers are traced with dashed lines. Abbreviations: Cambrian (C), Devonian (D), Mississippian (M), Jurassic Fernie and Kootenay (Jf + Jk), Cretaceous Blairmore (Kbm), Blackstone (Kbk), Wapiabi (Kwp), Belly River (Kbr), and Edmonton (Ked).

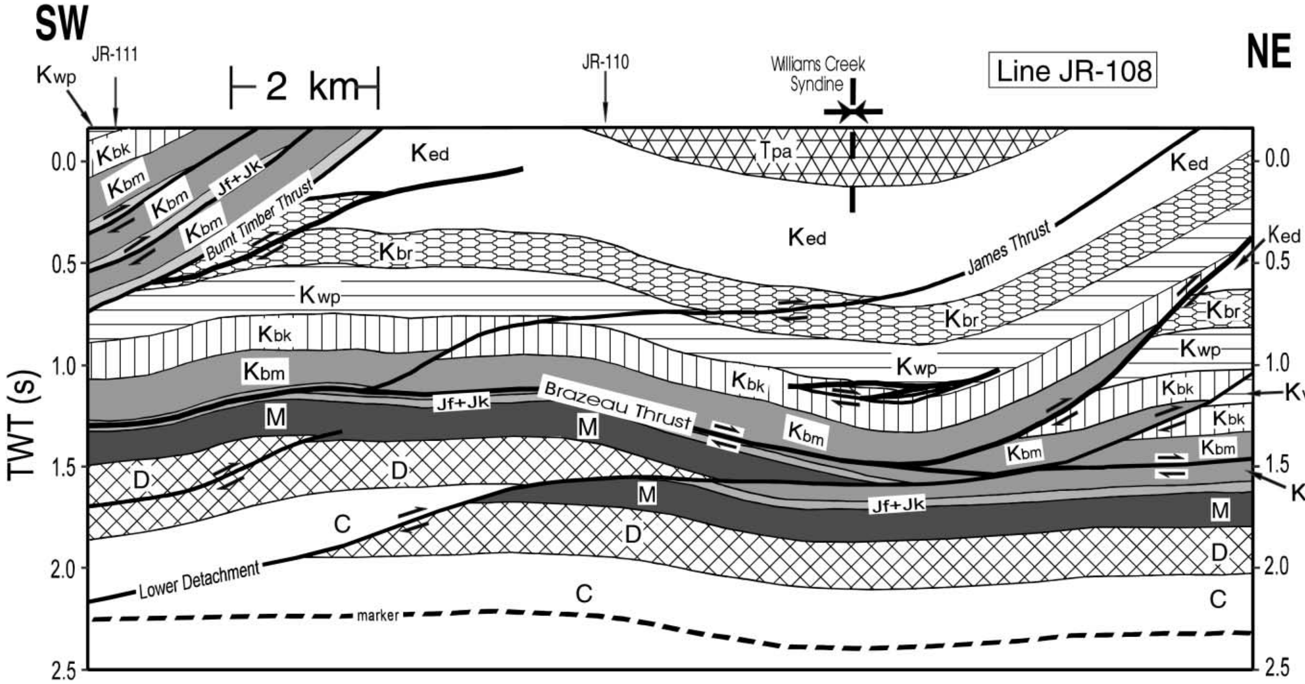

Fig. 6. Interpreted cross-section from seismic profile of the southernmost dip line, JR-108, showing ties with lines JR-111 and JR-110. In this profile, the Roof Thrust is interpreted to have merged with the Brazeau Thrust. Abbreviations: Cambrian (C), Devonian (D), Mississippian (M), Jurassic Fernie and Kootenay (Jf + Jk), Cretaceous Blairmore (Kbm), Blackstone (Kbk), Wapiabi (Kwp), Belly River (Kbr), and Edmonton (Ked).

Thrust is a bedding-parallel flat in Jurassic shales, and Cretaceous strata above it are preferentially imbricated above the leading edge of the duplex (Fig. 5). The Brazeau Thrust is one of the faults within the duplex, and the Burnt Timber Thrust sheet is a separate structure carried in its hanging wall. Stacking of high-velocity Paleozoic carbonate units (5000–6000 m/s) results in time pull-up and makes it possible to identify the leading, trailing and lateral edges of the duplex in seismic sections. The geometry of the duplex and overlying structures change significantly along strike, as outlined below.

4.1.1. Line JR-101

JR-101 is the northernmost dip line, where the height of the duplex is largest (Figs. 2a and 4a). The interpretation shows that Cambrian, Devonian and Mississippian carbonates have been repeated by at least four thrusts over the autochthonous platform. The height of the duplex is accentuated by 300–400 ms of velocity pull-up of the regional Cambrian marker caused by the extra sheets of high-velocity carbonates in the northeast part of the section. Major sheets have been carried by the east-verging thrusts, namely the James, Brazeau, Number-2 and Lower Detachment. Stacking of these thrust sheets has contributed to the build-up of the antiformal duplex culmination at Limestone Mountain. The James, Brazeau and Number-2 thrusts merge with the Lower Detachment at the southwestern end of the interpreted line. The basal detachment rides in rheologically-weak Cambrian rocks. The Brazeau Thrust is inferred to have been an early basal detachment of the deformed belt, with the Number-2 Thrust and Lower Detachment forming later as a result of structural collapse of the footwall of the Brazeau sheet. The James Thrust appears as a frontal ramp in the backlimb of the antiformal culmination, cutting up-section from the Cambrian to the Lower Cretaceous Blairmore units with a ramp angle of about 15° to bedding. The thrust dips nearly 60° and has either been rotated by antiformal stacking in the Limestone Mountain Culmination or formed in this orientation as a result of faulting of the backlimb of the culmination synchronously with motion on the underlying Number-2 Thrust and Lower Detachment. We favor the early origin based on its 3D geometry, which is discussed later in the paper.

Mesozoic units in the hanging wall of the Burnt Timber Thrust represent the northern extension of the eastern limb of the Burnt Timber Syncline (Figs. 1 and 4). Interpretation of the Cretaceous seismic markers reveals the presence of a conspicuous kink, separating sub-horizontal and steeply-dipping beds above the Burnt Timber Thrust (Fig. 4a). This scale of kink folding is not typical of Alberta synclines and is probably related to steepening of the beds during the very localized pile-up of underlying thrust sheets. Another uncommon feature is the backthrust that offsets Paleozoic markers in the footwall of the Burnt Timber Thrust (note the approximately 100 ms offset). This backthrust merges with the James Thrust at ~2.0 s and is interpreted to have developed in response to steepening of the James Thrust during stacking of the underlying thrust sheets. Therefore, motion on this backthrust could be coeval with the formation of any of the deeper thrust faults.

4.1.2. Line JR-102

Line JR-102 (Fig. 4b) is located 4 km southeast of line JR-101 (Fig. 2a). The principal structural difference between the two lines is the absence of the Number-2 thrust sheet seen in Line JR-102. This has led to a decrease in amplitude of the Limestone Mountain Culmination, with about 250 ms less structural relief. The loss of one major thrust sheet has also contributed to reducing the dip of the structures above the Lower Detachment. The James Thrust now dips about 45° (Fig. 4b), compared with nearly 60° on line JR-101 (Fig. 4a). The along-strike decrease in elevation of the highest structures gives an indication of the overall southeast plunge of the Limestone Mountain Culmination. The crest of the Limestone Mountain Culmination is now in the hanging wall of the James Thrust (Fig. 4b), as opposed to the footwall as seen further north in line JR-101 (Fig. 4a).

4.1.3. Lines JR-103 and JR-109

Combined, lines JR-103 and JR-109 (Fig. 5) represent a transect of about 25 km across the southern closure of the Limestone Mountain Culmination (Fig. 2a) that is located 1.7 km southeast of JR-102 (Fig. 4b). Although JR-109 is offset 1.5 km along strike from JR-103, the two lines can be spliced together with only minimal mismatch of the deeper reflectors. Two distinct structural packages can be delineated (Fig. 5a). The lower structural package is the southern extent of the Limestone Mountain Culmination, with Paleozoic carbonates carried by the Brazeau Thrust and Lower Detachment. In line JR-109, there is a prominent set of northeast-dipping seismic markers that is correlative with those produced by Cambrian to Mississippian carbonates in the hanging walls of the Brazeau Thrust and Lower Detachment in line JR-103 (Fig. 5b). The structurally-higher package is the northern extension of the Williams Creek Syncline and consists of an imbricate stack of Cretaceous units folded over the Limestone Mountain Culmination such that the west flank of the syncline is tilted toward the foreland in line JR-109 (Fig. 5). Note that the imbricates of Cretaceous strata are preferentially developed on the eastern flank of the culmination but are not present on the western flank (Fig. 4). The stacking and foreland-directed displacement of large carbonate thrust sheets in the Limestone Mountain Culmination contributed to further displacement of the overlying stack of Cretaceous units. Faults such as the McMurtry and West Keystone thrusts branch from a common detachment that also serves as the roof thrust of the stack of carbonate thrust sheets and is labeled Roof Thrust (Fig. 5a). The Roof Thrust is interpreted as a bedding-parallel flat in Jurassic shales and must continue west of line JR-109 to accommodate the shortening exhibited in its hanging wall, so it is also identified on lines JR-101 and JR-102 (Fig. 4). The combined seismic interpretation of lines JR-103 and JR-109 (Fig. 5a), therefore, provides some critical structural links and timing relationships between the antiformal duplex of Paleozoic carbonates in the Limestone Mountain Culmination and the overlying imbricates of Mesozoic clastic rocks.

The interpreted Paleozoic markers in JR-103 all occur at greater times, and hence depths, than those in dip lines further north (JR-101 and JR-102, Fig. 4). This is a consequence of the southerly plunge of the Limestone Mountain Culmination as it loses subsurface horses and exposes progressively younger and lower velocity rocks at the surface, resulting in push-down of the Paleozoic markers beneath the slower rocks. There is also significant time structure on the regional Paleozoic markers across strike in lines JR-109 and JR-103. The top of Cambrian is at least 350 ms higher in the core of the Limestone Mountain Culmination (line JR-103, Fig. 5) than it is at the northeast end of line JR-109. This time structure is due to stacking of high-velocity carbonate units (5000–6000 m/s) above the Lower Detachment. This represents 3–4 km of thickening, assuming the above seismic velocities. East of the leading edge of the Limestone Mountain Culmination in line JR-109, the autochthonous Paleozoic markers are seismically restored to a near-regional level, indicative of no velocity pull-up.

Preferential development of the imbricated stack of Mesozoic rocks has occurred in the leading edge of the Limestone Mountain Culmination (Fig. 5). According to Boyer's (1992) model, this positioning of imbricates implies that they formed synchronous with motion on thrusts of the underlying duplex. The James Thrust also supports the synchronous motion model. Part of the James Thrust is folded along with bedding in the vicinity of the 5-19-32-9W5 well (Fig. 5a), indicating that it formed early enough to be folded; but the fault slightly offsets the Roof Thrust, implying later motion. The position of the backthrust in the James sheet (Fig. 4a), at the base of the steep backlimb of the duplex, also might suggest synchronous faulting as the height of the culmination increased.

The geometry of the hanging wall of the Burnt Timber Thrust sheet is not well-constrained by the seismic data due to migration artifacts at the edges of the sections. We do see Blairmore strata repeated at the surface in the vicinity of lines JR-103 and 108 (shown schematically in Figs. 5 and 6), but not further north (Fig. 4), indicating that localized imbrication has occurred. Construction of much longer cross-sections would be necessary to constrain the true geometry of these Blairmore imbricates, which may be similar to that seen in the hanging wall of the Roof Thrust in JR-109 (Fig. 5).

4.1.4. Line JR-108

The Limestone Mountain Culmination is not evident in the southernmost line, JR-108 (Fig. 6), which extends from the hanging wall of the Burnt Timber Thrust to the eastern

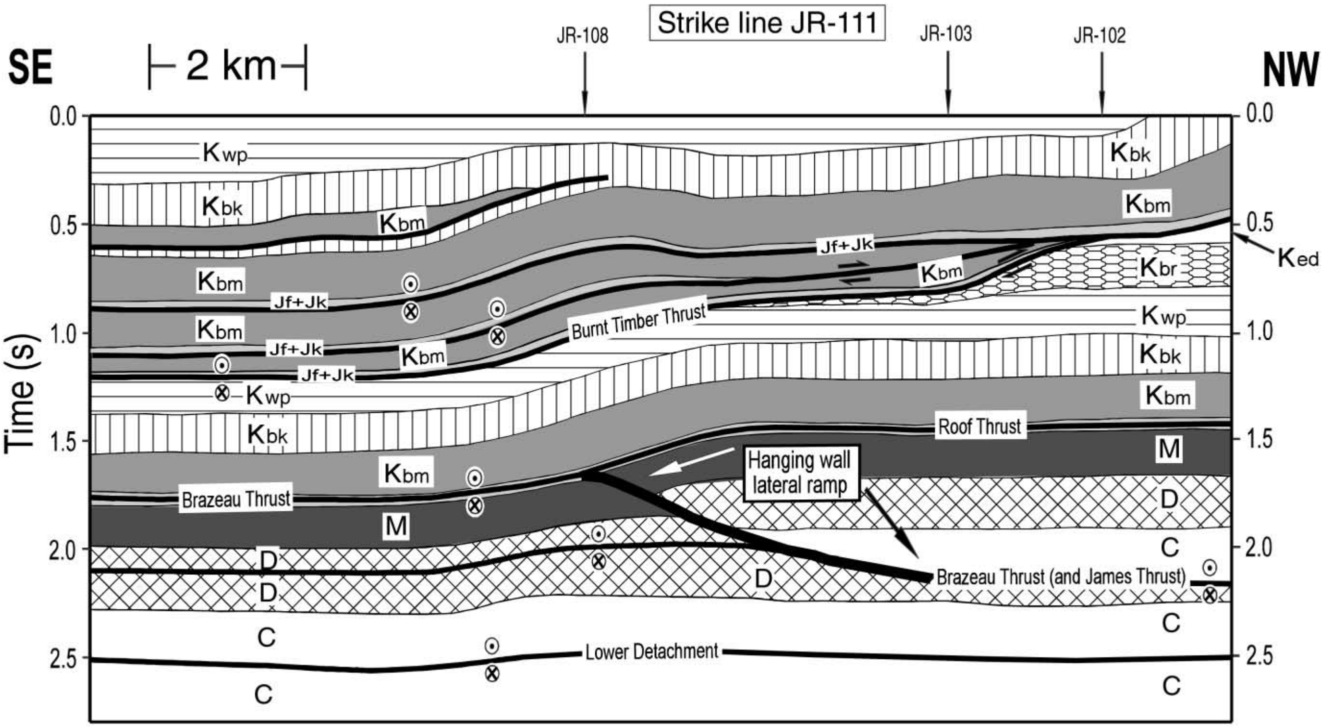

Fig. 7. Interpreted cross-section from seismic profile of strike line JR-111, showing ties with dip lines JR-102, JR-103 and JR-108. The Roof Thrust of the Brazeau sheet is shown as a bedding-parallel fault in the Fernie shales, merging with the upper segment of the lateral ramp in the Brazeau Thrust. Abbreviations: Cambrian (C), Devonian (D), Mississippian (M), Jurassic Fernie and Kootenay (Jf + Jk), Cretaceous Blairmore (Kbm), Blackstone (Kbk), Wapiabi (Kwp), Belly River (Kbr), and Edmonton (Ked).

flank of the Williams Creek Syncline (Fig. 2a). Broadly-folded Cretaceous and Tertiary rocks of the syncline dominate the interpreted profile. The base of the Williams Creek Syncline is defined as the Brazeau Thrust, which rides as a bedding-parallel flat in the Blairmore units in line JR-108. Here, no Paleozoic rocks are carried by the Brazeau Thrust, and the Roof Thrust is interpreted to have merged with the Brazeau Thrust. Because of this change in structural level of the Brazeau Thrust between profiles JR-103 (Fig. 5) and JR-108 (Fig. 6), the Limestone Mountain Culmination completely disappears along strike over a distance of less than 4 km. The time pull-up anomaly on the autochthonous Cambrian marker has also been considerably reduced, with only one fault repeat of Paleozoic units on the Lower Detachment (Fig. 6). This lowest sheet extends more than 10 km further south as seen in Figs. 7 and 8.

In JR-108 the James Thrust has the same 15° ramp cutoff angle seen in the other dip lines, but exhibits a shallower dip in this section (Fig. 6). The bedding and fault planes are only gently warped in the core of the Williams Creek Syncline. This further supports our interpretation that the James Thrust formed early, when the strata were sub-horizontal, and has been progressively folded as the culmination grew in height and lateral extent. The thrust cuts up-section through the Cretaceous units before dying out in a bedding-parallel flat within the Upper Cretaceous Edmonton Group both in cross-section (Fig. 6) and in map view (Fig. 2a). Seismic data parallel to strike also support the presence of a lateral ramp in the James Thrust, as it cuts up-section from north to south (Figs. 7 and 8).

4.2. Strike lines

Two strike lines, JR-110 and JR-111 (Figs. 2a, 7 and 8), are most crucial in establishing the mechanism responsible for the along-strike attenuation and termination of the Limestone Mountain Culmination against the Williams Creek Syncline. In interpreting these two strike lines, one must keep in mind that they were shot over moderately-dipping rocks. This leads to the possibility of out-of-plane reflectors when the seismic lines are processed. With a suspected major transverse fault, there also may be several secondary structures because of the associated out-of-plane strains (Apotria, 1995; Dixon and Spratt, 1999). However, given the observations made in the five dip lines, along with the surface geology and well data, the interpreted strike profiles are relatively well constrained.

4.2.1. Line JR-111

The western strike line, JR-111 (Fig. 7), is located along the eastern limb of the Burnt Timber Syncline and ties with three dip lines (JR-102, JR-103 and JR-108, Fig. 2a). Here the James Thrust has merged with the Brazeau Thrust, as constrained by dip lines JR-102 and JR-103 (Figs. 4 and 5). At the northwest end of JR-111, there is a complete section

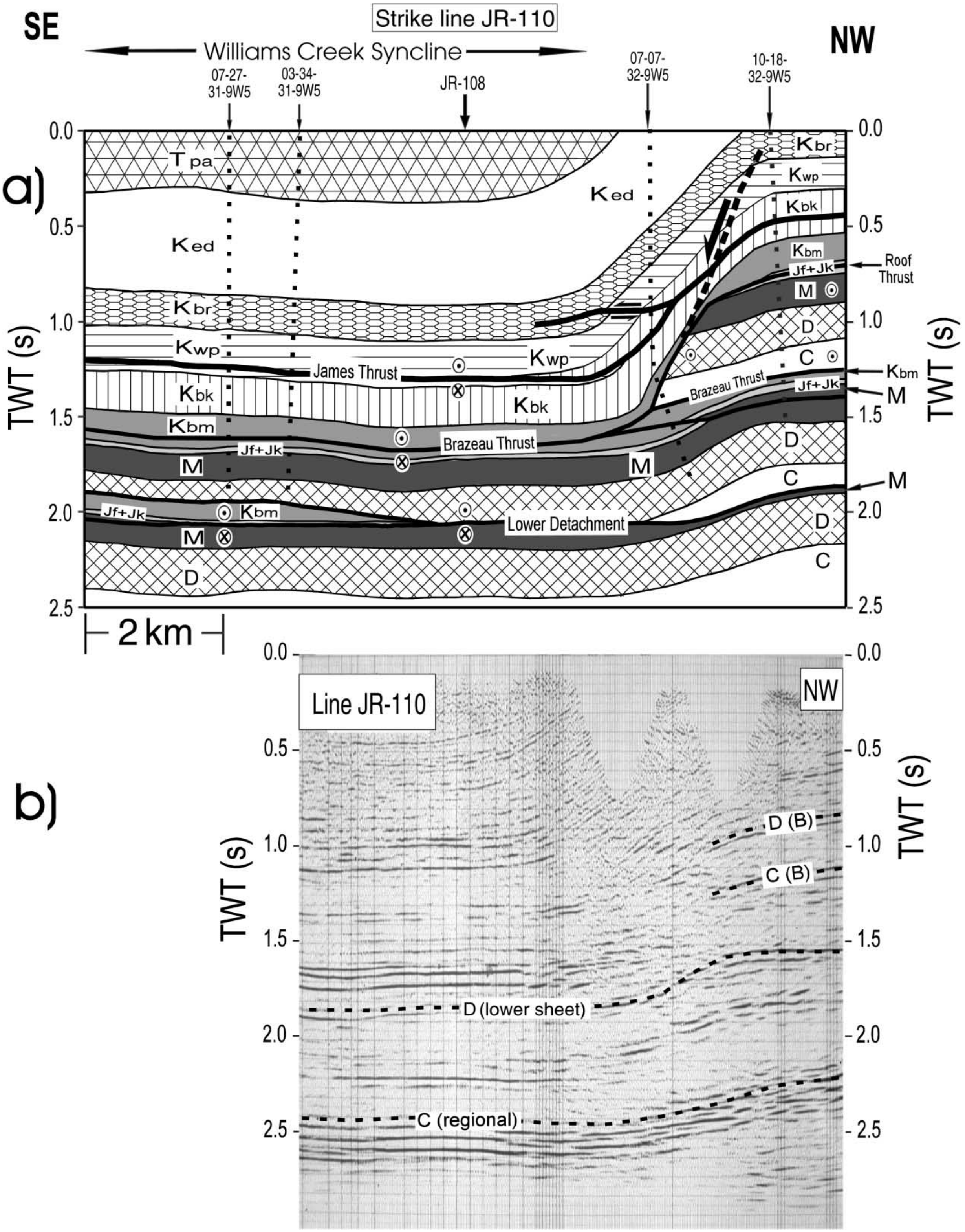

Fig. 8. (a) Interpreted cross-section from seismic profile of strike line JR-110. Projected traces of wells 7-27-31-9W5, 3-34-31-9W5, 7-7-32-9W5 and 10-18-32-9W5 are shown as dotted lines. Cretaceous section above the Roof Thrust is passively folded. Thick dashed line corresponds to the incipient trace of an extension fault in the Cretaceous rocks, above the nearly vertical segment of the transverse fault. (b) Pre-stack, time-migrated seismic profile for line JR-110. Tops for the Cambrian and Devonian markers for the regional, Lower Detachment sheet and Brazeau sheet are outlined. Abbreviations: Cambrian (C), Devonian (D), Mississippian (M), Jurassic Fernie and Kootenay (Jf + Jk), Cretaceous Blairmore (Kbm), Blackstone (Kbk), Wapiabi (Kwp), Belly River (Kbr), and Edmonton (Ked).

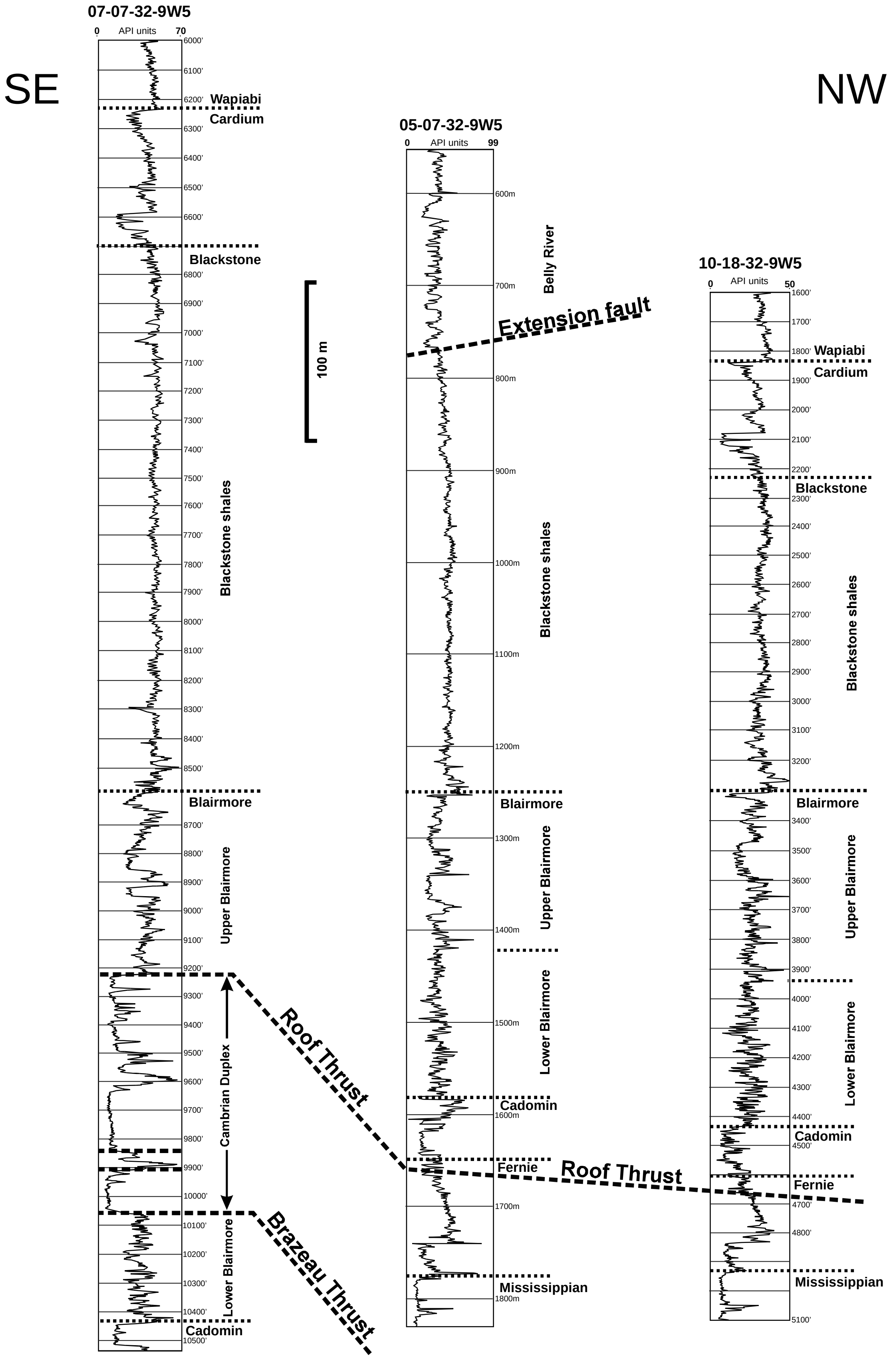

Fig. 9. Gamma-ray logs for portions of wells 7-7-32-9W5, 5-7-32-9W5 and 10-18-32-9W5. Depths in feet and meters; all logs plotted at the same scale. 1560 m of Cambrian, Devonian and Mississippian strata are carried in well 10-18-32-9W5 (not all shown here), but only 250 m of Cambrian strata are encountered in well 7-7-32-9W5. Well 5-7-32-9W5 is missing about 500 m of the Cardium and Wapiabi formations, between the Belly River sandstones and the Blackstone shales, across the extension fault discussed in the text.

of Upper Cambrian to Upper Cretaceous Belly River strata preserved in the hanging wall of the Brazeau Thrust and below the Burnt Timber Thrust. Above the Burnt Timber Thrust, the Jurassic rocks and Lower Cretaceous Blairmore Group have been repeated three times by faults that detach in the Jurassic Fernie shales. A significant 30° northwest-dipping, lateral ramp in the Brazeau Thrust is interpreted to eliminate the allochthonous Cambrian section toward the southeast. The Brazeau thrust cuts up-section laterally from the Cambrian carbonates and merges with the Roof Thrust in Jurassic shales. The apparent offset of the Mississippian–Devonian contact seen in the strike section (Fig. 7) is small; however the primary displacement of the Brazeau sheet is 14 km toward the foreland (in Fig. 5), parallel to the lateral ramp. The overlying Roof Thrust, Burnt Timber Thrust, and imbricates of Jurassic and Cretaceous strata have been folded and plunge southward as a result of the extra thickness of lower Paleozoic units carried above and terminating at the lateral ramp (Fig. 7). The subsurface location of the lateral ramp in the Brazeau Thrust coincides closely with the bend in the Burnt Timber Thrust trace at the current erosion level on Ollerenshaw's (1976) geological map (Fig. 1). A time pull-up anomaly of 100 ms on the Cambrian marker disappears where the allochthonous Mississippian is cut out by the lateral ramp (Fig. 7).

The northwest-dipping lateral ramp with its shallow-angle cut-off of the Paleozoic markers and passive folding of overlying units is exactly what we would expect to find at the trailing edge of a classic duplex (see Boyer and Elliott, 1982, fig. 25, B–B′). However, this structure is much more complex to the east, in line JR-110 (Fig. 8), where high-angle cutoffs of Paleozoic markers and steep to nearly vertical transverse faults occur.

4.2.2. Line JR-110

Strike line JR-110 (Fig. 8) is located about 5.5 km northeast of JR-111 along the western limb of the Williams Creek Syncline where it ties with dip line JR-108 (Fig. 2a). The base of the line is characterized by relatively parallel seismic reflectors corresponding to the autochthonous carbonate sequence and the sheet of Paleozoic units carried by the Lower Detachment (Fig. 8). Autochthonous Cambrian reflectors are pulled up to 2.2 s at the northwestern end of the line and return to the 2.4 s level below the Williams Creek Syncline (Fig. 8b). The width of the pull-up gradient zone constrains the along-strike extent of the lateral culmination wall (southeast limb of the Limestone Mountain Culmination) to less than 2.5 km.

The most impressive feature on this strike line is the abrupt termination of the Paleozoic units in the Brazeau sheet between the wells 7-7-32-9W5 and 10-18-32-9W5 (Fig. 8a). Seismic markers for the Cretaceous Wapiabi, Belly River and Edmonton formations in the Williams Creek Syncline are interpreted to be continuous to the surface without significant offset (Fig. 8a) because they do not appear to be offset by major transverse faults in map view and outcrops. We have field-checked the geological maps of Beach (1942) and Ollerenshaw (1965, 1968, 1969, 1976), specifically looking for transverse faults, slickenlines and evidence for SE-side-down offset of stratigraphic contacts between lines JR-101 and JR-108 (Fig. 2a). Units are well-exposed in the James River valley, along its tributaries, and on the intervening ridges. Both the east and west limbs of the Williams Creek Syncline are continuous across James River and the outcrop pattern of the northern closure of the syncline is broken, in only one place, by the James Thrust (Fig. 2a). The short NE–SW segment of the folded James Thrust is the only transverse fault exposed at the surface, however, the present-day vertical separation of the basal Belly River contact is 300–400 m, with the SE side up. It is unlikely that this short segment of the James Thrust was reactivated as a major SE-side-down normal fault. Transverse (NE–SW) extension fractures are common in the area, however, no more than 20 m of offset of the basal Belly River and basal Edmonton contacts can be accommodated across data gaps between outcrops. We therefore conclude that the transverse fault terminating the Limestone Mountain Culmination at the Paleozoic level is blind.

Well 7-7-32-9W5 provides a critical tie for strike line JR-110 (Fig. 8a). The well was drilled through the southeast-dipping Cretaceous units of the Williams Creek Syncline, down to the upper Blairmore Group, before intersecting 250 m of Cambrian carbonates (Shell geologists also identified these rocks as Cambrian; P. Fermor, pers. comm.). The well then encountered interbedded Blairmore sandstones and shales beneath the Brazeau Thrust and terminated in Devonian carbonates of the Lower Detachment sheet. The gamma-ray logs of three wells in the vicinity of the transverse termination of the Limestone Mountain Culmination are compared in order to document lateral ramping of the Roof and Brazeau Thrusts and the presence of an extension fault developed in Cretaceous rocks folded over the southeast flank of the culmination (Fig. 9; see Fig. 2a for well locations). Despite the underlying complexities and lateral ramps, the Cretaceous strata above the Blackstone shales have consistent thicknesses and log characters, suggesting that they have been transported as a coherent package, cut only by the discrete extension fault. The Blackstone shales are thickened in the wells (Fig. 9) and serve as a glide horizon in Fig. 8, accommodating passive folding of the overlying sheet.

When Blairmore intervals above and below the Cambrian section in well 7-7-32-9W5 are compared with the unfaulted Blairmore in wells 5-7-32-9W5 and 10-18-32-9W5, we see that the Blairmore above the Cambrian duplex in 7-7-32-9W5 is typical of the Upper Blairmore, with thick sand and shale packages. Thinner interbedded sand and shale units, consistent with the Lower Blairmore, are represented in logs below the Cambrian duplex. The three wells are juxtaposed in Fig. 9, using the top of the Blairmore as a datum, to show

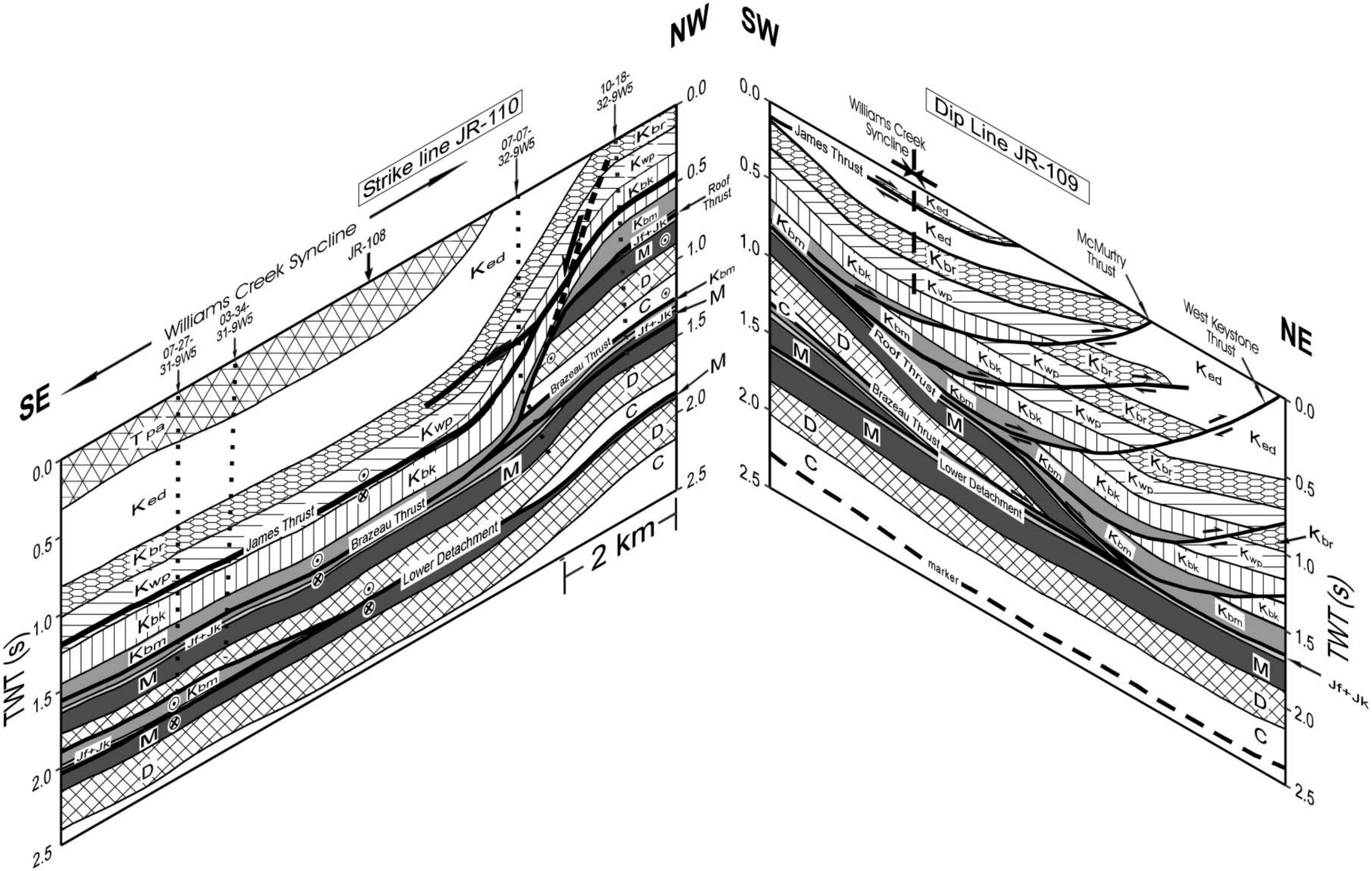

Fig. 10. Combined interpreted cross-sections from profiles of lines JR-110 and JR-109 showing the southeastern termination of Paleozoic carbonates in the LMC by means of a steep transverse fault to the southeast (Line JR-110) and a hanging wall ramp in the Brazeau Thrust (Line JR-109). The Roof Thrust in the Jurassic shales represents a decoupling surface between the Mesozoic imbricates and Paleozoic carbonates of the Brazeau sheet. Abbreviations: Cambrian (C), Devonian (D), Mississippian (M), Jurassic Fernie and Kootenay (Jf + Jk), Cretaceous Blairmore (Kbm), Blackstone (Kbk), Wapiabi (Kwp), Belly River (Kbr), and Edmonton (Ked).

that the Roof Thrust cuts 205 m up-section to the southeast, from a detachment in the Jurassic Fernie shales to a detachment near the middle of the Blairmore Group. Note that the Brazeau thrust also cuts up-section laterally between these two wells to a mid-Blairmore detachment. The Brazeau sheet carries only a portion (250 m) of the Cambrian stratigraphy in the southeast 'corner' of the duplex in 7-7-32-9W5, but only 1.8 km to the northwest, in well 10-18-32-9W5, it carries 1560 m of Cambrian, Devonian and Mississippian strata (not all shown in Fig. 9). Thus, the Brazeau Thrust ramps 1310 m up-section laterally over a distance of less than 2 km.

At the Paleozoic level, our interpretation of this line is identical to Fermor's (1999, fig. 13), but it is very different at the Upper Cretaceous level. He shows the base of the Belly River Formation as shallowly dipping and down-dropped by 700 m on the southeast side of his sub-vertical, emergent transverse fault. However, surface mapping indicates that no more than 20 m of southeast-side-down offset of the basal Belly River and basal Edmonton contacts can be accommodated across data gaps between outcrops in this area. Paleozoic markers in the Brazeau sheet do end abruptly against a steeply southeast-dipping transverse fault (Fig. 8), but Cretaceous units are continuous around the northern closure of Williams Creek Syncline (i.e. above this transverse fault). This implies that they were passively folded over the 1560-m-thick competent beam of Paleozoic carbonates carried by the Brazeau Thrust, and that the transverse fault is blind and likely very steep, as it is not imaged in 2D seismic profiles. The presence of Cretaceous Upper Blairmore faulted over Cambrian strata in well 7-7-32-9W5 suggests a normal displacement on this transverse fault and a southwest dip where penetrated by the well (JR-110, Fig. 10). However, differential displacement of the Paleozoic rocks across the transverse fault indicates that the primary motion is dextral strike-slip, as the leading edge of the Paleozoic is 14 km farther toward the foreland on the northwest side of the lateral ramp (Fig. 5). Paleozoic carbonates in the Brazeau sheet of Fig. 8a are coming out of the page and are uplifted as they are transported over frontal ramps toward the foreland. Uplift of 1560 m over a distance of 14 km yields a mean transport vector of 6° up to the northeast. Normal movement probably took place on the transverse fault where line JR110 is located, but it would not have been the primary mechanism to explain the abrupt truncation of Paleozoic units in the Brazeau sheets against the Cretaceous units of the Williams Creek Syncline.

The 5-7-32-9W5 well (Figs. 2a and 9) also intersects an interesting feature developed in mid-Cretaceous rocks above the transverse fault. The marine Cardium Formation is regional in extent and has one of the most distinctive log characters in the Foothills, as seen in the nearby 7-7-32-9W5 and 10-18-32-9W5 wells (Fig. 9), but the Cardium Formation and overlying Wapiabi shales were not encountered in the 5-7-32-9W5 well, where Belly River sandstones directly overlie Blackstone shales above the Roof Thrust. This represents about 500 m of missing section across an extension fault, which developed over the steepest portion of the blind transverse fault (Fig. 8). Because of its low angle relative to bedding, the extension fault may splay upward, following detachments in shale and coal horizons of the Belly River Formation, such that no more than 20 m of offset can be measured at the surface. The major normal fault discussed by Fermor (1999) extends upward, offsetting the Cretaceous beds. He indicates, with a question mark, that the fault may die out upward, but it is difficult to imagine how a steep normal fault can lose more than 1500 m of displacement in the distance of less than 1500 m from the top of the Paleozoic to the present-day ground surface. Rotational strain can take place in these transverse structures, as shown by recent physical modeling by Dixon and Spratt (1999). In our interpretation, the transverse fault truncating Paleozoic strata merges upward with the Roof Thrust in JR-109 (Fig. 5a) and its displacement does not directly continue into the overlying sheet. Extension faults such as that found in well 5-7-32-9W5 (Fig. 9) would be secondary in origin, associated with gravitational instability of the hanging wall Mesozoic rocks draped over the lateral edge of the uplifted Paleozoic duplex.

The high-angle truncation against the steep to nearly vertical transverse fault in line JR-110 (Fig. 8a) contrasts sharply with the northwest-dipping lateral ramp and with the shallow angle cut-off of the Paleozoic markers seen in JR-111 (Fig. 7). This suggests that the geometry of the structure is much more complex in three dimensions than Fermor's (1999, fig. 14) 'trap-door' model of a vertical transverse fault with uplift of the Paleozoic sheet on the northwest side of the fault diminishing toward the hinterland.

5. Discussion

The overall 3D structural geometry of the Limestone Mountain Culmination and Williams Creek Syncline area is dominated by two lithotectonic packages separated by a major detachment. The lower structural package is represented by a southeast-plunging antiformal stack of Paleozoic carbonate platformal rocks that define the Limestone Mountain Culmination. The upper structural package comprises Mesozoic siliciclastic foreland basin rocks, deformed into an east-verging thrust-and-fold belt. The Williams Creek Syncline is the structurally highest element of the area, with Tertiary rocks preserved in the core of the syncline. The seismic interpretation outlined in dip and strike lines constrains the southern and eastern extent of the Limestone Mountain Culmination and overlying imbricated Cretaceous units.

Fig. 10 combines lines JR-109 and JR-110, showing dip and strike sections through the lateral termination of the

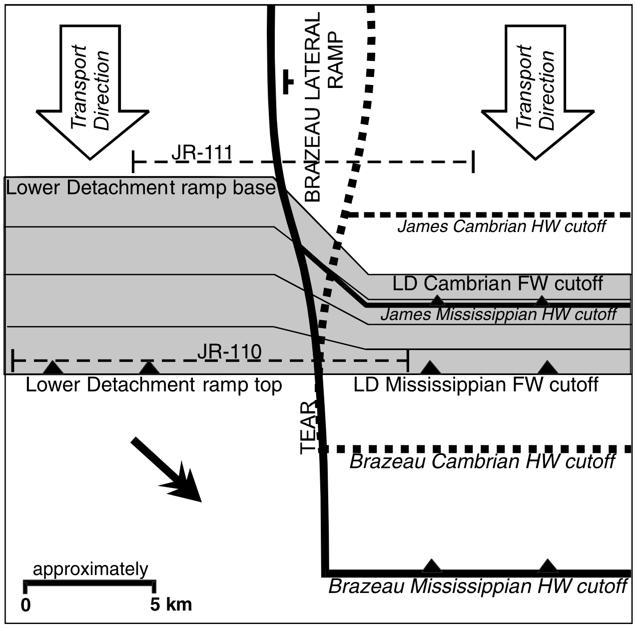

Fig. 11. Schematic map of the geometry of the Lower Detachment (LD) surface and hanging wall cutoffs on the overlying Brazeau and James Thrusts. Bedding-parallel flats in the LD surface are white areas; oblique and frontal ramp portions are shaded grey. The Mississippian footwall cutoff marks the top of the LD ramp and the Cambrian marker footwall cutoff marks the base of the LD ramp; thin black lines represent structure contours on the LD ramp. The frontal and lateral Mississippian hanging wall cutoff on the Brazeau Thrust is shown as a thick solid line and its frontal and lateral Cambrian marker hanging wall cutoff as a thick dashed line. Medium weight solid and dashed lines show the frontal and lateral Mississippian and Cambrian cutoffs on the James Thrust, which merge laterally with the Brazeau Thrust ramps. Positions of strike lines JR-110 (Fig. 8) and JR-111 (Fig. 7) are marked by thin dashed lines.

Limestone Mountain Culmination. In the dip section (JR-109), we see the antiformal-stack geometry of a classic foreland-dipping duplex with frontal ramp cutoff angles typical of the region, but in the strike section (JR-110) the geometry of the lateral ramp is atypical. The Roof Thrust of the duplex represents a decoupling surface between the underlying Paleozoic horses and the overlying Cretaceous imbricates, which were passively folded and tilted to the northeast and southeast (Fig. 10) as the culmination developed. Folding of the Cretaceous rocks becomes less pronounced as the Limestone Mountain Culmination attenuates toward its leading edge, where the Brazeau Thrust cuts up-section through the Paleozoic strata and merges with the Lower Detachment in the basal Cretaceous Blairmore Group (JR-109, Fig. 10). Along strike toward the southeast, the Limestone Mountain Culmination gradually loses structural relief as thrust sheets disappear (i.e. Number-2 sheet; Fig. 4) and the Brazeau and James Thrusts cut up-section from line JR-103 to JR-108 (Figs. 5a and 6), which is typical of duplexes, but then the structure terminates abruptly.

Paleozoic carbonates in the Brazeau sheet are cut off by a transverse fault that possesses a complex geometry along its length. To the southwest it is a simple lateral ramp that dips ~30°NW (Fig. 7), but to the northeast the transverse fault is a vertical to steeply southeast-dipping fault (Fig. 8). Dahlstrom's (1970) and Fermor's (1999) models interpret it as a steep tear/normal fault, but do not address the problems associated with changes in dip along the fault and how the overlying Mesozoic rocks were deformed during emplacement of the Brazeau sheet. We present a third model that incorporates the actual, complex geometries of the ramps and all the surface, well and seismic data. North of the transverse fault the Brazeau Thrust sheet has been transported 14 km toward the foreland along several long flats, so its shape mimics the ramps and flats in the underlying Lower Detachment surface. It is therefore useful to compare their 3D geometries with each other and with the overlying James Thrust. Frontal, lateral and oblique ramps have developed approximately parallel (0–10°), normal (80–90°) and oblique (10–80°) to the regional trend at different structural levels in the Limestone Mountain area, and those at the southeastern termination of the culmination do not all have the same strike and dip (Fig. 11).

The well data and seismic interpretations (Figs. 4–9) constrain the ramp geometries in Fig. 11 and show that the Brazeau and James thrust sheets are stacked above frontal and oblique ramps in the Lower Detachment surface. The southwestern segment of the Lower Detachment's frontal ramp is more shallowly dipping than the northeastern segment and they are linked by a short, moderately-dipping oblique ramp. Vertical to shallowly-dipping lateral ramps have developed in the Brazeau and James Thrusts in the same geographic location, but the frontal hanging wall cutoffs on the Brazeau Thrust have been transported onto the footwall flat of the Lower Detachment sheet, whereas the James Thrust sheet has been transported only a short distance up the frontal ramp.

It is expected that the footwall cutoffs of the Brazeau sheet would have the same basic geometries as their corresponding hanging wall cutoffs shown in Fig. 11, although some strain at the leading edge is probable for such a large, far-traveled thrust sheet. With the Lower Detachment footwall geometry shown in Fig. 11, the trailing Brazeau hanging wall lateral ramp would have been transported obliquely up the ramp, resulting in the hanging wall lateral ramp over footwall oblique ramp geometry seen in JR-111 (Fig. 7).

If the transverse fault is vertical at the leading edge and shallowly dipping at the trailing edge of the Brazeau Thrust sheet, one wonders how the trailing hanging wall lateral ramp could have been transported past the vertical portion of the leading footwall lateral ramp (14 km to the southwest of Fig. 11) and retain its simple geometry and continuous seismic markers in JR-111 (Fig. 7). Rather than sliding horizontally past the leading vertical lateral ramp, the sheet may have instead moved upward on the backs of frontal footwall duplexes, such that the trailing lateral ramp was transported over the vertical portion of the leading

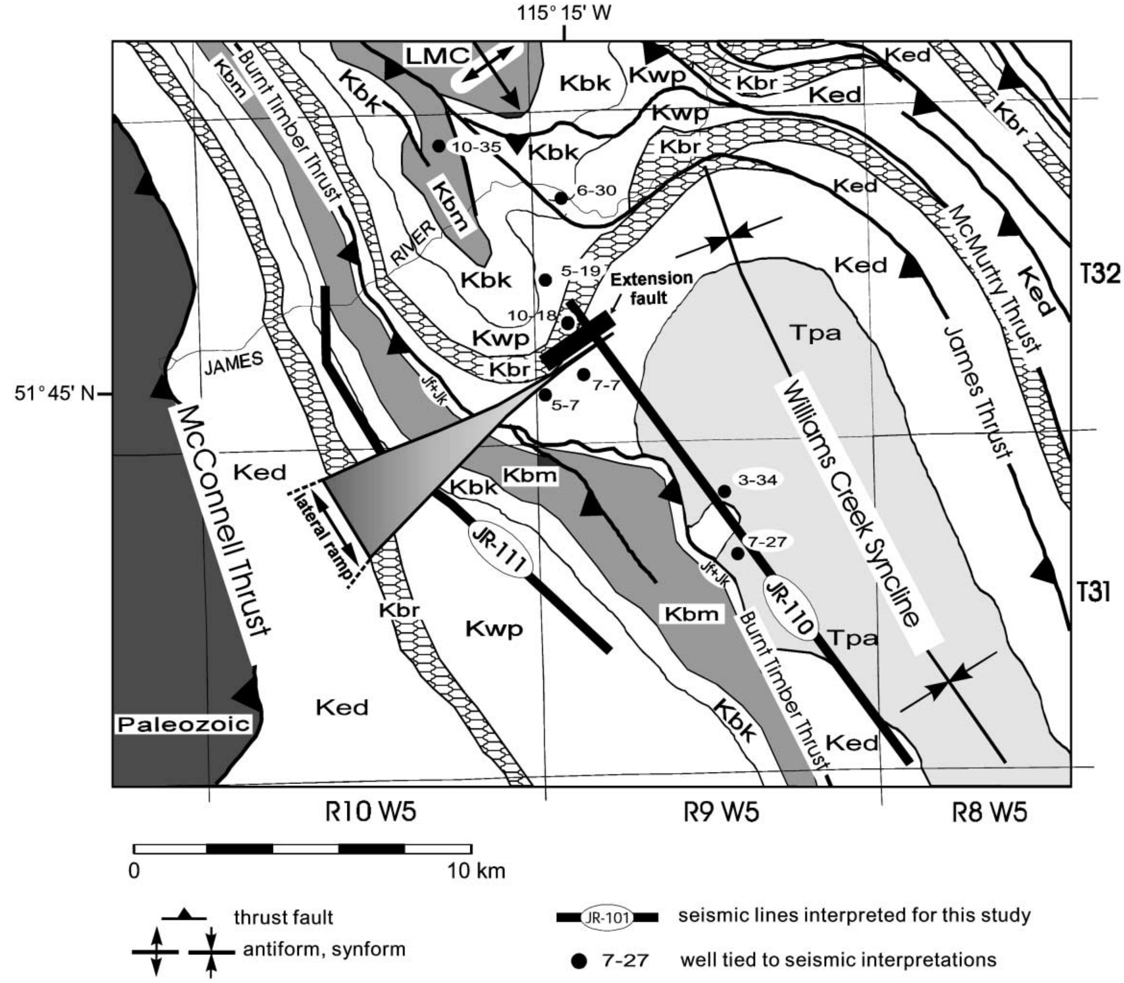

Fig. 12. Map showing positions of the blind transverse fault and the blind extension fault developed in Cretaceous strata draped over it. The transverse fault is a northwest-dipping lateral ramp in the southwest, and a steep or nearly vertical tear fault in the northeast.

footwall ramp along a higher detachment level. Fermor's (1999) regional study shows that footwall imbricates are very common beneath ramps and culminations of the Brazeau and other major thrust sheets, and in the Limestone Mountain Culmination the Brazeau sheet is carried on the Lower Detachment sheet. Foreland translation of the leading edge was likely hampered by the steep lateral ramp in the southeast, causing the pile up of horses in an antiformal stack. Synchronous thrusting (Boyer, 1992) is expected in such situations and geometrically substantiated here by preferential imbrication over the forelimb of the antiformal stack, offset of the Roof Thrust, and the folded and steep segments of the James Thrust. The leading edge of the transverse fault through the Brazeau sheet dips southeast today (Figs. 8 and 10), but it may have been vertical to steeply northwest-dipping initially. Internal deformation and lateral spreading as a duplex is emplaced on a footwall flat is common (Boyer and Elliott, 1982), and likely at Limestone Mountain as there was an extra 1.5 km of Paleozoic thrust sheets on the northwest side of the lateral ramp (Fig. 10).

Where the transverse fault is characterized by a steep tear component in the northeast (Figs. 8, 11 and 12), a mechanical instability in the overlying Cretaceous units may have resulted in SE-side-down gravity sliding, juxtaposing them against the Paleozoic carbonates of the Brazeau sheet. The extension fault may sole into the Roof Thrust and/or the steepest segment of the transverse fault, since it has the same geometry as faults seen in forced (drape) folds over rigid basement uplifts (Stearns, 1978; Keller and Lynch, 2000).

The current location of this transverse fault may not be fortuitous. The study area lies directly over the transition between two major tectono–chronological domains of the Alberta crystalline Precambrian basement, as defined by Ross et al. (1991) and Eaton et al. (1995). There is a northeast-trending boundary between a magmatic arc known as the Rimbey magnetic high (Ross et al., 1991) and the supracrustal domain of the Thorsby magnetic low. Such a preexisting basement crustal boundary may have preferentially localized the development of a major transverse fault during the Laramide orogeny (Schedl and Wiltschko, 1987).

Although not directly involved in the Laramide deformation, the rheological contrast between the more competent Rimbey magmatic domain and the less competent Thorsby supracrustal domain may have promoted ramping of the Brazeau Thrust to the southeast. The northern limit of the Moose Mountain Culmination (Fig. 1) coincides with the northern limit of the Matzhiwin magnetic high (Eaton et al., 1995, 1999) another magmatic domain. Elsewhere in Alberta and the Northwest Territories, Precambrian basement features have been known to control the depositional history of Mississippian platform carbonates (Brandley et al., 1996) and northeast-trending Devonian reef complexes (McLaren, 1955; Hargreaves, 1959; Cecile et al., 1997). These depositional trends later controlled some major changes in structural styles during the Laramide orogeny (Spratt and Dixon, 1999). Therefore, the origin of major transverse faulting may lie in the pre-existing structural elements of the crystalline basement. The development of major antiformal culminations cored by Paleozoic carbonates (i.e. Panther River, Moose Mountain, and Limestone Mountain) east of the McConnell Thrust could therefore have been indirectly controlled by the structural architecture of the Precambrian basement.

Acknowledgements

Funding for this study was provided by the Natural Sciences and Engineering Research Council (NSERC) of Canada and industry sponsors of the Fold–Fault Research Project (FRP) at The University of Calgary. Husky Oil, PanCanadian Petroleum, Petro-Canada and Shell Canada are warmly thanked for giving access to the seismic data, so critical in carrying out this research project. Without their collaboration, this work would not have been possible. We also thank Mark Cooper, Paul MacKay, Greg Soule, Andy Newson and Bob Quartero for several fruitful discussions on ideas generated in this paper. Peter Fermor, Mike McGroder and Scott Wilkerson provided insightful reviews of the manuscript, but the interpretations presented are ours.

References

Apotria, T.G., 1995. Thrust sheet rotation and out-of-plane strains associated with oblique ramps: an example from the Wyoming salient, USA. Journal of Structural Geology 17, 647–662.

Bally, A.W., Gordy, P.L., Stewart, G.A., 1966. Structure, seismic data and orogenic evolution of southern Canadian Rocky Mountains. Bulletin of Canadian Petroleum Geology 14, 337–381.

Beach, H.H., 1942. Marble Mountain Map-area, Alberta. Geological Survey of Canada Paper 42-3.

Bégin, N.J., Lawton, D.C., Spratt, D.A., 1996. Seismic interpretation of the Rocky Mountain Thrust Front near the Crowsnest Deflection, southern Alberta. Bulletin of Canadian Petroleum Geology 44, 1–13.

Boyer, S.E., 1992. Geometric evidence for synchronous thrusting in the southern Alberta and northwest Montana thrust belts. In: McClay, K.R. (Ed.). Thrust Tectonics. Chapman and Hall, London, pp. 377–390.

Boyer, S.E., Elliott, D., 1982. Thrust systems. American Association of Petroleum Geologists, Bulletin 66, 1196–1230.

Brandley, R.T., Krause, F.F., Varsek, J.L., Thurston, J., Spratt, D.A., 1996. Implied basement-tectonic control on deposition of Lower Carboniferous carbonate ramp, southern Cordillera, Canada. Geology 24, 467–470.

Cecile, M., Morrow, D.W., Williams, G.K., 1997. Early Paleozoic (Cambrian to Early Devonian) tectonic framework. Canadian Cordillera. Bulletin of Canadian Petroleum Geology 45, 54–74.

Dahlstrom, C.D.A., 1970. Structural geology of the eastern margin of the Canadian Rocky Mountains. Bulletin of Canadian Petroleum Geology 18, 331–406.

Dixon, J.M., Spratt, D.A., 1999. Centrifuge modelling of three-dimensional deformation associated with thrusting over tear faults and lateral ramps. Geological Society of America Annual Meeting Program and Abstracts. Abstract 50698.

Douglas, R.J.W., 1950. Callum Creek, Langford Creek and Gap map areas, Alberta. Geological Survey of Canada Memoir 255, Callum Creek Map 982A, scale 1:63,360.

Douglas, R.J.W., 1951. Pincher Creek, Alberta. Geological Survey of Canada, Paper 51-22, Preliminary Map, scale 1:31,680.

Eaton, D.W.S., Milkereit, B., Ross, G., Kanasewich, M.E.R., Geis, W., Edwards, D.J., Kelsch, L., Varsek, J., 1995. Lithoprobe basin-scale seismic profiling in central Alberta: basement influences on the sedimentary cover. Bulletin of Canadian Petroleum Geology 43, 65–77.

Eaton, D.W., Ross, G.M., Clowes, R.M., 1999. Seismic-reflection and potential-field studies of the Vulcan structure, Western Canada; a Paleoproterozoic Pyrenees? Journal of Geophysical Research, B, Solid Earth and Planets 104, 23255–23269.

Fermor, P., 1999. Aspects of the three-dimensional structure of the Alberta Foothills and Front Ranges. Geological Society of America Bulletin 111, 317–346.

Hargreaves, G.E., 1959. Nisku lithofacies of Rocky Mountains, Alberta. In: Austin, G.H. (Ed.). Moose Mountain — Drumheller. Alberta Society of Petroleum Geologists 9th Annual Field Conference Guidebook, pp. 1–196.

Jones, P.B., 1996. Triangle zone geometry, terminology and kinematics. Bulletin of Canadian Petroleum Geology 44, 139–152.

Keller, J.V.A., Lynch, G., 2000. Displacement transfer and forced folding in the Maritimes Basin of Nova Scotia, Eastern Canada. In: Cosgrove, J.W., Ameen, M.S. (Eds.). Forced Folds and Fractures. Geological Society Special Publication 169, pp. 87–101.

Lawton, D.C., Spratt, D.A., Hopkins, J.C., 1994. Tectonic wedging beneath the Rocky Mountain foreland basin, Alberta, Canada. Geology 22, 519–522.

Lawton, D.C., Sukaramongkol, C., Spratt, D.A., 1996. Seismic characterization of a “compound tectonic wedge” beneath the Rocky Mountain foreland basin, Alberta. Bulletin of Canadian Petroleum Geology 44, 258–268.

Lebel, D., Langenberg, W., Mountjoy, E.W., 1996. Structure of the central Canadian Cordilleran thrust-and-fold-belt, Athabasca–Brazeau area, Alberta: a large, complex intercutaneous wedge. Bulletin of Canadian Petroleum Geology 44, 282–298.

MacKay, P.A., 1996. The Highwood Structure: a tectonic wedge at the foreland edge of the southern Canadian Cordillera. Bulletin of Canadian Petroleum Geology 44, 215–232.

MacKay, P.A, Spratt, D.A., Soule, G.S., Lawton, D.C., 1994. The triangle zone of southern Alberta — geometry, lateral variations and associated oil and gas fields. Field-Trip Guidebook, (PR-2), Canadian Society of Exploration Geophysicists/Canadian Society of Petroleum Geologists, 1994 Joint National Convention, Calgary, Alberta, pp. 1–105.

McLaren, D.J., 1955. Devonian formations in the Alberta Rocky Mountains between Bow and Athabasca Rivers. Geological Survey of Canada Bulletin 35, 1–87.

McMechan, M.E., 1995. Geology, Rocky Mountain Foothills and Front Ranges in Kananaskis Country, Alberta. Geological Survey of Canada Map 1865, scale 1:100,000.

Moffat, I.W., Spang, J.H., 1984. Origin of transverse faulting, Rocky Mountain Front Ranges, Canmore, Alberta. Bulletin of Canadian Petroleum Geology 32, 147–161.

Norris, D.K., 1993. Geology and structure cross-sections, Blairmore (West Half), Alberta. Geological Survey of Canada Map 1829A, scale 1:50,000.

Norris, D.K., 1993. Geology and structure cross-sections, Langford Creek (West Half), Alberta. Geological Survey of Canada Map 1837A, scale 1:50,000.

Ollerenshaw, N.C., 1965. Burnt Timber Creek, Alberta. Geological Survey of Canada Map 11-1965, scale 1:63,360.

Ollerenshaw, N.C., 1968. Limestone Mountain, Alberta. Geological Survey of Canada Map 8-1968, scale 1:50,000.

Ollerenshaw, N.C., 1969. Marble Mountain, Alberta. Geological Survey of Canada Map 7-1969, scale 1:50,000.

Ollerenshaw, N.C., 1976. Geology of Calgary, West of Fifth Meridian, Alberta–British Columbia. Geological Survey of Canada Map 1457A, scale 1:250,000.

Price, R.A., 1967. The tectonic significance of mesoscopic subfabrics in the southern Canadian Rocky Mountains of Alberta and British Columbia. Canadian Journal of Earth Sciences 4, 39–70.

Price, R.A., 1981. The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains. In: McClay, K.R., Price, N.J. (Eds.). Thrust and Nappe Tectonics. Geological Society Special Publication 9, pp. 427–448.

Price, R.A., 1986. The southeastern Canadian Cordillera: thrust faulting, tectonic wedging, and delamination of the lithosphere. Journal of Structural Geology 8, 239–254.

Price, R.A., Fermor, P., 1985. Structure section of the Cordilleran foreland thrust and fold belt west of Calgary, Alberta. Geological Survey of Canada Paper 84-14, 1 sheet.

Ross, G.M., Parrish, R.R., Villeneuve, M.E., Bowring, S.A., 1991. Geophysics and geochronology of the crystalline basement of the Alberta Basin, western Canada. Canadian Journal of Earth Sciences 28, 512–522.

Sanderson, D.A., Spratt, D.A., 1992. Triangle zone and displacement transfer structures in the eastern Front Ranges, southern Canadian Rocky Mountains. American Association of Petroleum Geologists Bulletin 76, 828–839.

Schedl, A., Wiltschko, D.V., 1987. Possible effects of pre-existing basement topography on thrust fault ramping. Journal of Structural Geology 9, 1029–1037.

Skuce, A.G., Goody, N.P., Maloney, J., 1992. Passive-roof duplexes under the Rocky Mountain foreland basin, Alberta. American Association of Petroleum Geologists Bulletin 76, 67–80.

Soule, G.S., Spratt, D.A., 1996. En échelon geometry and two-dimensional model of the triangle zone, Grease Creek Syncline area, Alberta. Bulletin of Canadian Petroleum Geology 44, 244–257.

Spratt, D.A., Lawton, D.C., 1996. Variations in detachment levels, ramp angles and wedge geometries along the Alberta thrust front. Bulletin of Canadian Petroleum Geology 44, 313–323.

Spratt, D.A., Dixon, J.M., 1999. Resolution of changes in fault-related fold geometries across oblique lithofacies boundaries based on field mapping, physical models, 2D and 3D seismic data. Geological Society of America Annual Meeting Program and Abstracts. Abstract 51319.

Spratt, D.A., Chantraprasert, S., MacKay, P.A., 1995. Triangle zone and foothills structures in the Turner Valley map area, Alberta. Geological Survey of Canada Current Research 1995, 105–111.

Stearns, D.W., 1978. Faulting and forced folding in the Rocky Mountains foreland. In: Matthews, V. (Ed.). Laramide Folding Associated with Basement Block Faulting in the Western United States. Geological Society of America Memoir 151, pp. 1–37.

Stockmal, G.S., MacKay, P.A., Lawton, D.C., Spratt, D.A., 1996. The Oldman River triangle zone: a complicated tectonic wedge delineated by new structural mapping and seismic interpretation. Bulletin of Canadian Petroleum Geology 44, 202–214.