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STRUCTURE AND HYDROCARBON OCCURRENCE, ROCKY MOUNTAIN FOOTHILLS AND FRONT RANGES, TURNER VALLEY TO WATERTON LAKES

by

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Structure and Hydrocarbon Occurrence, Rocky Mountain Foothills and Front Ranges, Turner Valley to Waterton Lakes[1]

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Field Trip Guidebook

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[1]Another version of this guidebook with the same title and authorship of K. Osadetz, G. Stockmal, and D. Lebel appeared as Field Trip Guidebook No. 11 for the GeoCanada 2000 meeting in Calgary, Alberta, May, 2000

ITINERARY

DAY ONE

The Triangle Zone from Turner Valley to Waterton National Park

University of Calgary: Trip overview, brief introduction to structural setting. *Participants can read Appendix 1: "History of Exploration in the Canadian Foothills" or Introduction, Part 3: "An Introduction to Upper Cretaceous and Tertiary Stratigraphy" en route to Turner Valley.*

Stop 1: Hell's Half Acre, Turner Valley.
Theme: Historical overview, Foothills structure, introduction to the triangle zone.
Purpose: (1) overview of Day 1, (2) introduction to guidebook description of the triangle zone and discuss the Turner Valley structures, and (3) view "natural gas seepage" on the bank of the Sheep River.

Stop 2: Highwood River Bridge, Highway 22
Theme: Triangle zone structure.
Purpose: To view the Longview Deformation Zone, and discuss the influence of mechanical stratigraphy on triangle zone structure.

Stop 3a: Chain Lakes Provincial Park
Theme: Triangle zone and Foothills structure.
Purpose: Discussion of triangle zone structure between Maycroft and Turner Valley; description of view of south-plunging Rice Creek Anticline outlined by the Milk River Group, and the map-scale folding of the Rice Creek Fault below the upper detachment.

Stop 3b (optional): St. Mary River Formation outcrop, approximately 1 km west on gravel road immediately south of Chain Lakes Park
Themes: Stratigraphic succession of the Foreland Basin, and triangle zone structure.
Purpose: To view the tilted St. Mary River Formation in the immediate hanging wall of the Big Coulee Fault (triangle zone upper detachment).

Stop 4 (**Provisional):** Outcrop of Willow Creek Formation, Highway 22, just south of junction with Highway 520, Maycroft map sheet
Theme: Stratigraphic succession of the Foreland Basin, and triangle zone and Foothills structure.
Purpose: Possible stop to view Willow Creek Formation outcrop, and view across triangle zone into Outer Foothills.

Stop 5a: Junction of turnoff to Oldman River campground from unnumbered gravel road, adjacent to Highway 22, immediately north of the Oldman River bridge.
Theme: Triangle zone structure.
Purpose: Overview of the triangle zone and discussion of map-scale structures in the hanging wall of the upper detachment.

Stop 5b: Oldman River campground, adjacent to Highway 22, immediately north of the Oldman River bridge.
Theme: Triangle zone structure and stratigraphic succession of the Foreland Basin.
Purpose: Lunch-stop/rest-stop, and casual examination of outcrops of St. Mary River Formation (including "dinoturbation").

Stop 6: Milk River Group outcrop, downstream of Lundbreck Falls Provincial Recreation Area, on Highway 3a near junction of Highway 3 and Highway 22.
Theme: Stratigraphic succession of the Foreland Basin
Purpose: Overview of the Upper Cretaceous stratigraphic succession from the uppermost Wapiabi Formation, through the Milk River Group, and view the lowermost Belly River Group strata.

Stop 7: Waterton Reservoir Dam Site
Theme: Triangle zone and Foothills structure.
Purpose: View deformation within Bearpaw, Blood Reserve, and lower St. Mary River strata in the footwall of the Hillspring Thrust.

Stop 8: Waterton Lakes viewpoint, Pine Ridge, Highway 6
Theme: Foothills structure.
Purpose: Overview of Lewis thrust sheet and Waterton Lakes National Park, and discussion of structural setting of the Pine Ridge Fault in relation to the Foothills

Overnight Accommodation and Dinner in Waterton Lakes Town Site

DAY TWO

Lewis Thrust Sheet and Crowsnest Reentrant

Stop 1: Waterton National Park, Prince of Wales Hotel
Theme: Introduction to the Lewis thrust sheet.
Purpose: View of Lewis thrust sheet structure and stratigraphy, and overview of Day Two.

Stop 2: East Bellevue Road Outcrop, Highway 3
Theme: Stratigraphic succession of the Foreland Basin
Purpose: View Contact Between Kootenay Group and Basal Blairmore Group

Stop 3: Frank Slide Interpretive Centre
Theme: Depositional patterns in foreland basins and proximal-distal relationships; and structure of Turtle Mountain (preview of *Day Three*).
Purpose: Views of the Frank Slide and discussion of its structural setting, and outcrop examination of the conglomeratic facies in the Mill Creek Formation (Blairmore Group).

Stop 4: East of Old MacGillvary Mine Office, West of Coleman, Highway 3
Theme: Stratigraphic succession of the Foreland Basin and contrast to stratigraphic succession at East Bellevue.
Purpose: Kootenay Group overlain by Cadomin and Gladstone formations

Stop 5: Crowsnest Formation volcanics outcrop, Highway 3
Themes: Stratigraphic succession of the Foreland Basin; structure of the Crowsnest reentrant; and paleomagnetism – tectonic displacements and remagnetizations in orogenic terrains.
Purpose: Outcrop examination of the Crowsnest Formation volcanics, and structural overview of the Lewis thrust sheet in the Crowsnest reentrant.

Stop 6a: Cambrian-Upper Devonian unconformity and stratigraphy, immediate hanging wall of the Lewis Thrust Sheet, Highway 3.
Theme: Lower Paleozoic stratigraphy.
Purpose: Outcrop examination of the Cambrian Elko Formation overlain by the Upper Devonian Fairholme Group.

Stop 6b: Palliser, Exshaw, and Banff formation outcrop, beside Crowsnest Lake, Highway 3.
Theme: Mesostructures and Lower Paleozoic stratigraphy.
Purpose: Outcrop examination of spectacular mesostructures (duplexes and tectonic wedges) within the Banff Formation; Palliser, Exshaw, and Banff formation stratigraphy.

Return to Coleman for Overnight Accommodation and Dinner

DAY THREE

The Inner Foothills

Stop 1: Blairmore Turnoff Road Cuts, Highway 3
Theme: Mesostructural elements, and Carboniferous stratigraphy
Purpose: Outcrop examination of Carboniferous Rundle Group stratigraphy, with a focus on mesostructure, especially tectonic stylolites.

Stop 2: Footwall of Livingstone Thrust, Highway 517
Themes: Foothills structure; informal boundary between Outer Foothills and Inner Foothills
Purpose: View the folded trace of the Livingstone Thrust, and Foothills structure in its hanging wall and footwall.

Stop 3a: Old Man River Gap (Eastern Side), Highway 517
Themes: Hydrocarbon resources of the Foreland Belt (notes to read during the drive up, Appendix 2), and characteristic structures of the Inner Foothills.
Purpose: View the folding of a thrust sheet that is partly the result of a superposition of hanging wall and footwall ramps. This structure is an exhumed model for a Foothills gas prospect.

Stop 3b: Oldman River Gap (West Side)
Theme: Porosity, diagenesis and thermochemical sulphate reduction (TRS) in Foothills reservoirs
Purpose: To view porosity in Livingstone (Turner Valley) Formation carbonates

Stop 4: Bruin Creek section, Forestry Trunk Road
Theme: Stratigraphic succession of the Foreland Basin
Purpose: To view Upper Blairmore section where the Crowsnest Volcanics are absent.

Stop 5: Savanna Creek structure
Theme: Structural geology of the Inner Foothills.
Purpose: Discuss structural setting of the Savanna Creek field.

Stop 6: Hailstone Butte overview
Theme: Structural geology of the Inner Foothills and Front Ranges.
Purpose: Discuss relationship between the Livingstone and McConnell thrusts.

Return to Calgary, end of trip

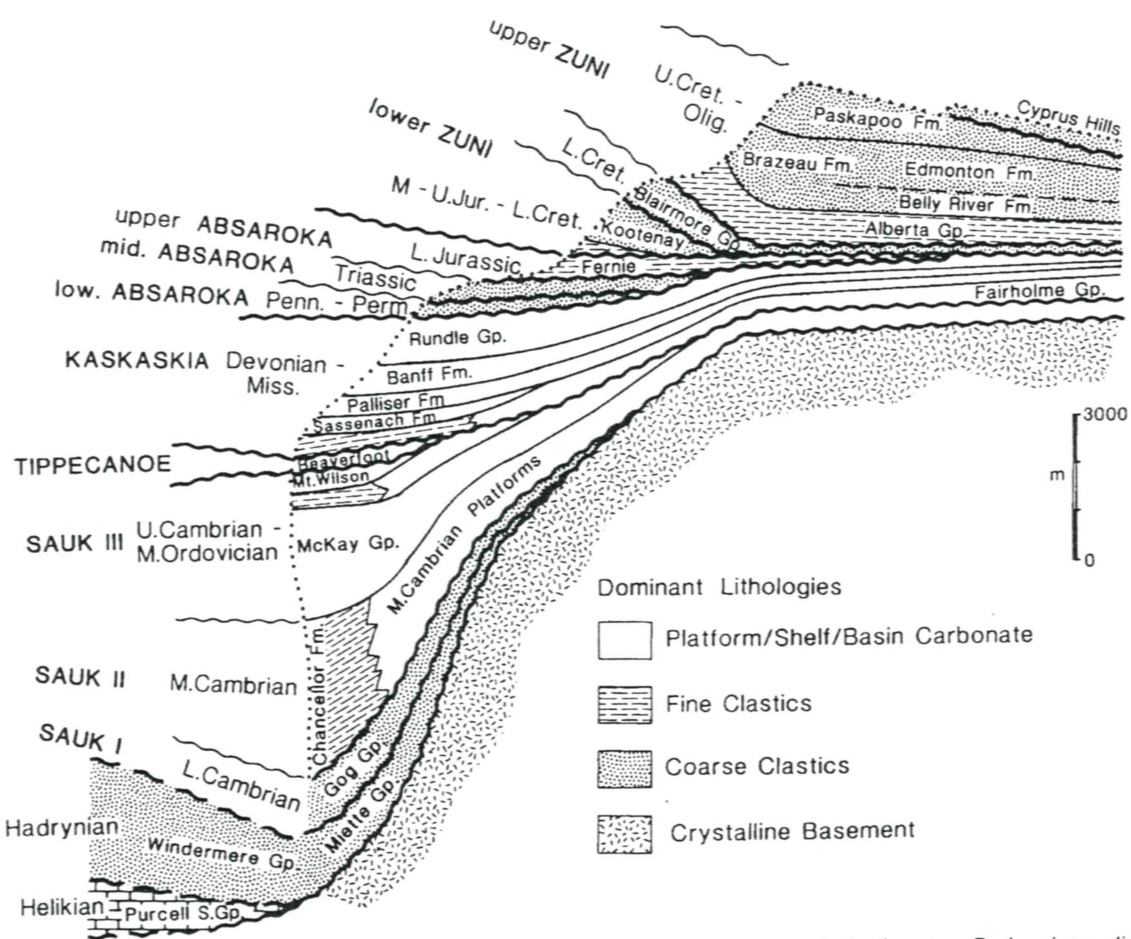
INTRODUCTION

Part 1: Tectonic Setting and Elements

The Eastern Cordilleran Structural Province, a.k.a. the Canadian Rocky Mountain Foreland thrust and fold belt, is an accretionary wedge of westward thickening Middle Proterozoic to Middle Jurassic platformal and miogeoclinal strata overlain by westerly derived and thickening foreland basin deposits (Figure I-1) related to Late Jurassic-Paleogene Cordilleran orogenesis (Gabrielse and Yorath, 1992). This sedimentary prism is itself composed of several paleotectonic elements that pre-date, record and signal the end of the Proto-Pacific ocean basin and its interaction with the North American craton.

Middle Proterozoic Belt (Purcell Supergroup) Basin: Successions include the Middle Proterozoic Belt (Purcell Supergroup) Basin (~1440-70 Ma, Aleinikoff et al., 1996; Anderson and Davis, 1995), a thick intracratonic rift basin that did not result in the formation of an ocean basin, but which has been inverted during Laramide orogenesis and transported as the Lewis thrust sheet.

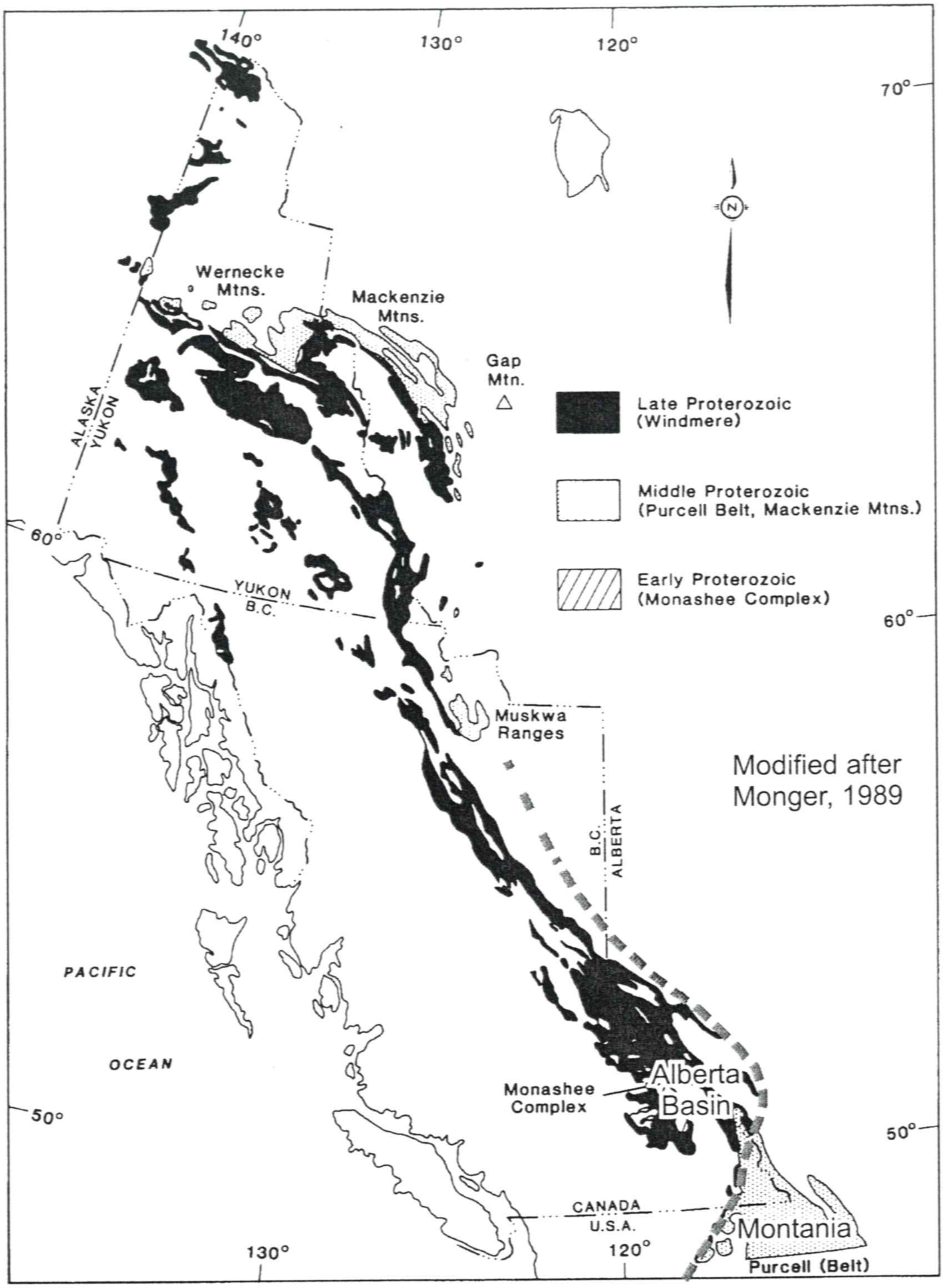
Proto-Pacific Passive Margin: The Upper Proterozoic to Middle Jurassic successions are conventionally interpreted as all having been deposited on the western passive margin of the North American craton. During the formation of the proto-Pacific margin the Belt/Purcell Basin remained "welded" to the North American craton resulting in a major transform offset in the passive margin. This salient of the North American craton lies south of the Crowsnest Pass and is known as "Montania". It is distinguished from the major reentrant into the passive margin commonly referred to as "Alberta Basin", in its Early Paleozoic manifestation (Figure I-2). Late Proterozoic rifting of the North American continent is recorded in the thick Upper



Generalized stratigraphic cross section of the westward thickening, Western Canada Sedimentary Basin miogeocline-platform and foreland basin succession, indicating the principle tectono-stratigraphic sequences and their bounding unconformities, time-stratigraphic and lithostratigraphic units.

Modified from Price et al. (1985).

Figure I-1. Generalized regional stratigraphy, Western Canada Sedimentary Basin (after Ricketts, 1989).



Distribution of Proterozoic strata within the Cordillera. Note the continuity of Late Proterozoic strata in comparison with older rocks (from Gabrielse and Yorath, in press).

Figure I-2. General positions of Late Proterozoic - Early Paleozoic "Montania" relative high and "Alberta Basin" relative low. During Late Proterozoic extension, the Purcell (Belt) Basin remained "welded" to the North American craton.

Proterozoic Windermere grits (780-570 Ma) and Lower Cambrian Gog quartzites (Sauk I sub-sequence) that typify the succession west of Lake Louise, Alberta. Subsequent thermal subsidence of the early Paleozoic passive margin of the North American craton is recorded in the carbonate-clastic "Grand Cycles" (Aitken, 1989; Bond and Kominz, 1984) of the Middle Cambrian to Middle Ordovician succession (Sauk II and Sauk III sub-sequences).

Depositional Sequences of Uncertain Tectonic Affinity: Remnants of an Ashgillian to Lower Silurian succession, of uncertain tectonic affinity, but which onlapped the eroded top of the Paleozoic passive margin succession, were generally stripped from the Alberta Basin prior to the onlap of the Middle to Upper Devonian succession (Kaskaskia I sub-sequence; Figure I-1). North of "Montania", Kaskaskia I strata directly overlie a deeply eroded and westerly rapidly thickening Sauk Sequence along the Western Alberta Ridge. On "Montania" the Sauk I clastics were never deposited, whereas the carbonate-dominated Sauk II carbonate dominated succession is eroded and very thin, and the Sauk III succession appears not have been deposited. On "Montania", Devonian strata overstep the thin Sauk succession to lie on Middle Proterozoic strata.

Although tectonics clearly controlled the onlap and offlap of Sauk-type sequences, the cause of the Kaskaskian onlap successions in Western Canada is uncertain and much debated. The Kaskaskian sequence has two components. The Middle and Upper Devonian succession onlaps a major interregional unconformity, as noted above. The second Kaskaskian sub-sequence begins with the drowning of the Fammenian Palliser/Wabamun carbonate platform that covered most of the western margin. Renewed subsidence and subsequent deposition of a major shallowing upward carbonate succession dominates Kaskaskia II subsequence. This succession is of uncertain tectonic affinity in Canada, even though it temporally overlaps Antler orogenic events in the United States. Several regional relationships suggest the transformation of the Paleo-Pacific passive margin into an arc – back-arc basin pair, but throughout cratonic Western Canada, south of 60° N, there are no *bona fide* Antler structures and there is no indication of an orogenic source of sediments until Late Jurassic time.

Transformation From Passive Margin To Orogenic Foreland: The first established transformation of the Proto-Pacific passive margin into a foreland basin occurs with the appearance of westerly derived coarse clastics in Late Jurassic time. The Middle Proterozoic to Mesozoic succession was scraped off the North American plate by an overriding tectonic collage of allochthonous terranes that collided with and were accreted to North America between Middle Jurassic and Late Paleocene (Figures I-3, and I-4; Monger and Price, 1979; Gabrielse and Yorath, 1992; Monger, 1989). Thrusting and folding has thickened the northeastward-tapering sedimentary wedge by >10 km. This accretionary wedge flexed the continental lithosphere and formed a foreland basin, in which syntectonic sediments accumulated (Price, 1973; Beaumont, 1981; Peper, 1993). The accretionary

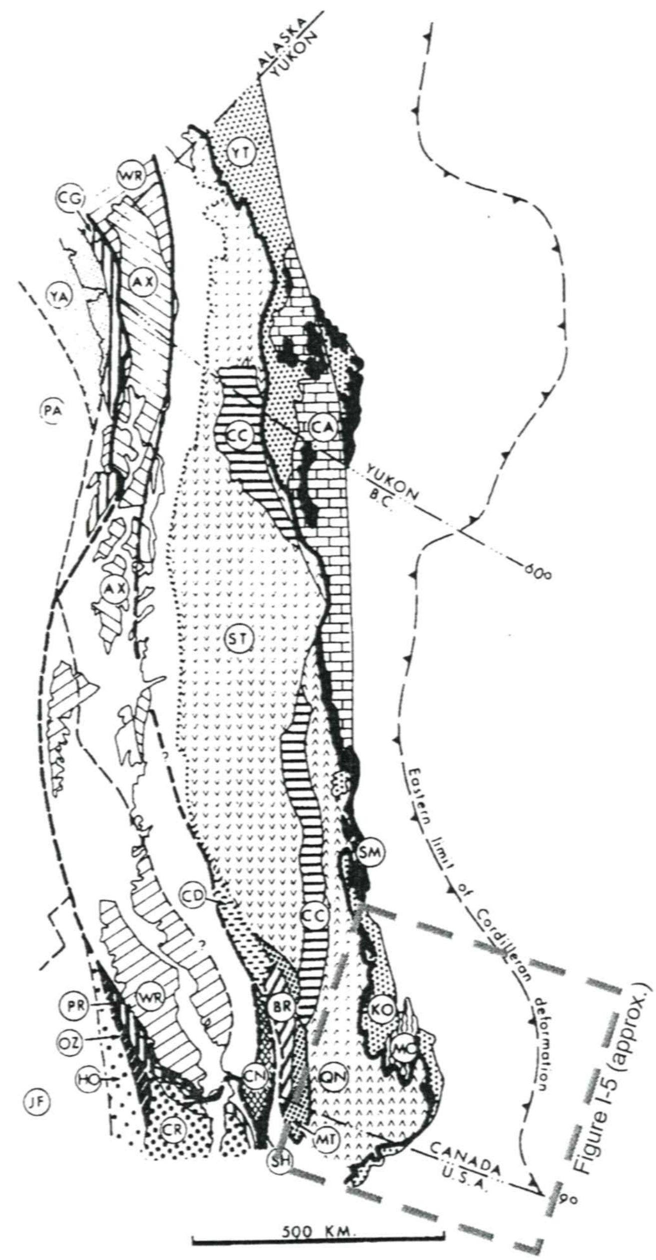


Figure I-3. Distribution of terraines in the Canadian Cordillera (modified from Monger et al., 1982).

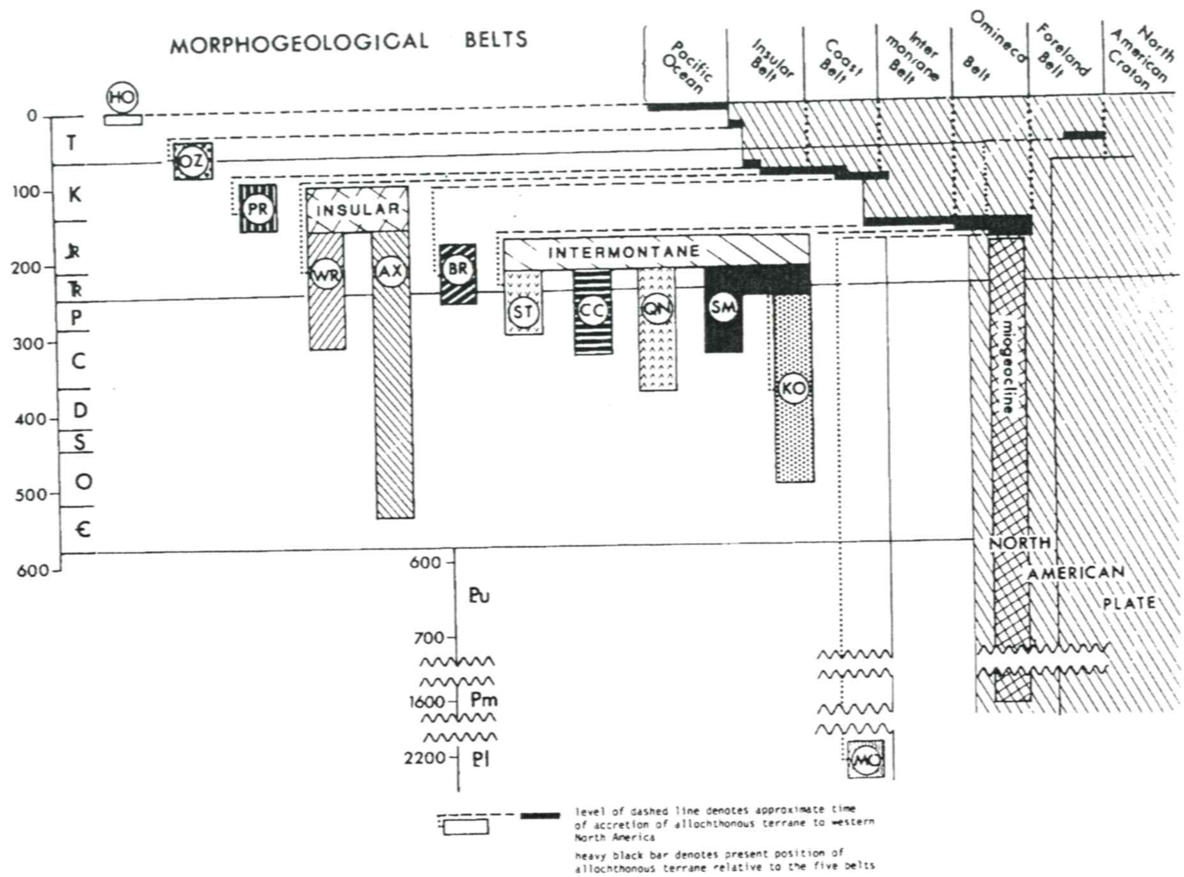


Figure I-4 Space and time relationships of suspect terranes in the southern Canadian Cordillera with the North American craton (see Figure I-3 for distribution of terranes). Figure shows (1) depositional time interval spanned by each terrane; (2) gaps between columns indicating unknown spatial relationships; (3) overlap assemblages that define superterranes, e.g. Insular and Intermontane assemblages; (4) hachured area showing western margin of continent built westwards by accretion of terranes; (5) spatial relationship of morphogeological belts to North American: accreted terrane boundaries; coincidence of high-grade metamorphic rocks in Omineca and Coast belts with boundaries of Intermontane and Insular superterranes suggests that these belts may be partly collisional in origin (modified from Monger et al., 1982).

Figure I-4. Timing of terrane accretion, southern Canadian Cordillera.

wedge and foreland basin extends into the United States (Jordan, 1981; Mudge, 1982).

Stott (1984) used stratigraphic analysis of the Upper Jurassic to Paleogene Foreland Basin succession to identify three orogenic phases. The three clastic "wedges" were: Upper Jurassic to Lower Cretaceous Fernie Formation-Kootenay Group; Lower Cretaceous Mannville Group; and the Lower Cretaceous-Paleogene post-Mannville Group succession. These were correlated with orogenic phases Columbian I, Columbian II and Laramide, respectively. The two older orogenic clastic wedges had Boreal faunas and prograded into a northern sea. The overlying Laramide clastic wedge contained a Gulfian fauna and was linked to the western Interior Seaway. The temporal and dynamic link among orogenic clastic wedges, the movement of individual structures and the accretionary growth of the western margin of North America are not well associated, either in time or space (cf., Cant and Stockmal, 1989; Stockmal et al., 1992).

The growing accretionary wedge encroached upon, and incorporated parts of its foreland basin (Bally et al., 1966; Price, 1973; Stockmal and Beaumont, 1987). Growth of the accretionary wedge probably ended in the Early and Middle Eocene when east-west crustal extension begins in the Omineca Belt (Carr et al., 1987). Underlying lithosphere has rebounded in response to thinning, uplift and erosion of the accretionary wedge and the accreted terranes (Beaumont, 1983; Stockmal and Beaumont, 1987). The documented, westerly increasing erosion is on the order of 2-3 km at the eastern edge of the Foothills (Magara, 1976; Hacquebard, 1977; Nurkowski, 1984; England and Bustin, 1986; Issler et al., 1990;

Majorowicz, 1990), and increases to >8 km where the Flathead Fault offsets the Lewis thrust sheet and preserves a sub-Lower Oligocene erosion surface (McMechan, 1981).

Part 2: Structural Setting

Basic Elements: All of the Western Canada Sedimentary Basin is deformed to some degree, and recent investigations suggest that the rather arbitrary and historical identification of major tectonic elements is a simplification. One major division, however, is very useful to employ. The Western Canada Sedimentary Basin is divided at either the surface trace of the easternmost thrust fault, or the hinge of the Alberta Syncline (the axis of the monoclinal fold which approximately overlies the tip of the triangle zone) into the Interior Platform Structural Province to the east and the Eastern Cordilleran Structural Province to the west (Douglas, 1970). This subdivision approximates the eastern limit of compressive deformation during Cordilleran orogenesis (Figures I-5, I-6, and I-7).

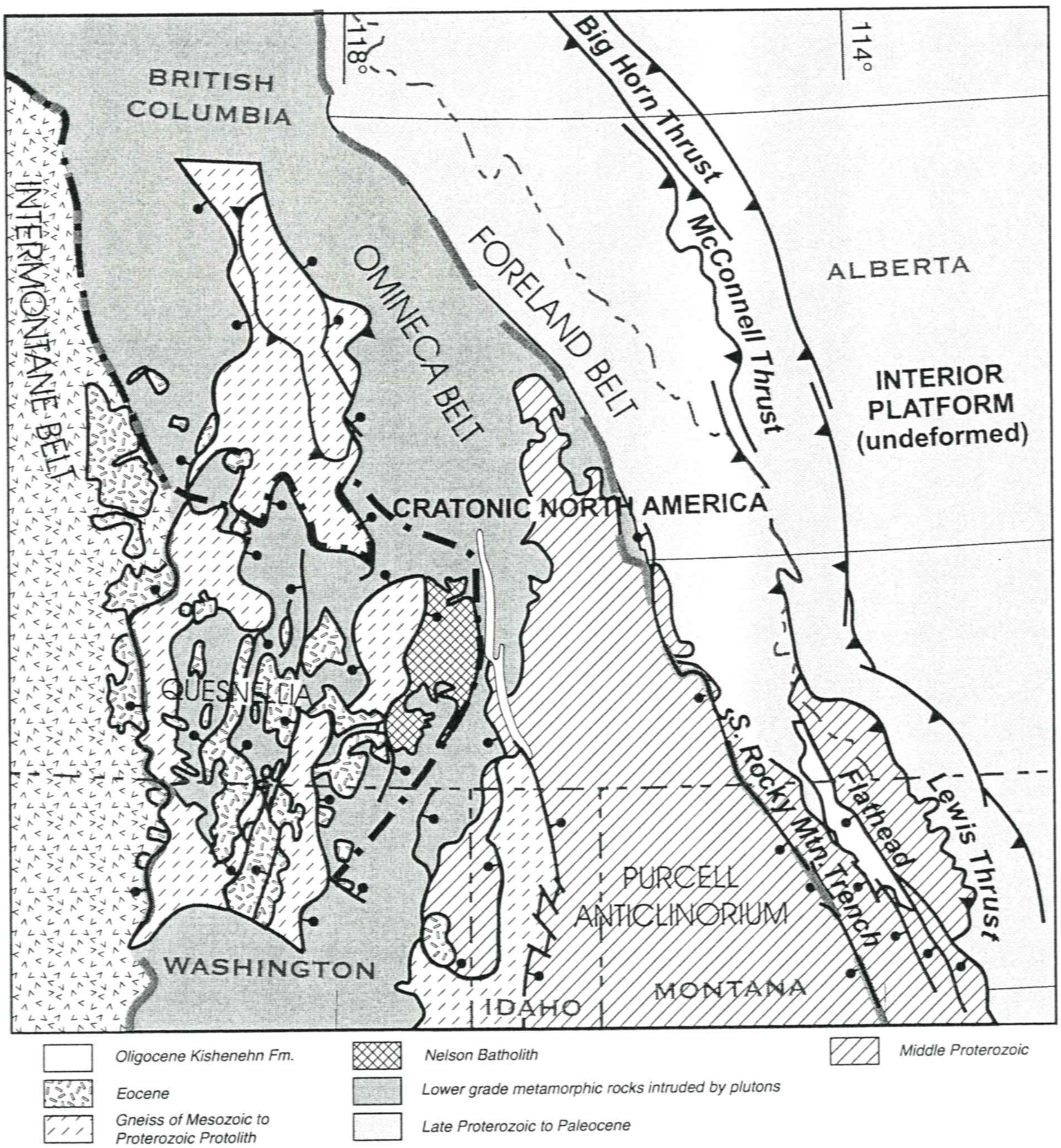


Figure I-5. Generalized map of the southeastern Canadian Cordillera, showing major compressional thrusts as well as major Cenozoic extensional faults.

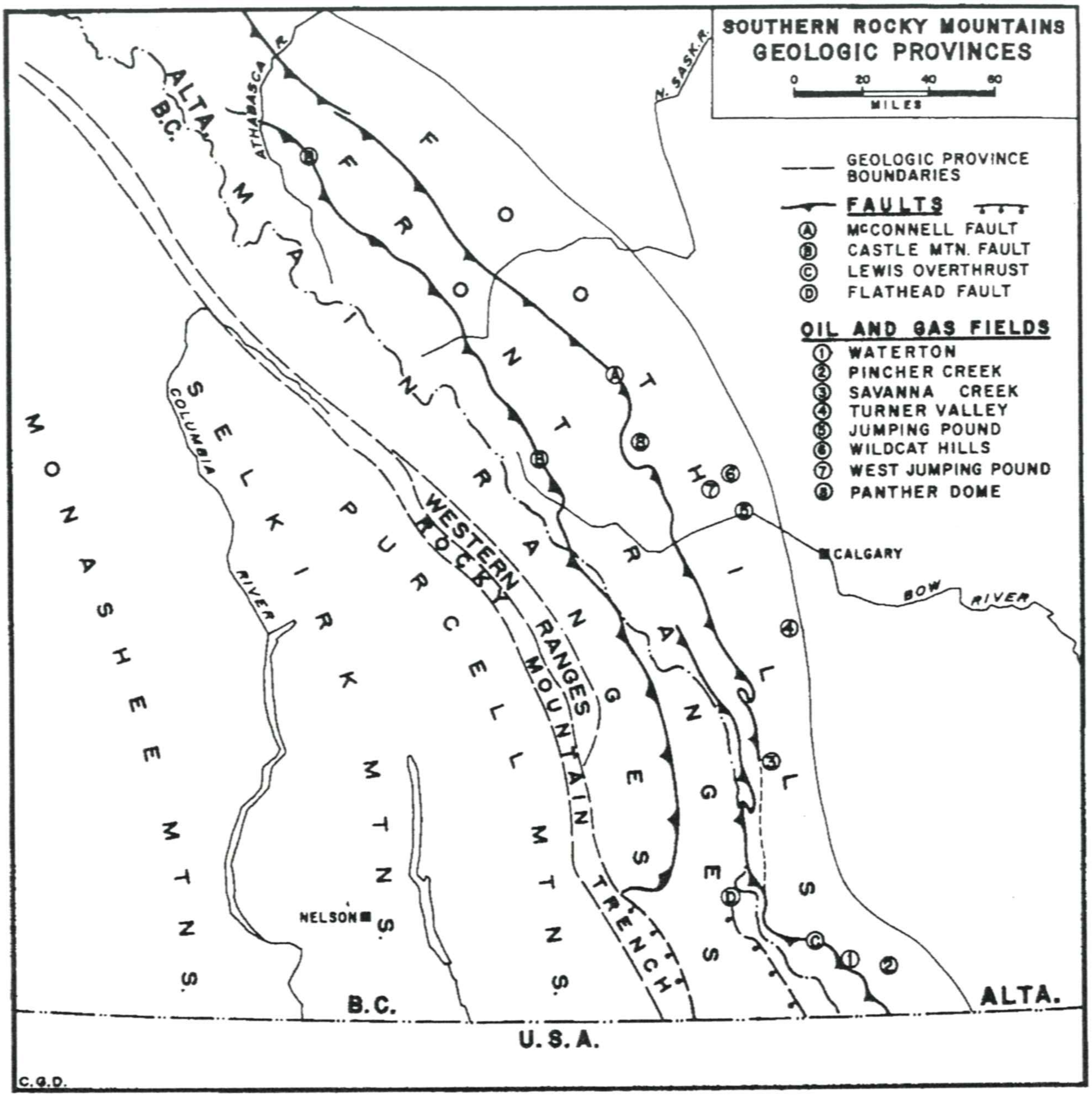


Figure I-6. Geological provinces of the Southern Canadian Rocky Mountains (from Bally et al., 1966).

Petroleum exploration in southwestern Alberta is limited to the Marginal Zone of the Eastern Cordillera, east of the Purcell Anticlinorium (Figure I-5), in the area where unmetamorphosed Paleozoic and Mesozoic rocks are preserved. The Marginal Zone of the Eastern Cordillera is commonly, and generally interchangeably, referred to by any of the following names: "Canadian Rocky Mountain Foreland thrust and fold belt", "Foreland Belt", "Disturbed Belt", "Overthrust Belt", "Thrust and Fold Belt", "Fold and Thrust Belt" – well you get the idea. The Marginal Zone is often also referred to as the "Foothills Belt", but this requires some careful qualification since it used both *sensu lato* to refer to the Marginal Zone of the Eastern Cordillera, including both the geographic foothills of the Rocky Mountains, *sensu stricto*, and portions of the Front Ranges of the Rocky Mountains.

Overlain on this terminological confusion is a rough equation between geology and geomorphology introduced in the southern portion of the Marginal Zone, but which has no applicability north of 54^{o}, about

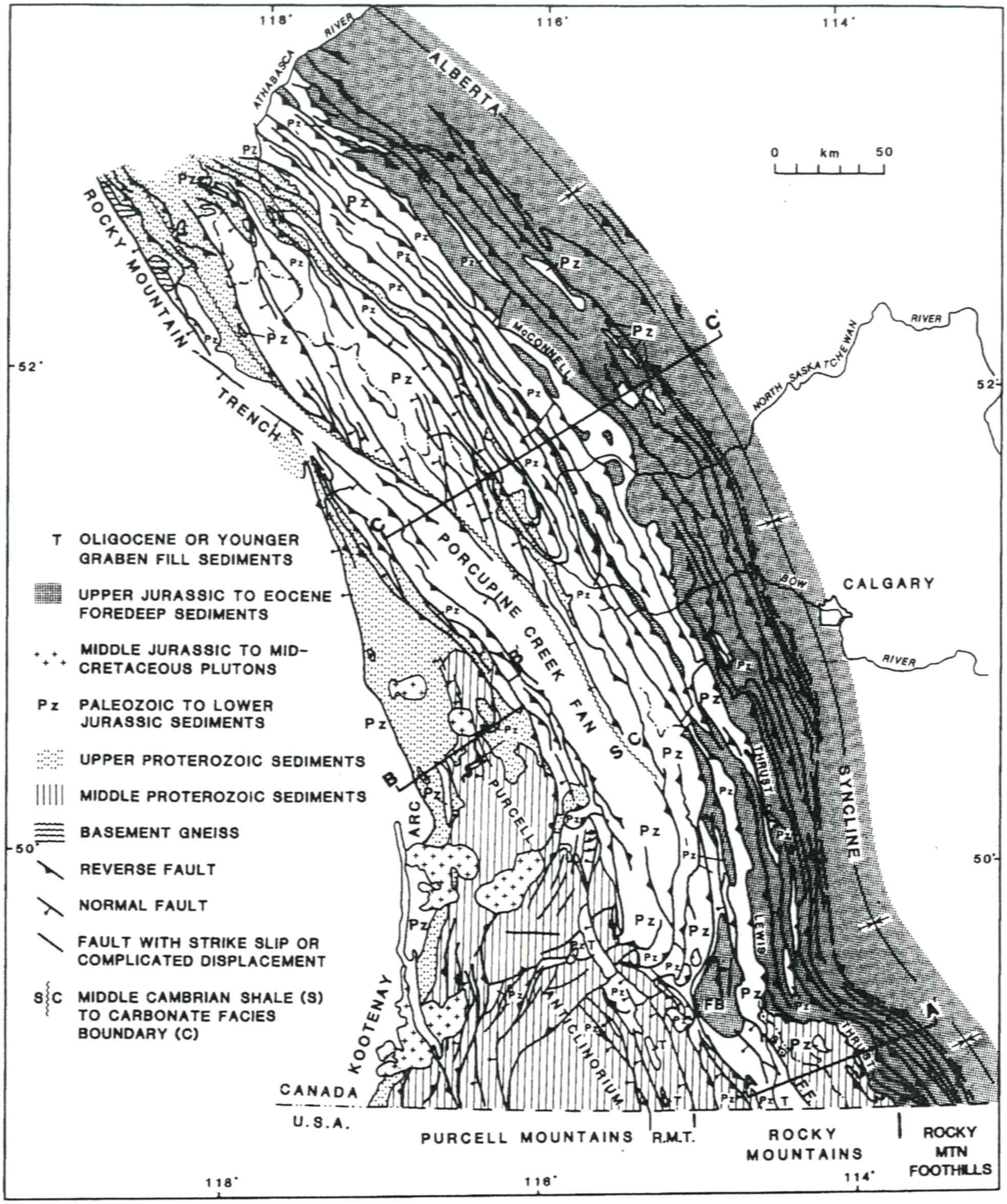


Figure I-7. Geological provinces of the Southern Canadian Rocky Mountains (simplified after Wheeler and McFeeley, 1987 from Bally et al., 1966).

the latitude of Edmonton. These definitions relate the current erosional level of outcropping structures to their geomorphic position. West of the frontal thrust that exposes Devonian or older strata in its hanging wall lie the Front Ranges of the Rocky Mountains (Figure I-6). To the east lie the Foothills, which are subdivided into the Inner Foothills, where individual thrusts expose Carboniferous strata in their hanging walls, and the

Outer Foothills, where strata younger than Carboniferous are exposed in thrust sheets. This set of definitions – although somewhat reflective of the "ramp and flat" nature of the major thrust faults and their trajectories up section toward the foreland – does not work in detail, even where it was erected (!). More importantly it obscures the true geometry of the overthrust sheets by focusing only on the strata exposed at the present erosion surface. Still, the general manifestations of this subdivision are real enough locally as the difference in topography and geology between Waterton and Blairmore shows (as clearly seen on Day 1). Similar subdivisions of the Front, Main, and Western ranges of the Rocky Mountains erected in the Banff to Golden area are also of limited geographic applicability (Figure I-6).

General Features of the Structural Style: Many structures have been mapped, named and analysed. The result of these investigations has been a comprehensive geometric and kinematic model of the Marginal Zone. Although the set of structural elements persists throughout the Marginal Zone, the structural and geomorphic style varies as a function of the position of the basal detachment, the magnitude of displacement, and the level of erosion. Throughout much of the Marginal Zone of the Eastern Cordillera penetrative strains are generally negligible so that volume, cross-sectional area, and bed length normal to the slip direction can be considered conserved. Beneath the Marginal Zone seismic experiments have indicated that rocks lying below the basal detachment are not involved in the deformation and that the basement, which dips smoothly to the west, is not involved. The basal detachment cuts deeper into the stratigraphic succession to the west and the movement on most (but definitely not all!) thrust faults is progressive from west to east with the youngest structures being the more easterly. Therefore, acceptable interpretations of the structure at depth must include or account for the complete volume (or cross sectional area) of the sedimentary succession above the position of the basal detachment. The test of any analysis is, therefore, the reconstruction of the predeformational sedimentary succession. This technique is called "palinspastic restoration" and shares many elements with the concept of "balanced cross sections". The geometric and kinematic principles of balancing cross sections is reviewed by a number of authors (Douglas, 1950; 1958; Dahlstrom, 1969; 1970; 1977). In practise the technique is only partly effective due to multiple detachments and lack of detailed information.

Southern Foreland Belt: The structural style of the Marginal Zone varies from south to north. In the southern Foreland Belt there are commonly three linear belts of distinctive style: the Foothills, Front Ranges, and Main Ranges of the Rocky Mountains (Figure I-6). The three belts reflect the progressive eastward change of the main detachment to progressively higher stratigraphic horizons. At the latitude of Calgary the bounding faults of these three belts are the Brazeau, McConnell and Bourgeau thrust faults, respectively. The Foothills are generally characterized by thrust faults that, at the erosion surface, have Tertiary and Mesozoic strata in their footwalls and either Mesozoic strata (Outer Foothills), or Carboniferous strata (Inner Foothills) in their hanging walls. The Front Ranges, marked by the Lewis and McConnell thrust faults (Figure I-6), thrust Devonian to Proterozoic strata onto Cretaceous formations at their eastern limit and are composed of thick sheets of predominantly carbonate strata that commonly overthrust Mesozoic strata preserved in the footwall sheet. The Main Ranges, are predominantly composed of Paleozoic and Proterozoic strata in areas where Mesozoic formations are not generally preserved.

Structure is dominated by discrete overthrust sheets and thrust faults with significant stratigraphic offset (Figure I-7). Much of the deformation occurs on major thrust faults with large displacements (Figure I-8). These faults show considerable supracrustal shortening and concentric folds commonly resulting from fault-bend folding of thrust plates accompanying the motion on younger, more easterly, thrusts (Dahlstrom, 1970). The Lewis Thrust is one of the largest structures and it typifies the structural elements of the southern Cordillera. Lewis Thrust is ~425 km in length, has a maximum displacement of ~70 km (plus 45 km more transport on underlying thrusts involving the Paleozoic section), and juxtaposes a very thick (>8 km) Middle Proterozoic to Turonian succession onto Maastrichtian and older strata (Price, 1965; Mudge and Earhart, 1980; van der Velden and Cook, 1994). The Clark Range is a fragment of the Lewis sheet, ~35 km wide, extending from an eroded leading edge near Waterton Alberta to its faulted western margin against Flathead half-graben (Figure I-9). Geological relationships around Flathead Fault constrain displacement on Lewis Thrust to occur between Maastrichtian and Middle Eocene. South of North Kootenay Pass, the Lewis sheet is cradled between underlying, antiformally stacked, duplexes in Phanerozoic carbonates forming Akamina Syncline (Figure I-9; Bally et al., 1966; Yin and Kelty, 1991; Fermor and Moffat, 1992; Boyer, 1992). These duplex structures contain large natural gas accumulations (Fritts and Klipping, 1987; Fermor and Moffat, 1992).

East of the Front Range thrust are the closely imbricated thrust sheets of the Foothills. Foothills structures are broadly folded like those of the Front Ranges, except that they reflect the migration of the basal detachment into progressively higher stratigraphic levels to the east (Figures I-8 and I-9). The Foothills structures extend eastward into a "triangle zone" or tectonic wedge (see Stop 1-1 discussion, below) that is bounded by a "roof" thrust, or upper detachment, which is hinterland-directed and into which the accretionary tectonic wedge has been inserted. This delamination of the sedimentary succession forms the east-dipping west limb of the Alberta Syncline (Figure I-7). The Alberta Syncline is an hermaphroditic, asymmetric fold. The fold is formed by the combination of the westward regional dip of the Precambrian basement and the overlying platform and foreland basin successions in its eastern limb, resulting from foreland loading and subsidence, and the west-verging thrust faults in its eastern limb, resulting from the triangle zone at the eastern margin of the Eastern Cordillera. The homocline of Lower Cretaceous and older rocks that forms the eastern limb of the Alberta syncline continues without folding past its hinge below the basal detachment of the accretionary wedge into the Foothills and Front Ranges. The generalized positions of the major southern Alberta Foothills gas fields are indicated in Figure I-10.

The eastern limb of the Alberta Syncline continues to the outcrop of the Paleozoic succession. On the northeastern edge of the Alberta Syncline the dissolution of Middle Devonian salts reaches a short distance down-dip of the erosional edge of Cretaceous rooks. Although the salt collapse structure plays an important role in the localization of the bituminous sand deposits it affects a relatively small portion of this tectonic element.

During the late middle Eocene Lewis sheet was cut by Flathead Normal Fault, the trace of which now roughly follows the eastern side of Flathead Valley (Figure I-9; Price, 1965; McMechan, 1981; Constenius, 1996). This extension, a not uncommon feature of the

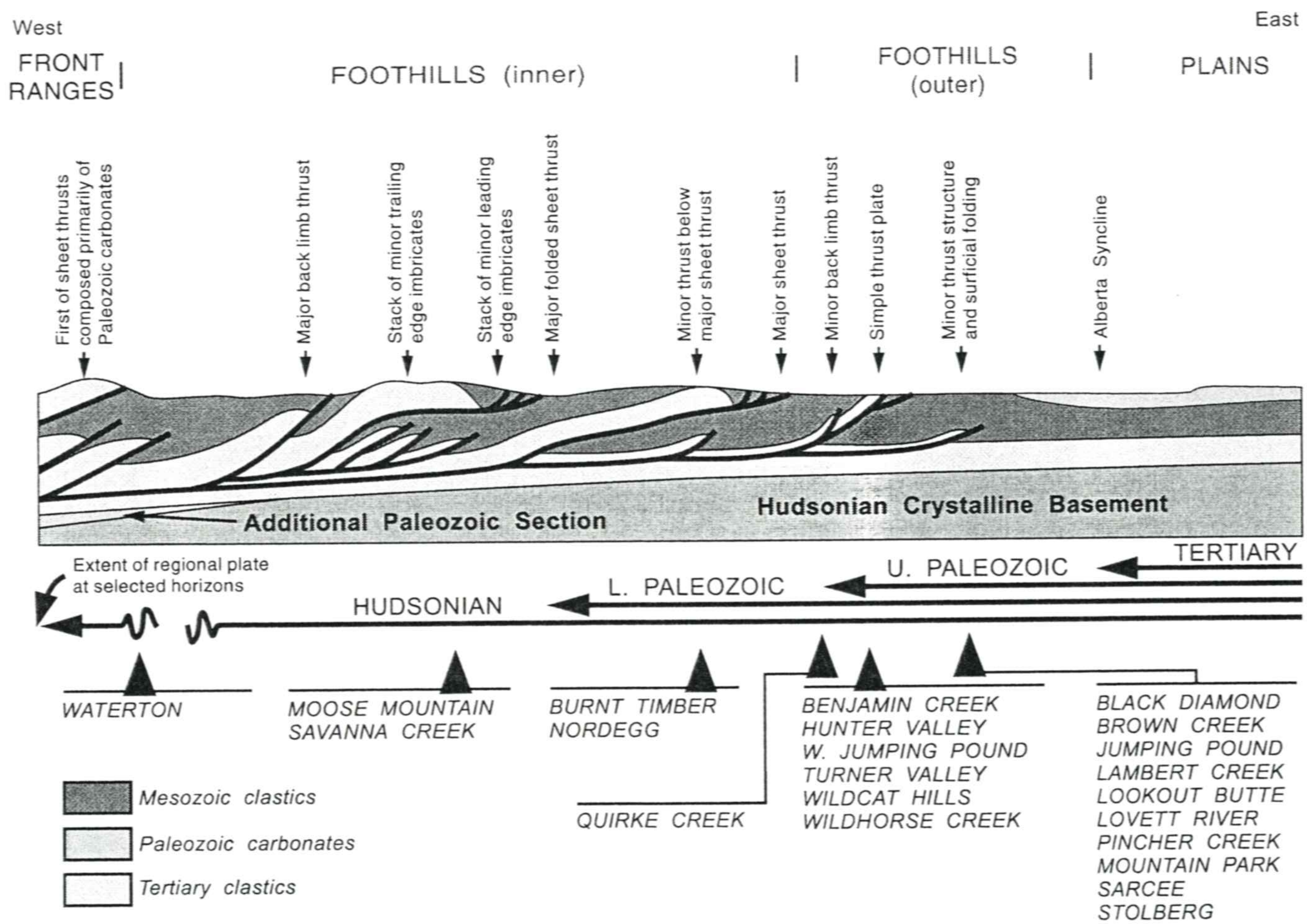
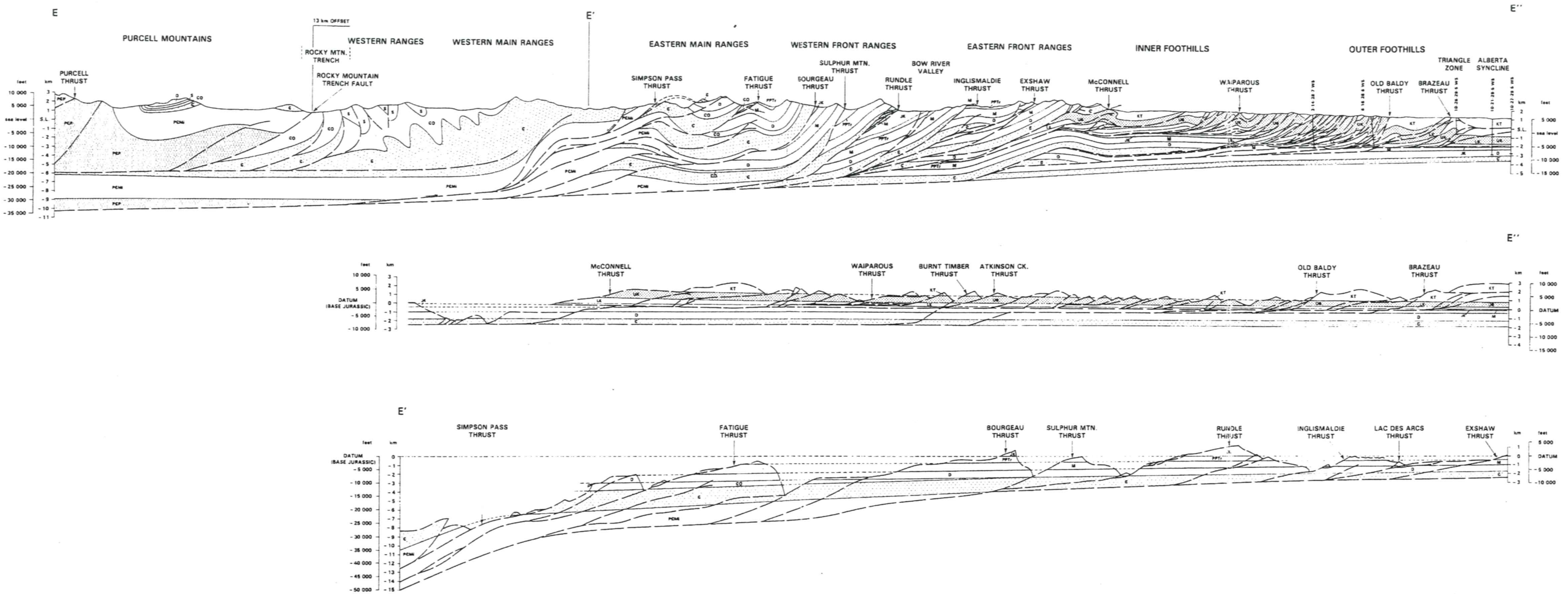
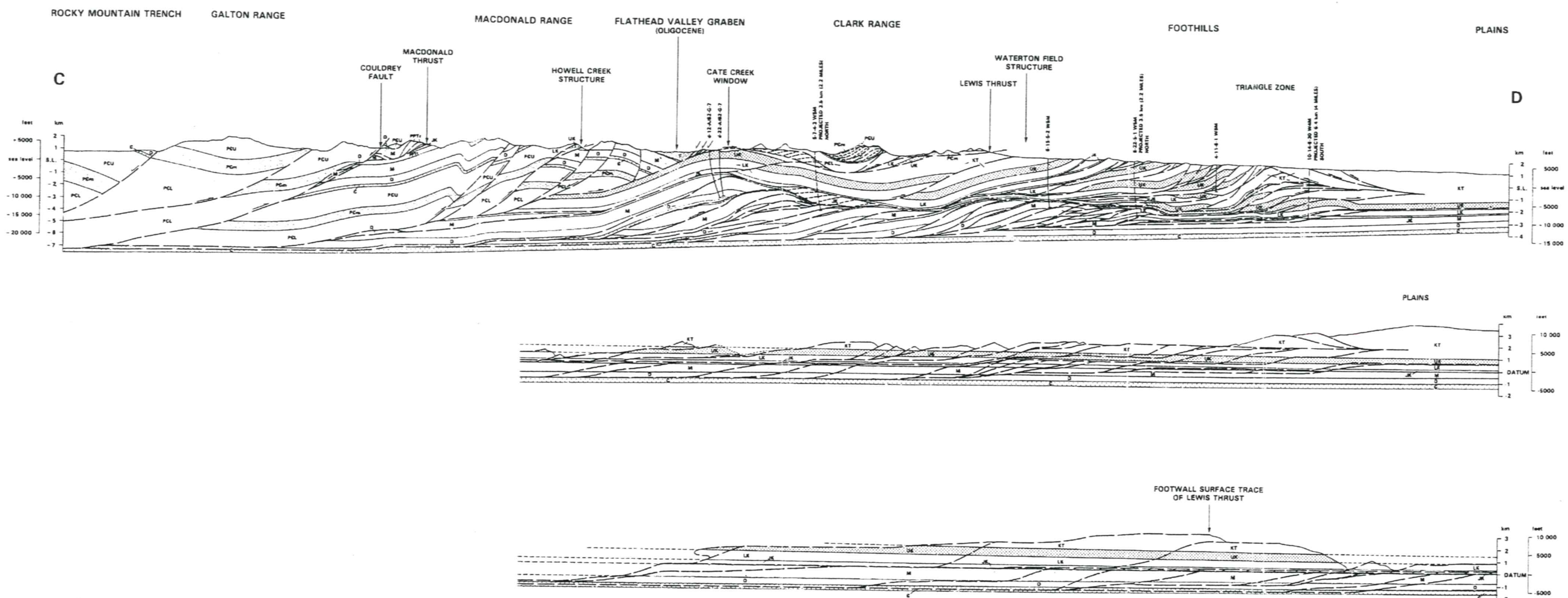


Figure I-10. Schematic cross section of structural styles of Foothills gas plays (from Dahlstrom, 1970).



Cross section and accompanying palinspastic restoration of the Foothills belt, Rocky Mountains, and eastern Purcell Mountains in the area west and southwest of Calgary. Location of section (E-E'-E") is shown in Figure 2. Note 13-km offset at location of Rocky Mountain trench; western portion of cross section offset to south. The accompanying palinspastic restoration covers only the eastern portion of the section between points E' and E". Stratigraphic abbreviations are as follows. PєP: Proterozoic Purcell Supergroup (shelf carbonates and clastics); PєMi: Late Proterozoic Miette Group (clastics); є: Cambrian (shelf carbonates and clastics to east, deeper-water shaly carbonates to west); єO: Cambrian-Ordovician (shelf carbonates and shales to east, and shelf carbonates and deeper-water shaly carbonates to west); S: Silurian (shelf carbonates and clastics); D: Devonian (shelf carbonates); M: Mississippian (shelf carbonates and shales); PPTr: Permian-Pennsylvanian and Triassic (shelf clastics and carbonates); JK: Jurassic-Lower Cretaceous (deeper-water shales and foredeep clastics); UK: Upper Cretaceous (marine shales and minor sands); KT: Upper Cretaceous and Tertiary (foredeep clastics). The interpretation drawn in the cross section shows Jurassic and Cretaceous strata in the western portion of the Foothills detached from older strata along a thrust fault that has been cut by later displacement on the McConnell thrust. As a result, in the palinspastic restoration the restored Jurassic-Cretaceous strata of the western Foothills "overhang" the restored positions of older strata. An alternative (and perhaps likelier) interpretation would be that the McConnell thrust follows the thrust detachment at the base of the Jurassic section for some considerable distance downdip and to the west before cutting downsection in its footwall into Paleozoic strata. Such an interpretation would result in a palinspastic restoration without the "overhang" shown here. The subsurface geometry shown in the foothills portion of the cross section is based on well control and published seismic sections. Reproduced with modifications from Price and Fermor (1985), with permission of the Geological Survey of Canada.

Figure I-8. Cross section and palinspastic restoration west and southwest of Calgary (from Fermor and Moffat, 1992).



Cross section and accompanying palinspastic restoration of the Foothills belt and Rocky Mountains in the area north of the Canada-U.S. boundary. Location of the section (C-D) is shown in Figure 2. The accompanying palinspastic restoration covers only the eastern portion of the cross section—that is, the Foothills and equivalent structures in the footwall of the Lewis thrust. Stratigraphic abbreviations are as follows. PεL: lower part of Proterozoic Purcell Supergroup (shelf carbonates and deeper-water shales); PεM: middle part of Proterozoic Purcell Supergroup (shelf carbonate); PεU: upper part of Proterozoic Purcell Supergroup (shelf carbonates, clastics, and minor volcanics); ε: Cambrian (shelf carbonates and clastics); D: Devonian (shelf carbonates); M: Mississippian (shelf carbonates and clastics); PPTr: Permian-Pennsylvanian and Triassic (shelf clastics and carbonates); JK: Jurassic-Lower Cretaceous (deeper-water shales and foredeep clastics); UK: Upper Cretaceous and Tertiary (foredeep clastics); T: Oligocene synorogenic clastic graben fill. Note small "overhang" at western end of palinspastic restoration, bounded by "S-shaped" restored fault trajectory. This is the restored position of an overturned fault slice inferred to be present in the footwall of the Lewis thrust. The restored fault trajectory is "impossible" and implies that the fault slice geometry has been modified subsequent to its involvement in deformation. The subsurface structure shown in the eastern portion of the cross section is based on well control and published seismic sections.

Figure I-9. Cross section and palinspastic restoration north of Waterton National Park (from Fermor and Moffat, 1992).

southernmost Foreland Belt, was previously of uncertain association, but is now (Constenius, 1996) temporally associated with the crustal extension in the Omenica Belt (Carr, 1992). Flathead Fault merges listrically downward with Lewis Thrust, west of the duplex underlying the west limb of Akamina Syncline (Figure I-9; McMechan, 1981). West of Flathead Fault, Lewis sheet Middle Proterozoic strata overlie the regional detachment near basement. Phanerozoic strata above Flathead Fault have rotated into the fault, forming MacDonald Dome (McMechan, 1981). In the half-graben, Lower Oligocene Kishenehn Formation, at least 3.35 km in thickness, but possible approaching ~10 km thick, (McMechan and Price, 1980; Constenius, 1988) unconformably overlies Lower Cretaceous Blairmore Group (Price, 1965). This relationship, and the provenance of Kishenehn Formation fanglomerates, shows Lewis sheet was still >8 km thick in the Early Oligocene (McMechan, 1981). Subsequent erosion has exposed strata below Lewis Thrust.

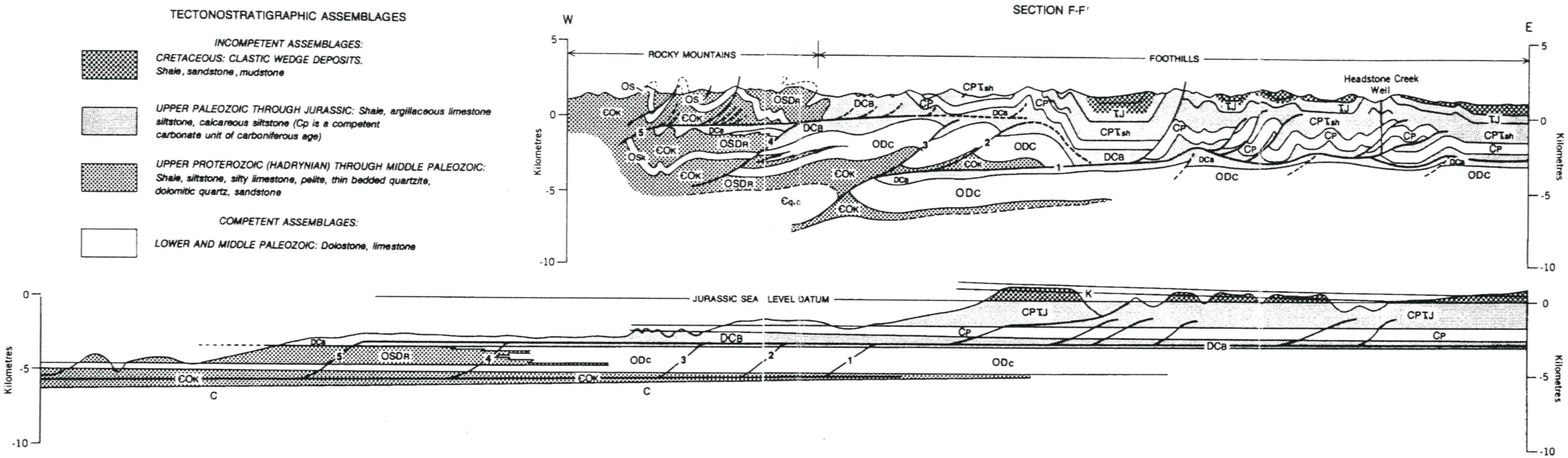
Central and Northern Foreland Belt: The change in structural style from south to north follows changes in the lithological composition of the sedimentary prism. To the north thick mudrock-dominated formations of Paleozoic age replace the carbonate platforms that characterize the southern terrane. To the north, in the central and northern parts of the Eastern Marginal zone the terrane is dominated at outcrop by large amplitude box and chevron style folds and thrust faults with little stratigraphic separation and apparently less shortening than to the south (Figure I-11).

North of the Peace River (56°N) , thrust faults cutting the Paleozoic carbonates disappear eastward and along strike into a thick late Paleozoic marine shale sequence apparently without compensating shortening in the east. These observations are explained if the thrust sheets of Paleozoic carbonates are "blind" in a tectonic wedge with its floor in the Paleozoic carbonate succession and its roof within late Paleozoic shales (Thompson, 1979). The upper detachment of the "blind" thrust acts as a lower detachment for an overlying panel of tightly folded Mesozoic strata. Thompson (1979) suggests the orogen-vergent thrust emerges within a monotonous and poorly exposed shale succession where it is not observed.

Age of the Deformation: The age and timing of the deformation is not well constrained, largely because of the substantial erosion of the Eastern Marginal Zone and western Interior Platform following the Laramide Orogeny. Unlike the American Foreland Structural Province there are no syndepositional sedimentary deposits to constrain the age of the structures. Major thrust faults within the Purcell Anticlinorium are cut by an early Cretaceous post-kinematic magmatic suite. Price and Mountjoy (1973) projected thickness and grain size trends in the Kootenay Group onto palinspastic reconstructions and suggested that the Bourgeau Thrust and the western side of the Fernie Synclinorium lay near the limit of the Lower Cretaceous Columbian orogen. However, the conglomeratic member of the Blairmore Group, like that behind the Frank Slide interpretation centre (seen on Day 2 of the trip; Leckie and Krystinik, 1995) show that rudaceous lithologies can form 100's of km east of the deformation front. Recently, the recognition of Maastrichtian strata in the footwall of the Lewis thrust fault (Jerzykiewicz et al., 1996) and the thermal history analysis of the Lewis Thrust Sheet (Osadetz et al., 1995) indicate a profound cooling of the Lewis thrust sheet at about the time the youngest sediments were being deposited in its footwall. This dates motion on Lewis Thrust as Maastrichtian, very nearly coincident with the transgression of the Bearpaw Sea, as might be expected from the tectonic loading associated with the motion of Lewis thrust sheet. Deformation probably continued into the Eocene as strata of latest Paleocene age are involved in Laramide structures in Coal Valley area, Alberta. Normal faulting and graben formation cutting the Lewis overthrust sheet in the Flathead River area of British Columbia is middle Eocene in age (Constenius, 1996). Graben-filling Kishenehn Formation lies on a pre-epeirogenic erosional surface that had entirely removed the upper Albian and younger succession from Lewis thrust sheet. The timing of the deformation can be no better constrained and the motion of individual Laramide structures is generally unknown.

Part 3: An Introduction to Upper Cretaceous and Tertiary Stratigraphy

In much of the often till-covered Outer Foothills of southern Alberta, only Upper Cretaceous and Tertiary rocks are exposed. The correlation of stratigraphic units from the Interior Platform into the Foothills and the definition of new map units has allowed recent regional mapping to outline structures in greater detail. The Upper Cretaceous succession results from a complex history in the southern Alberta Plains and Foothills. The succession that commonly crops out in the Alberta Foothills (Figure I-12) is equivalent to the Colorado Group (shale), Eagle Formation (sandstone), Claggett Formation (shale), Judith River Formation (sandstone) and Bearpaw Formation (shale) typical of north-central Montana.



Structural styles of the eastern part of the northern Rocky Mountains and Foothills subprovince where thick competent Middle Proterozoic strata are absent. Section location shown by F-F' in Figure 4.21 (after Thompson, 1981).

Figure I-11. Cross section and palinspastic restoration, northern Rocky Mountains and Foothills, northeastern British Columbia (from McMechan and Thompson, 1989).

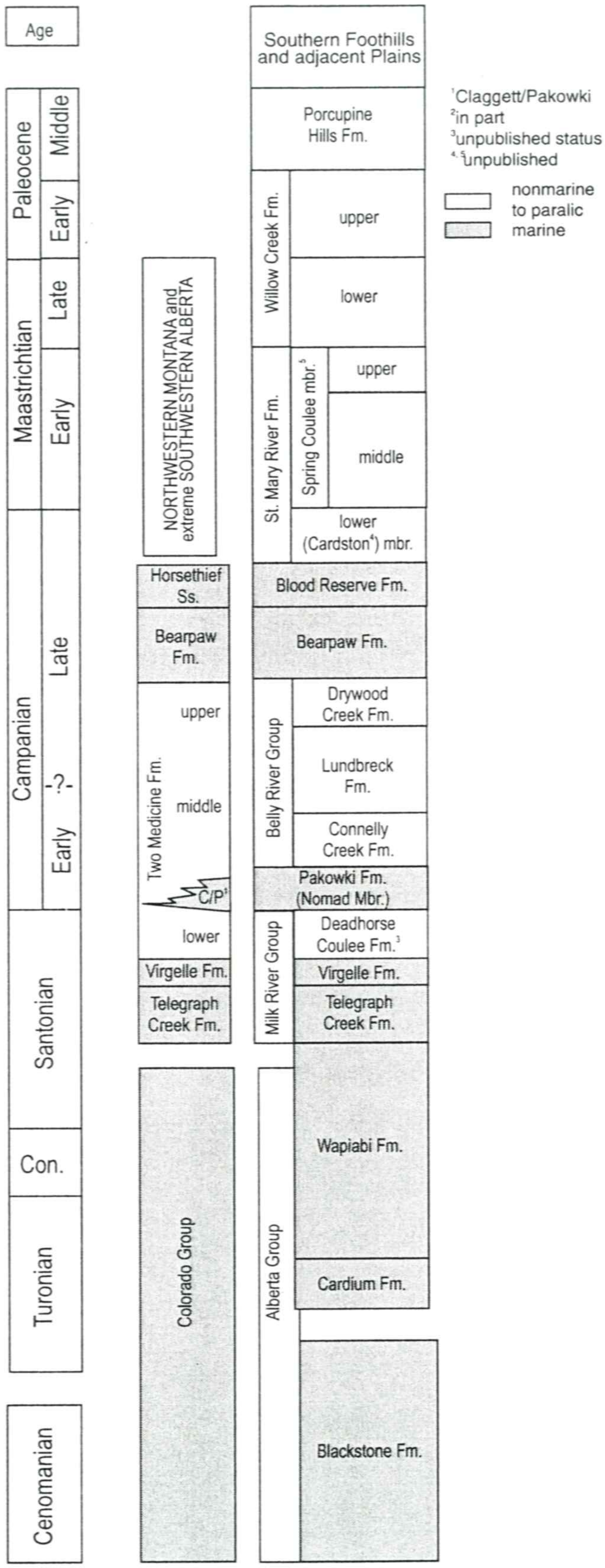


Figure I-12. Upper Cretaceous and Tertiary stratigraphy, southern Alberta Foothills and Plains, and northwestern Montana.

The Upper Cretaceous (Cenomanian to Santonian) Alberta Group (Stott, 1963) includes Blackstone, Cardium, and Wapiabi formations, in ascending order (Figure I-12). All units thicken to the west, consistent with their being deposited in the Laramide foreland basin; stated thicknesses apply generally to the Outer Foothills. The Blackstone Formation, dark grey shale and siltstone, is on the order of 150 to 300 metres thick. Overlying the Blackstone is the Cardium Formation, fine to medium grained, dark-grey sandstone with interbeds of siltstone and silty shale, and commonly 40 metres thick. The overlying Wapiabi Formation, dark grey silty shale and lesser sandstone is about 250 to 300 metres thick. Portions of the Alberta Group up to and including the Thistle Member of the Wapiabi Formation are equivalent to the Colorado Group of the Plains.

The uppermost member of the Wapiabi Formation, the Thistle Member, a "speckled" (coccolithic) shale, is overlain by the Santonian Milk River Group (formerly the Chungo Member, of either the Wapiabi or Belly River formations). The Milk River Group (Figure I-12) has a total thickness of approximately 150 metres, and includes the Telegraph Creek, Virgelle, and Deadhorse Coulee formations, in ascending order. The Milk River Formation is overlain by the earliest Campanian Pakowki Formation (formerly Nomad Member) marine shale, which thickens to the east but is on the order of 25 metres thick or less in the Outer Foothills. The Milk River and Pakowki terminology has been "imported" from the subsurface of the Plains (Stockmal, 1995). The Milk River/Chungo sandstones and Pakowki/Nomad shale are equivalent to the Eagle and Claggett Formations of the Montana Plains.

The Campanian Belly River Formation (Dawson, 1883), now elevated to Group status, overlies the Milk River Group (Figure I-12). The Belly River Group includes the Connelly Creek, Lundbreck, and Drywood Creek formations, in ascending order (Jerzykiewicz and Norris, 1994), though these units are not clearly mappable everywhere. Commonly yellowish-green to beige, fine to occasionally coarse grained sandstone, it often shows rusty iron staining and well developed sedimentary structures with interbeds of light green shale and thin coals in its upper part, especially just downstream of the Lundbreck Falls stop (Stop 1-6). Approximately 450 metres thick in the Blairmore map area, the Belly River Group thickens westward to approximately 1370 metres near the Lewis Thrust Fault. Douglas (1952) mapped the Chungo and Nomad members in the lower Belly River Formation throughout this area.

Working from the Plains, Hamblin (1997) suggested that the Connelly Creek, Lundbreck and Drywood Creek succession was generally correlative to the Foremost (recessive, thick and thin fining upward fluvial deposits overlying a thick marine shoreface sandstone) , Oldman (stacked incised valley fill channel units) and Dinosaur Park (a disconformably overlying, onlapping estuarine and shoreface deposit) formations of the Belly River Group to the east (Figure I-13). The Oldman Formation is present throughout southern and central Alberta, as a result of both depositional thinning and truncation below the Dinosaur Park Formation. The Oldman Formation is informally divided into two mappable units (Hamblin, 1997), the lower Comrey Member sandstone and the "upper siltstone" member. The Comrey Member consists of light grey, fine to coarse grained, stacked channel sandstones that have a sheet-like geometry (Figure I-13). Variations in Comrey Member thickness suggest that it is arranged in sharp-based linear WSW/ ENE-oriented incised valley fill trends, up to 33 m thick, composed of stacked lenticular fining-upward channel units. Paleoflow within these valleys was eastward. Potential reservoir intervals are up to 25 m thick. The "upper siltstone" member, thinly interbedded, noncalcareous mudstone and fine sandstone, is characteristically pale-coloured with abundant rooting and pedogenic horizons.

The Late Campanian Bearpaw Formation overlies the Belly River Group (Figure I-12) with a sharp, but conformable contact. The basal part of the Bearpaw Formation, dark grey marine shale, is overlain by interbedded dark grey, thin-bedded to fissile shale and grey to reddish-brown grey weathering coarse grained, cross-bedded sandstone (Douglas, 1950) that together are approximately 100 metres thick. Overlying the Bearpaw Formation are the Late Campanian Blood Reserve Formation (shoreface sandstone; occurs only in the southernmost Foothills) and latest Campanian to Maastrichtian St. Mary River Formations (nonmarine) that are on the order of 80 and 600 metres in thickness, respectively. These are in turn overlain by the nonmarine Late Maastrichtian to Early Paleocene Willow Creek Formation (850 m) and the nonmarine Early Paleocene Porcupine Hills Formation, respectively (Figure I-12). The Cretaceous-Tertiary boundary has been identified within the Willow Creek Formation (T. Jerzykiewicz and A. Sweet, pers. comm., 1993).

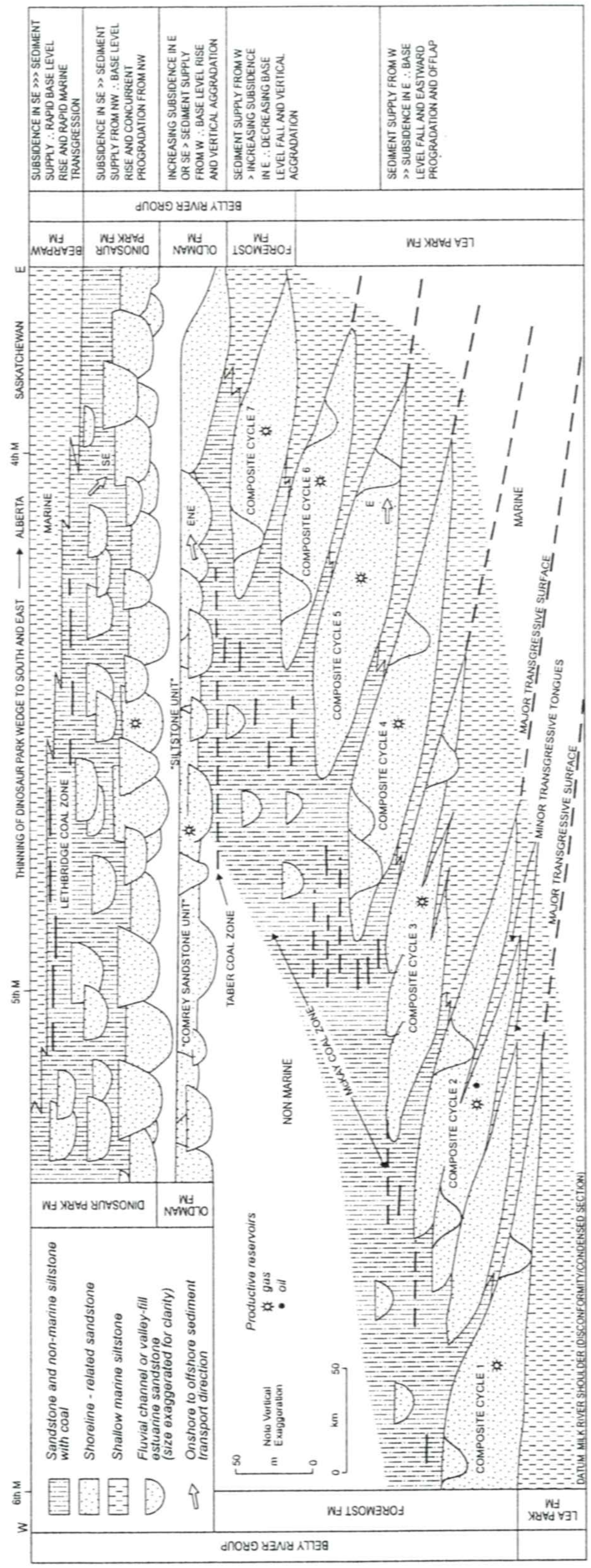


Figure I-13. Schematic west-east cross section illustrating complex internal architecture and tectono-stratigraphic interpretations of Belly River Group, southern Alberta (from Hamblin, 1997).

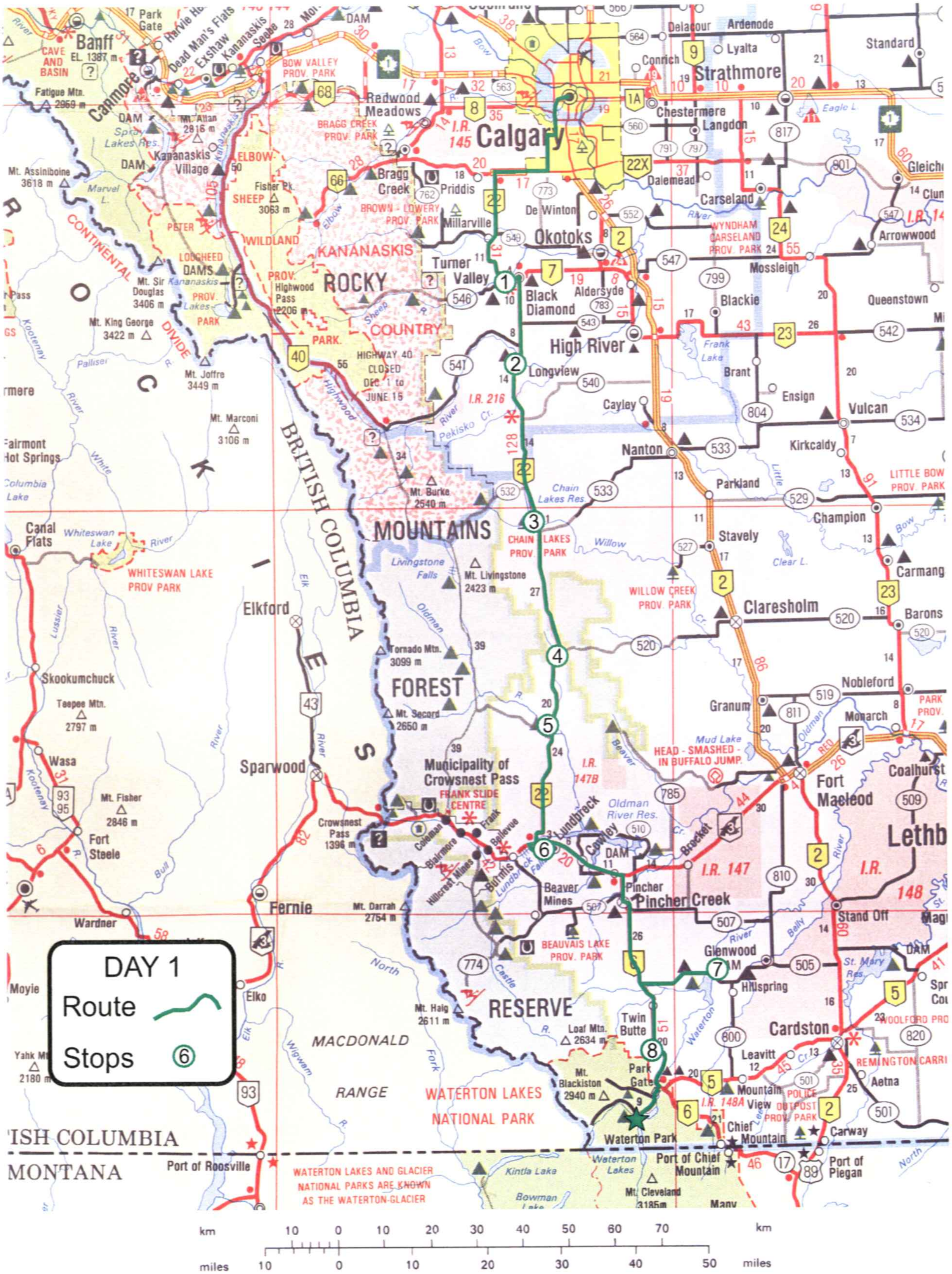


Figure 1-0-1. Road map of southern Alberta showing the route and stop locations for Day 1.

DAY ONE

The Triangle Zone from Turner Valley to Waterton National Park

(refer to Figure 1-0-1)

General Directions from Southwest Calgary:

Proceed through southwest Calgary to the intersection of Anderson Road and 37th Street SW. Turn south (left).

0.00 km Intersection of Anderson Road and 37th Street SW – drive south on 37th Street

2.40 km Cross bridge over Fish Creek (far west end of Fish Creek Provincial Park, the largest "urban" park in Canada)

3.20 km T-junction; **turn west (right)**

3.45 km T-junction; **turn south (left)** onto Route 773

6.70 km Junction of Route 773 and Highway 22X; stop and turn west (right)

11.60 km Calgary city limit

17.80 km Junction of Highway 22X with Highway 22 – **TURN SOUTH (LEFT)** and follow Highway 22 south to Turner Valley

45.60 km Four-way Stop in centre of Turner Valley – proceed straight through to south

46.55 km T-junction – turn east (left)

47.20 km Hell's Half Acre Bridge, across the Sheep River

47.30 km **Stop 1**; park on the east side of the road

Reset odometer to ZERO.

Stop 1: Hell's Half Acre, Turner Valley.

Distance: 0.0 km (47.30 km from intersection of Anderson Road and 37th Street, Southwest Calgary)

Access: Parking is available on the south side of Hell's Half Acre bridge, east (left) of the road.

Theme: Historical overview, Foothills structure, introduction to the triangle zone.

Purpose: (1) overview of Day 1, (2) introduction to guidebook description of the triangle zone and discuss the Turner Valley structures, and (3) view "natural gas seepage" on the bank of the Sheep River.

Geology: At this location (Figure 1-1-1), we are on the crest of the Turner Valley structure, underlain by a blind thrust carrying a Mississippian carbonate thrust sheet and expressed at the surface as a broad fold culmination in the Late Cretaceous clastic foreland succession. The generalized stratigraphy of the southern Alberta Foothills is summarized in Figure 1-1-2, which also shows those units which act as major detachment horizons (large black arrows) and lesser but still significant detachments (smaller grey arrows). Surface exposures within most Foothills map-sheets considered here are dominated by Cretaceous and Tertiary strata of the foreland basin succession, which are marine and nonmarine siliciclastics. Underlying platformal carbonates of Carboniferous age, the principal target here at Turner Valley and elsewhere in the Foothills, crop out to the west within the "Inner Foothills". The Turner Valley field is the southernmost of a series of gas fields west of Calgary at or very near the edge of significant Cordilleran deformation (Figure 1-1-3).

Facing northeast, a fenced, burning, natural gas seepage can be seen on the north bank of the Sheep River (Figure 1-1-4). This seepage is reported to be either the site where William Herron cooked his famous "shore lunch" (see historical discussion in Appendix 1 under "Turner Valley"), or just seepage from around the split casing of an old well.

The west-dipping outcrop seen adjacent to the seep is the Ram Member of the Turonian Cardium Formation. It lies on the west limb of an anticline, which is the westernmost fold of an anticline-syncline-anticline triplet mappable within the antiformal core of the Turner Valley structure (Figure 1-1-1). This antiformal culmination is the surface expression of the crest of the triangle zone.

The Triangle Zone: A triangle zone (a thin-skinned "tectonic wedge") is defined by (1) a basal decollement, which is foreland-directed, (2) an upper detachment, which is hinterland-directed (a backthrust), and (3) the first, emergent, foreland-directed thrust adjacent to the upper detachment (Figure 1-1-5). These three faults form a triangular region, hence the descriptive term (Gordy et al., 1977). The triangle zone is commonly filled with "blind" duplex and/or antiformal stack structures, whose displacement is transferred to the upper detachment. Additional back-thrusts may or may not be present above the upper detachment.

Three variations on the basic triangle zone geometry, applicable to the area in southern Alberta, are considered here (Figure 1-1-6). The simplest style is that of a "passive roof duplex", where strata above the upper detachment are folded passively in a broad monocline, but not otherwise significantly deformed. Associated minor structures are dominantly foreland-vergent. Alternatively, strata above the upper

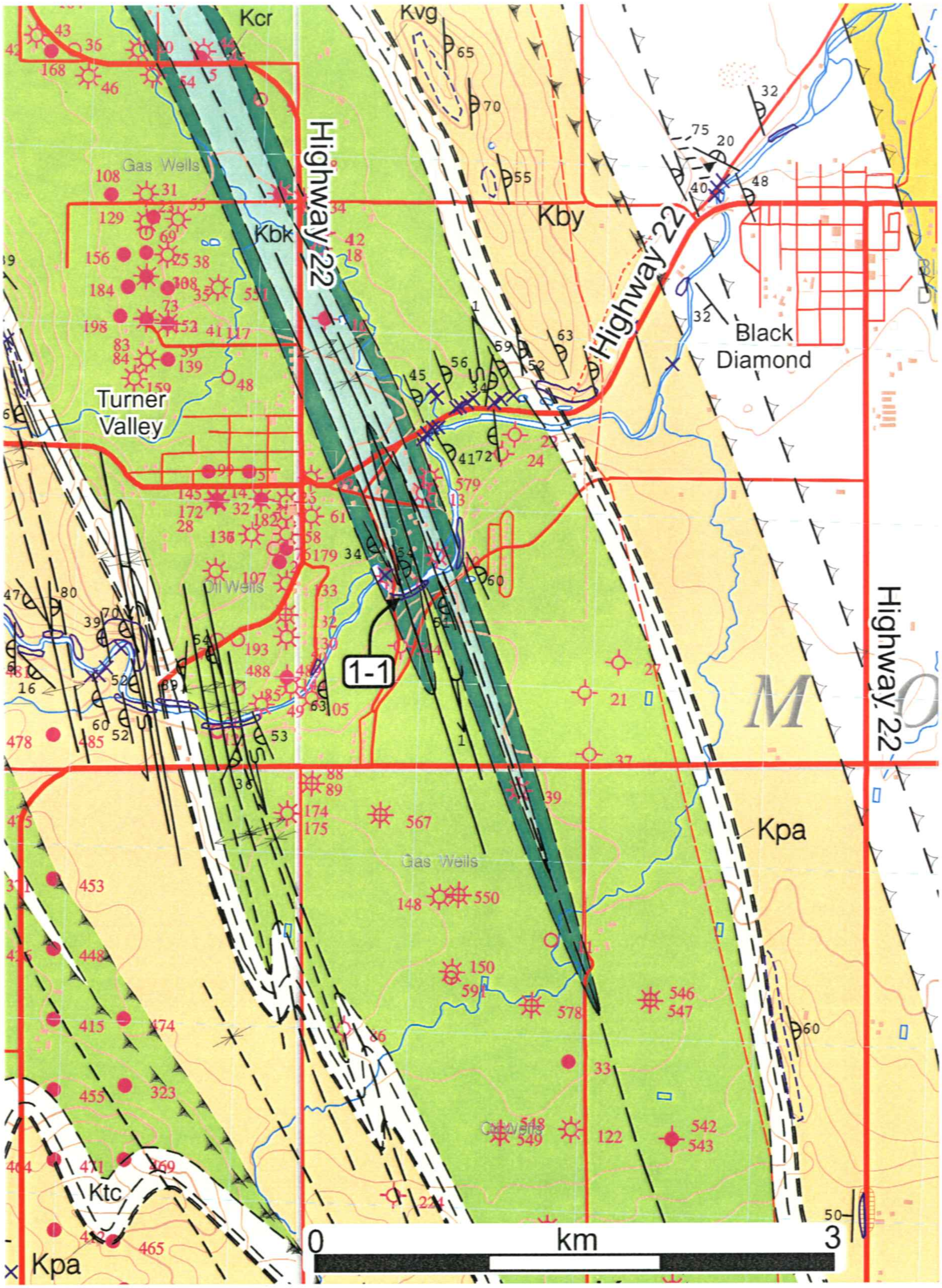


Figure 1-1-1. Detail of GSC Open File #3875, map of Turner Valley (Lebel and Kisilevsky, 2000), centred on approximately 50°40'00"N, 114°15'30"W, showing location of Stop 1-1.

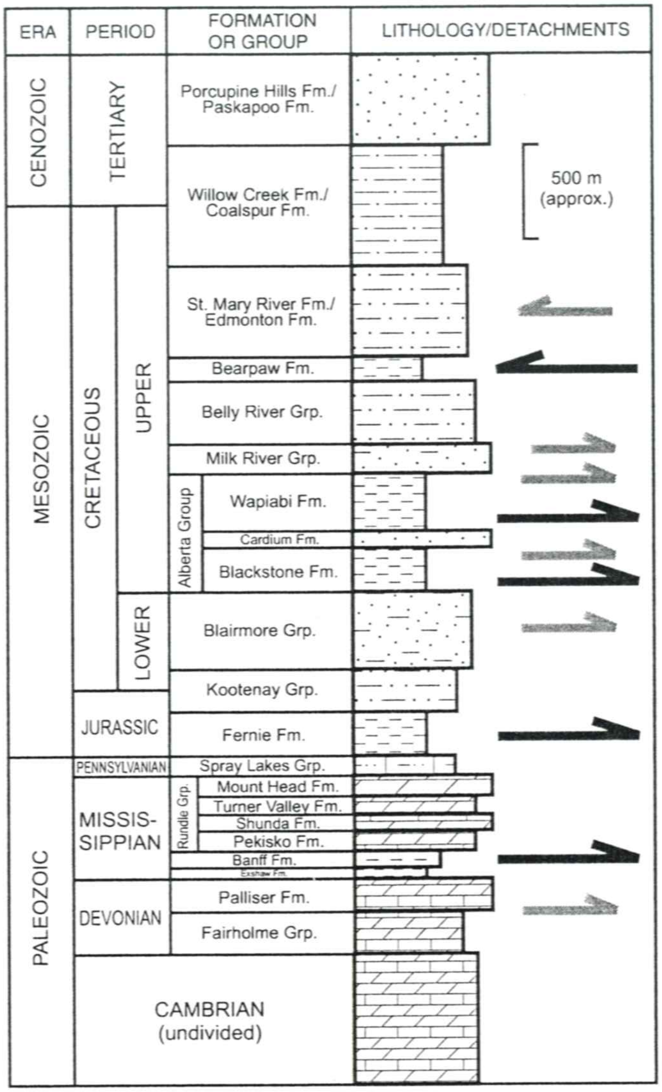


Figure 1-1-2. Generalized surface and subsurface stratigraphy, southern Alberta Foothills. Major and minor detachments are indicated by black and gray arrows, respectively.

detachment may be deformed by one or more back-thrusts, where the thrusts and associated minor structures are dominantly hinterland-vergent. Note that sense of vergence should be used with caution in the field, since the sense can be scale-dependent, reflecting the position within a larger structure. A third variation is where the upper detachment is replaced by a more diffuse zone of strain (an "intracutaneous wedge"; Lawton et al., 1994a). This broad "deformation zone" is characterized by detachment horizons that do not merge. The sense of strain within this zone can be quite variable, with mixed senses of vergence reflecting a complex history.

Triangle Zone Variations: The eastern margin of the Foothills belt in SW Alberta is characterized by a structural triangle zone (tectonic wedge) and steep, imbricated, dominantly foreland-vergent thrusts. New, detailed 1:50,000 scale mapping, undertaken for the Geological Survey of Canada's Southeastern Cordillera NATMAP project (designed to remap the Foothills between the international border and Turner Valley; Lebel and Stockmal, 1994; Lebel et al., 1997a, 1997b), demonstrates that structures between Oldman River (49°45' N) and Turner Valley (50°40' N) vary significantly (Stockmal, 1996, 1997; Lebel and Kisilevsky, 2000; McMechan, in prep.). These variations are a focus of field trip stops on the morning of Day 1. They occur in concert with lateral changes in Cretaceous-Tertiary foreland stratigraphy (e.g., Stockmal, 1995; McMechan and Stockmal, 1996) and the composition of units structurally inserted into the triangle zone (Stockmal and MacKay, 1997). Therefore, these variations are interpreted to reflect in part the influence of mechanical stratigraphy.

Road Log:

0.0 km Drive back across the bridge, and follow the road north and west
0.65 km T-junction; turn north (right) to Turner Valley main intersection
0.95 km 4-way stop, Turner Valley main intersection; turn east (right) toward Black Diamond on Highway 22
2.60 km Outcrop to north of east-dipping Belly River Group (Connelly Creek Formation) in east limb of Turner Valley Anticline
4.10 km Bridge over Sheep River; outcrops of deformed St. Mary River Formation within the Longview Deformation Zone
4.90 km Black Diamond Bakery
5.00 km 4-way stop, centre of Black Diamond; turn south (right), continuing on Highway 22
6.10 km Oilfields Hospital driveway; vista of Foothills and Front Range (McConnell Thrust Sheet)
11.10 km Turnoff to Naphtha
13.30 km Expansive vista of the Front Range; first view of Livingstone Thrust Sheet; Longview Hill at 11:00, SSE of highway
19.00 km Crest of hill; pumpjack on left
21.00 km Descending into Longview; Plateau Mountain at 1:00
22.10 km Junction of Highway 22 and Highway 541 (Kananaskis Trail); town of Longview ("Little Chicago")
22.90 km Home of Longview Beef Jerky
23.50 km Highwood River bridge
23.85 km Turnout for **Stop 2**, west (right) side of Highway 22

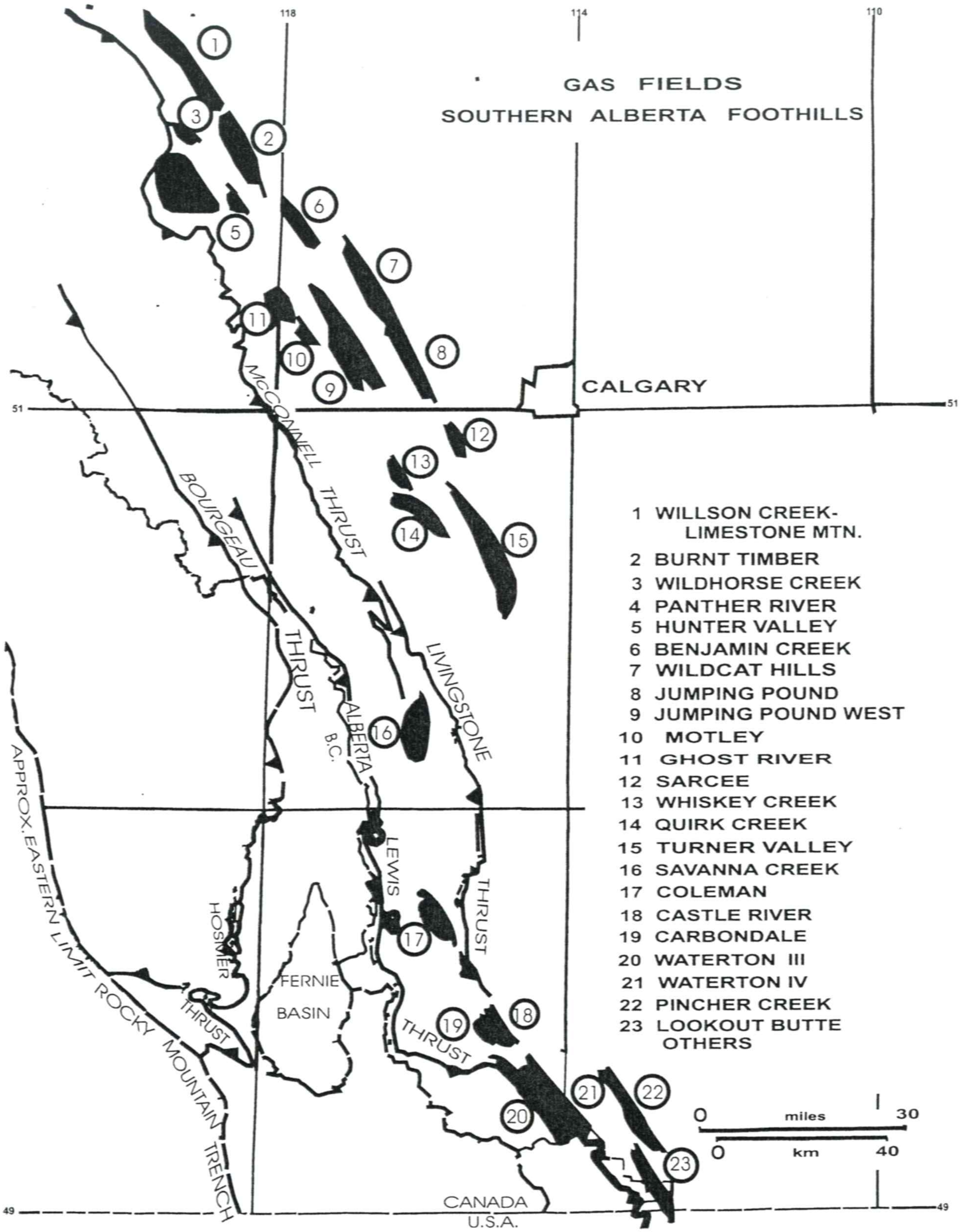


Figure 1-1-3. Locations of major gas fields, southern Alberta Foothills.

Figure 1-1-4. Burning gas seep adjacent to an outcrop of the Ram Member, Turonian Cardium Formation, north bank of the Sheep River in Turner Valley town site.

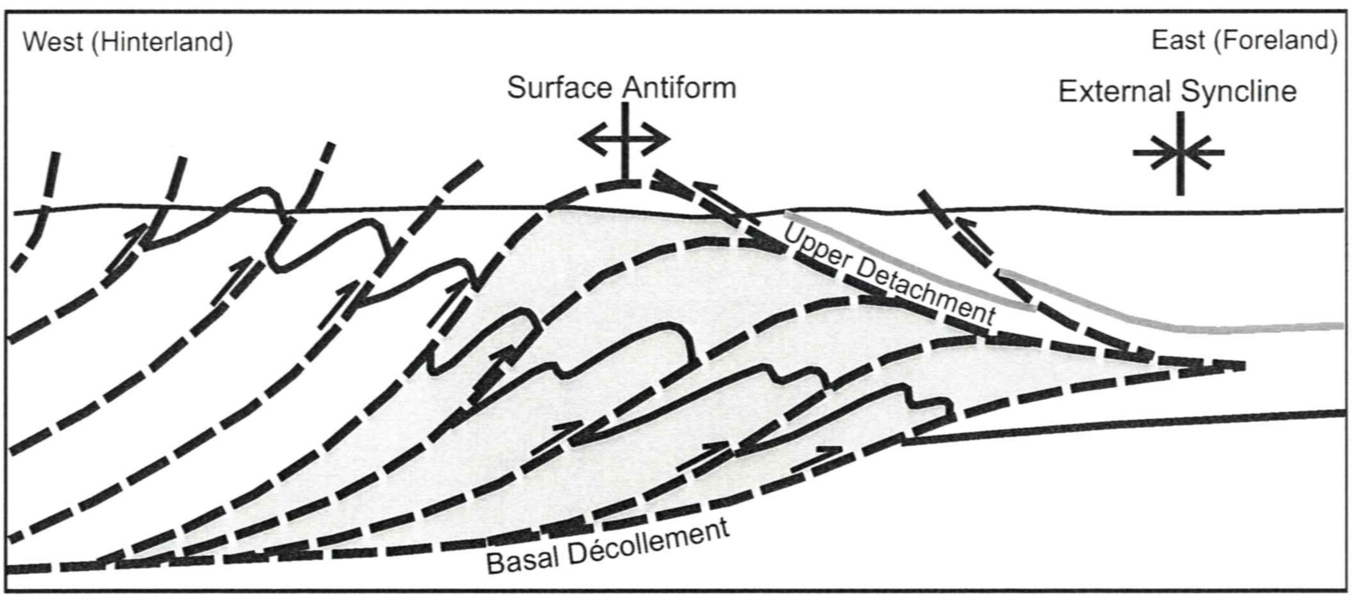


Figure 1-1-5. Schematic diagram of triangle zone terminology (modified after MacKay, 1996).

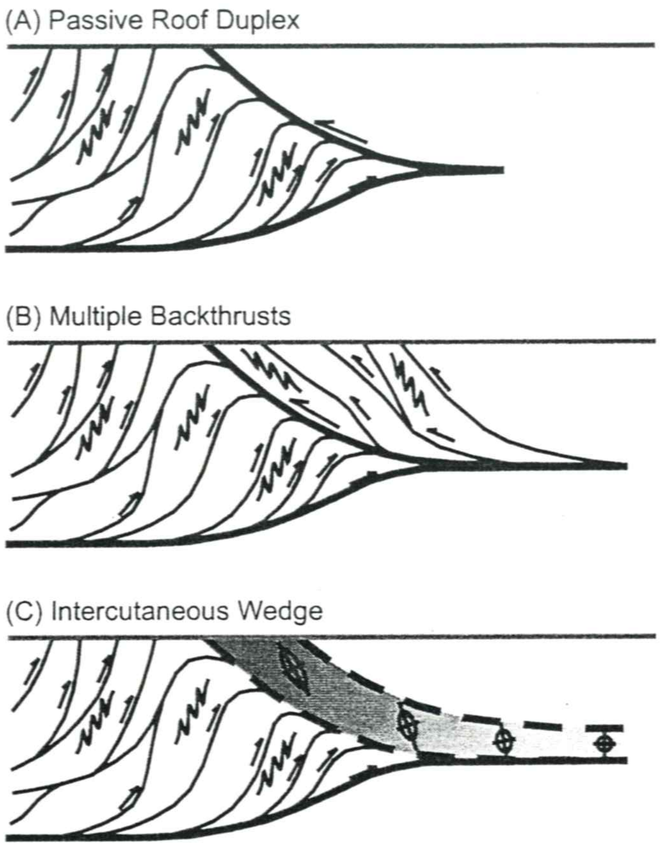


Figure 1-1-6. Style variations of the triangle zone present in southern Alberta.

Stop 2: Highwood River Bridge, Highway 22
Distance: 23.85 km from Stop 1
Access: Parking for a few vehicles is available at the gated well-site entrance just south of the river, on the west side of the road; please do not block the gate entrance. Walk north to the bridge, and follow a faint path down the steep grassy slope to the river's edge, being cautious of a downed barb-wire fence.
Theme: Triangle zone structure.
Purpose: To view the Longview Deformation Zone, and discuss the influence of mechanical stratigraphy on triangle zone structure.

Geology: At this location (Figure 1-2-1) we are very near the southern termination of the Turner Valley oil and gas field (Figure 1-2-2). The spectacularly folded and moderately faulted outcrop on the north side of the Highwood River (Figure 1-2-3) lies approximately in the middle of the 2-km wide Longview Deformation Zone (Figure 1-2-1) that at this latitude essentially forms the upper detachment of the triangle zone. The Longview Deformation Zone incorporates moderately to strongly deformed strata belonging to the upper Belly River Group (Drywood Creek Formation, and possibly uppermost Lundbreck Formation) and the lower St. Mary River Formation. The marine Bearpaw Formation may be present within this interval also, but it is probably very thin (30 metres in 11-12-19-2W5; Dawson et al., 1994). The rocks at this stop have been correlated palynologically with the lowermost St. Mary River Formation (Blood Reserve Formation equivalent). The Bearpaw formation increases in thickness to the south, becoming the exclusive locus of the upper detachment. At this latitude, however, this unit is very thin, resulting in the distribution of shear strain into adjacent units.

Similar brittle deformation occurs for a few kilometres both upstream and downstream from this locality, attesting to the width of the Longview Deformation Zone. Where the rocks are dominated by siltstones and shales, shear strain is evidenced by a pervasive "scaly" fabric, in which the rocks are very friable, separating easily into centimetre to millimetre-sized irregular fragments bounded by smooth, polished surfaces (Figure 1-2-4). This fabric is common to fine-grained sediments deformed in shear under significant fluid pressures (e.g., within accretionary wedges, and the classic Argille Scagliose of Italy).

The position of this outcrop is seen in Figure 1-2-5, which is a simplified cross section across the Turner Valley map sheet. This cross section is constrained by numerous wells (there are over 300 wells in this 1:50,000 scale map sheet) and by a seismic line (Figure 1-2-6) located immediately south of the map sheet. The position and width of the Longview Deformation Zone is seen in this figure and the map (Figure 1-2-1). The deformation zone is bounded below by the Longview Fault, probably equivalent to the Big Coulee Fault mappable to the south on the Oldman River, and above by the Carroll Canyon Fault (both backthrusts). The shear zone is folded, as indicated in cross section, above the Mississippian carbonate beam carried inserted into the Turner Valley structure. This folding is similar to that interpreted by MacKay (1991) and MacKay et al. (1994) but we place the upper detachment at a higher stratigraphic level.

Between Pekisko Creek (50°26') and Sheep River (50°40'), the Bearpaw stratigraphic level remains the locus of an internally complex, hinterland-directred upper detachhment zone. However, the Bearpaw thins substantially from south north, becoming an increasingly poor detachment to the triangle zone. We interpret the development of the Longview Deformation Zone to be a direct result of this thinning, i.e., shear

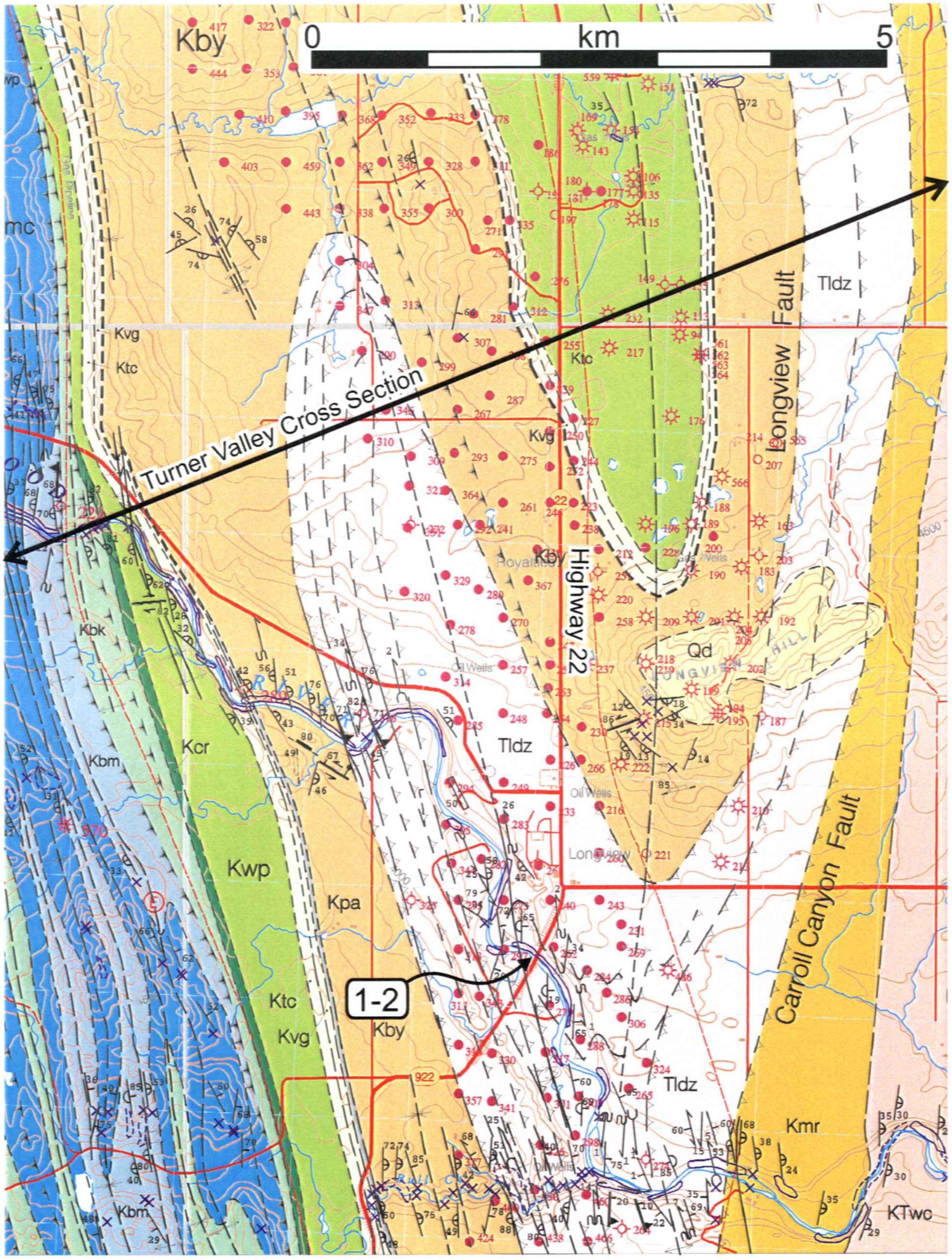


Figure 1-2-1. Detail of GSC Open File #3875, map of Turner Valley (Lebel and Kisilevsky, 2000), centred on approximately 50°33'00"N, 114°15'45"W, showing location of Stop 1-2, and line of cross section.

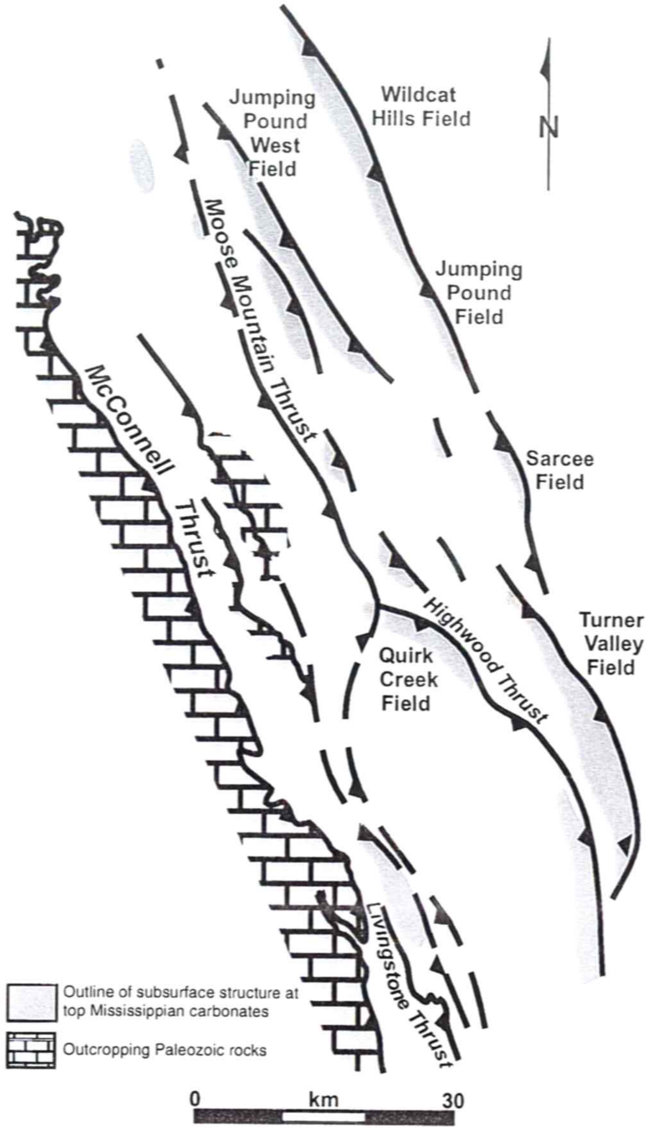


Figure 1-2-2. Generalized map showing outlines of subsurface structural closure at top Mississippian carbonates, and surface outcrop of Paleozoic rocks, between Highwood Junction and Wildcat Hills.

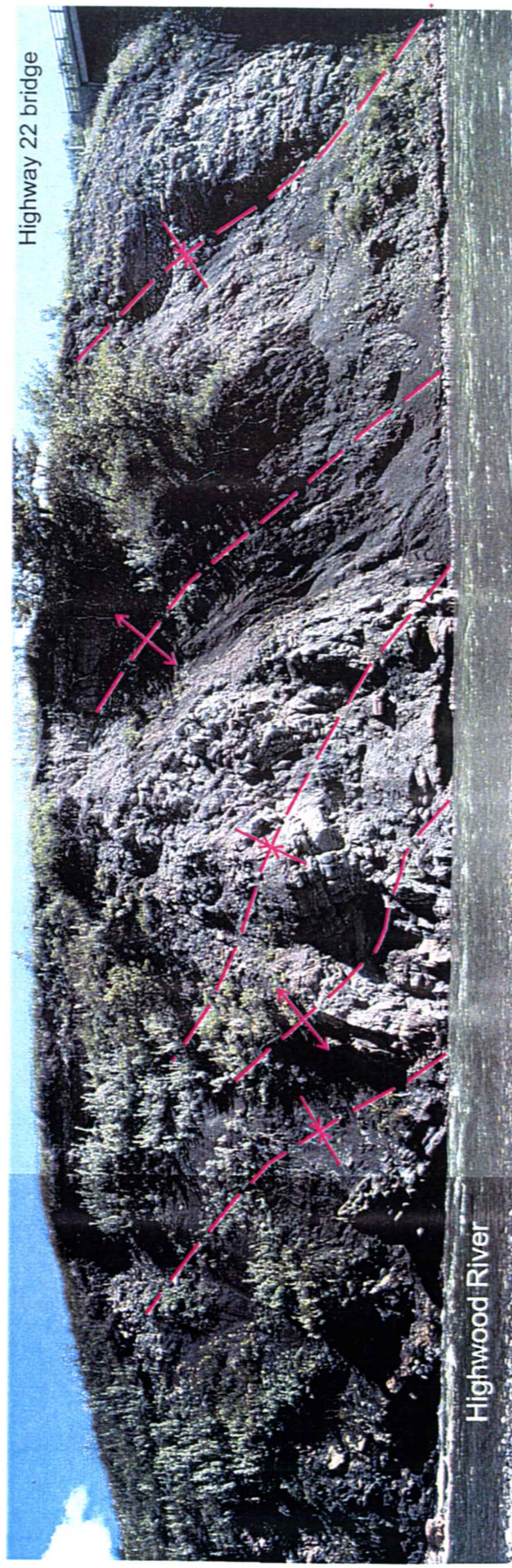


Figure 1-2-3. Panorama of deformed Bearpaw-equivalent section on Highwood River, immediately upstream of the Highway 22 bridge. These west-facing and west-vergent folds, viewed here in an oblique direction, lie within the Longview Deformation Zone, which behaves effectively as the upper detachment of the triangle zone.

Figure 1-2-4. Detail of small-scale folds and pervasive "scaly" deformation fabric (incipient cleavage) and polished surfaces typically developed in mudstone/siltstone units within the Longview Deformation Zone. Fabric is reminiscent of argille scagliose.

strain is distributed over a broad zone, involving marginal marine sediments in adjacent units, as seen here on the Highwood River. To the south, on Pekisko Creek, primarily hinterland-vergent folds and faults are developed in the overlying St. Mary River Formation, forming a mappable zone 2 km wide (McMechan, in prep.). This broad, mappable zone of intense strain may represent a transition to the "intracutaneous wedge"-style triangle zone documented farthe rnorth (Lawton et al., 1994b).

Preliminary interpretation of mapping in Stimson Creek map-sheet, south of Turner Valley, suggests that an emergent splay from the Outwest Thrust may override the triangle zone upper detachment. This splay apparently offsets the hinterland-vergent upper detachment in the Bearpaw Formation. In addition, a minor, younger, hinterland-vergent roof thrust has developed to the east in stratigraphically younger strata at Stimson Creek (McMechan, in prep.).

Road Log:

23.85 km From turnout for Stop 2 – Continue south on Highway 22

26.50 km View to south and west of typical Outer Foothills topography

33.40 km Pekisko Creek Bridge, very near the base of the Longview Deformation Zone

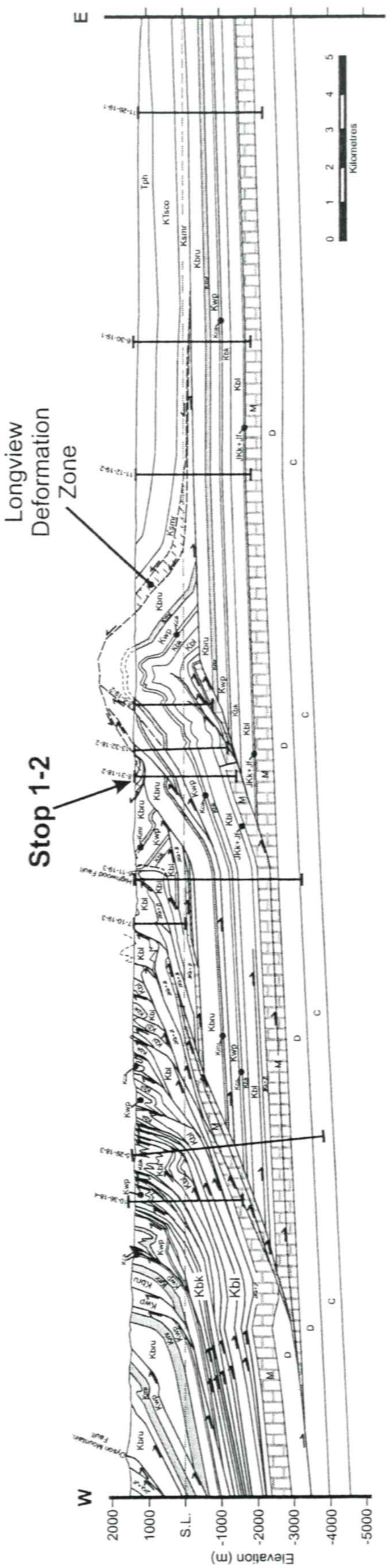


Figure 1-2-5. Geological cross section across the Turner Valley map sheet, constrained by well and seismic data; only a few wells are projected here, though many tens were used (there are almost 600 wells in this 1:50,000 sheet). Note the folding of the Longview Deformation Zone above the Turner Valley Structure, and the development of the Highwood Structure on the blind Outwest Thrust to the west.

36.30 km Turnout to Bar U Ranch (National Historical Site); to the east and southeast, the Porcupine Hills appear, underlain by the Paleocene Porcupine Hills Formation; at 1:00 in far distance is the Livingstone Range (Mississippian carbonates), and in middle distance are ridges of Belly River and Milk River group strata

39.55 km Bridge over Stimson Creek

45.30 km Junction, continue straight on Highway 22

46.80 km Immediately to west is a small outcrop of near-vertical, east-facing, Virgelle Formation sandstone. Underneath us on the Highway is St. Mary River Formation, constraining the outcrop width (and therefore thickness) of the Belly River Group to be unusually small. This has been interpreted to indicate a small-displacement, east-vergent thrust overriding the triangle zone (strike length ~8-9 km). This thrust is probably a splay from the blind Outwest Thrust (discussed at Stop 3a).

49.20 km View to Plateau Mountain at 2:00

50.30 km Power line crosses road at bend to east

50.70 km Junction with Highway 532, road to Indian Graves Recreational Area and the Savanna Creek gas field (last two stops on Day 3)

51.60 km Appearance of Chain Lakes Reservoir in near distance to west

53.40 km View to west of St. Mary River Formation outcrop, west side of Chain Lakes Reservoir

56.75 km Willow Creek Formation outcrop in gully on west side of highway

59.10 km Willow Creek Formation outcrop in gully on west side of highway; good view to west

61.65 km Turnoff to Chain Lakes Provincial Park (west) and Nanton (east)

Turn into Chain Lakes Provincial Park

61.10 km Administration Building; continue on main access road

62.40 km Turn left on turnoff into lakeshore parking lot (outhouses) – **Stop 3a**

Stop 3a: Chain Lakes Provincial Park

Distance: 62.40 km from Stop 1

Access: Turn west at the signed entrance to the Provincial Park, continue past the campground entrance and the Municipal District offices to the first day-use parking lot. Pit toilets are available.

Theme: Triangle zone and Foothills structure.

Purpose: Discussion of triangle zone structure between Maycroft and Turner Valley; description of view of south-plunging Rice Creek Anticline outlined by the Milk River Group, and the map-scale folding of the Rice Creek Fault below the upper detachment.

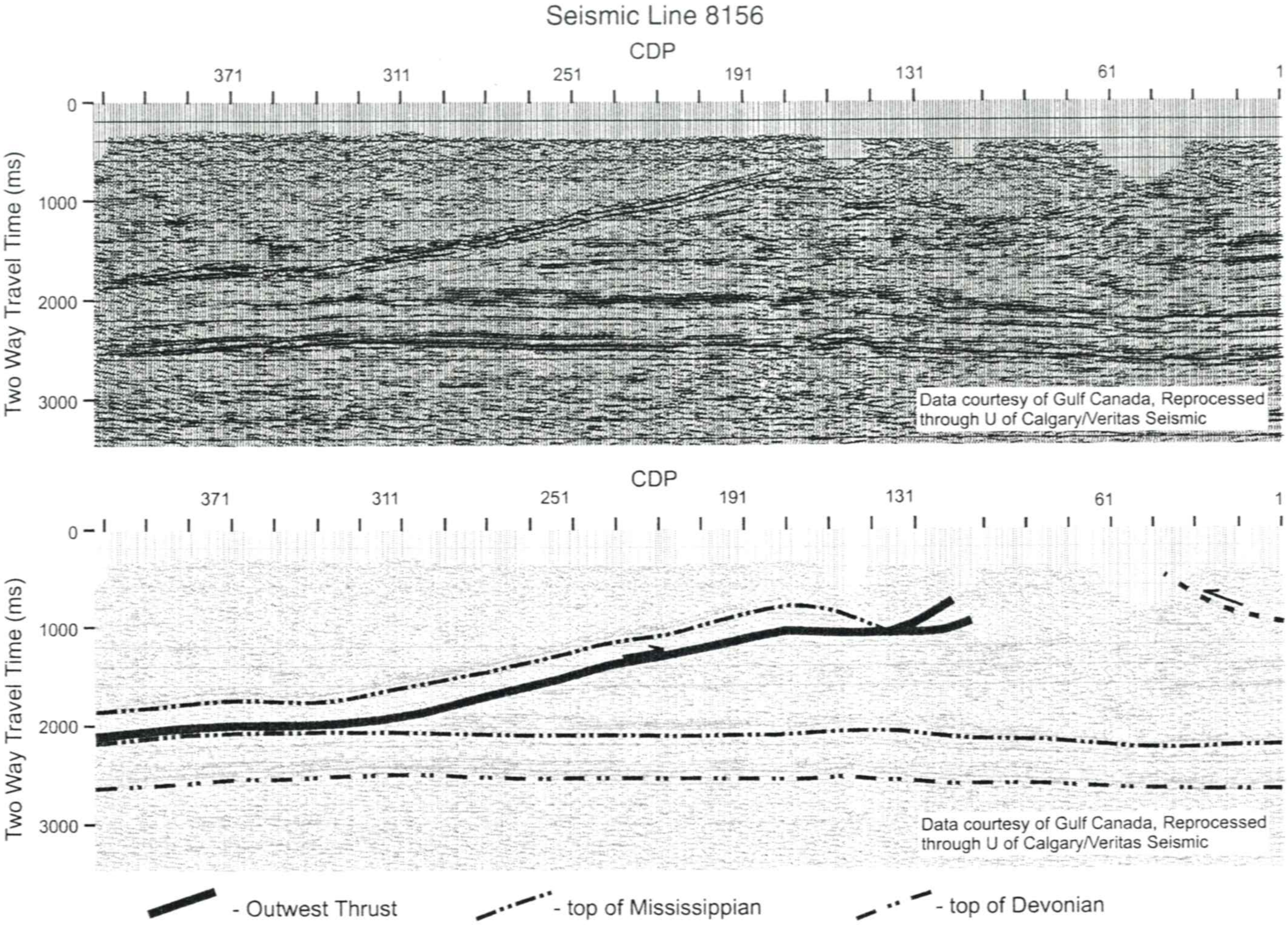


Figure 1-2-6. Seismic reflection data (dynamite source, 50-fold, acquired 1981) reprocessed through the University of Calgary in support of the southeastern Cordillera NATMAP Project. Line is located immediately south of the Turner Valley map sheet, and clearly images the Mississippian carbonates carried on the Outwest Thrust (Highwood Structure).

Geology: From this locality (Figure 1-3-1) we have an unobstructed view across the Chain Lakes Reservoir into the antiformal stack (Rice Creek Anticline) forming the crest of the triangle zone (Figure 1-3-2). As indicated on Figure 1-3-1 and in the cross section (Figure 1-3-3; the west half constrained by seismic line shown in Figure 1-3-4), the St. Mary River Formation lies in the immediate hanging wall of the upper detachment (Big Coulee Fault). The antiformal stack is developed within Belly River, Milk River, and uppermost Alberta Group strata. As indicated on Figure 1-3-2, the folded trace of the Rice Creek Fault can be seen from this point on either side of the Rice Creek Anticline (compare to map, Figure 1-3-1). Early Cretaceous Blairmore Group rocks are exposed along the crest of the antiformal stack to the north, only one kilometre from the trace of the upper detachment (Stockmal, 1997).

At this latitude the upper detachment of the triangle zone is localized within a narrow belt, presumably within the Bearpaw Formation shale. This zone is exposed to the south, along Chaffen Creek (Figure 1-3-6), but is expressed just west of Chain Lakes Reservoir only by a narrow, grassy valley.

To the south, as seen at the left edge of Figure 1-3-2, is a prominent hill transected by the axial surface trace of the Rice Creek Anticline. An annotated view of this hillside from a closer vantage point (photo location indicated in Figure 1-3-1) is shown in Figure 1-3-5, where the individual formations of the Milk River Group are mappable. Outcrop is not as scarce as this view suggests, since vegetation tends to be thickest on the more moist north-facing slopes.

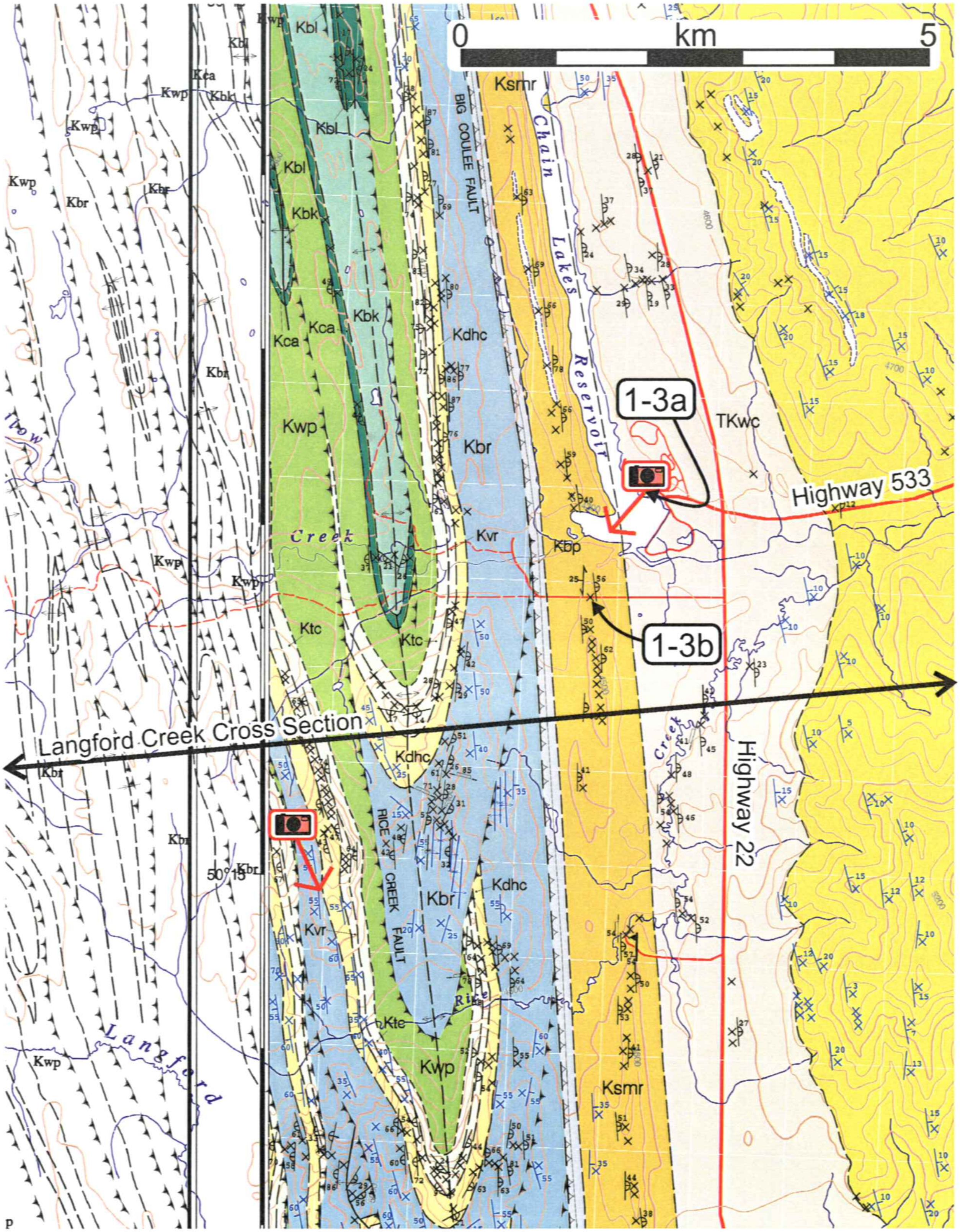


Figure 1-3-1. Detail of GSC Open File #3568, map of Langford Creek east half (Stockmal, 1997), and line work of GSC Map 1837A (Norris, 1993), centred on approximately 50°08'30"N, 114°12'30"W, showing locations of Stops 1-3a and 1-3b, and location of cross section. Camera icons and red arrows indicate photo locations and view directions.

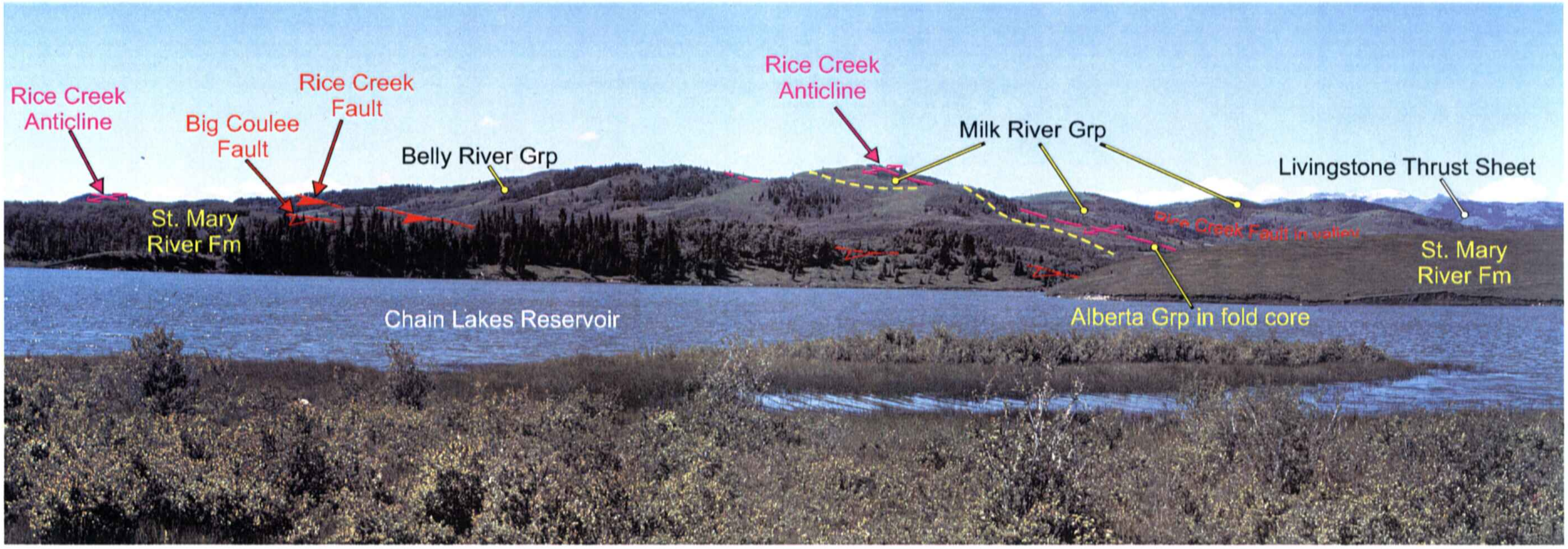


Figure 1-3-2. Panoramic view to the southwest from the southeast shore of Chain Lakes Reservoir. Passively tilted St. Mary River strata lie in the immediate hanging wall of the upper detachment (Big Coulee Fault). The Big Coulee Fault lies in the next valley to the west, as indicated by the unfilled thrust-teeth symbols. The Rice Creek Fault, which duplicates Milk River and Belly River strata, is folded across the Rice Creek Anticline. From this viewpoint, the trace of the folded and east-dipping Rice Creek Fault on the east flank of the anticline can be seen to the south (as indicated by filled thrust-teeth symbols). On the west flank of the anticline, the Rice Creek Fault lies in the next-distant valley, as labeled. In the far distance are Mississippian carbonates carried by the Livingstone Thrust.

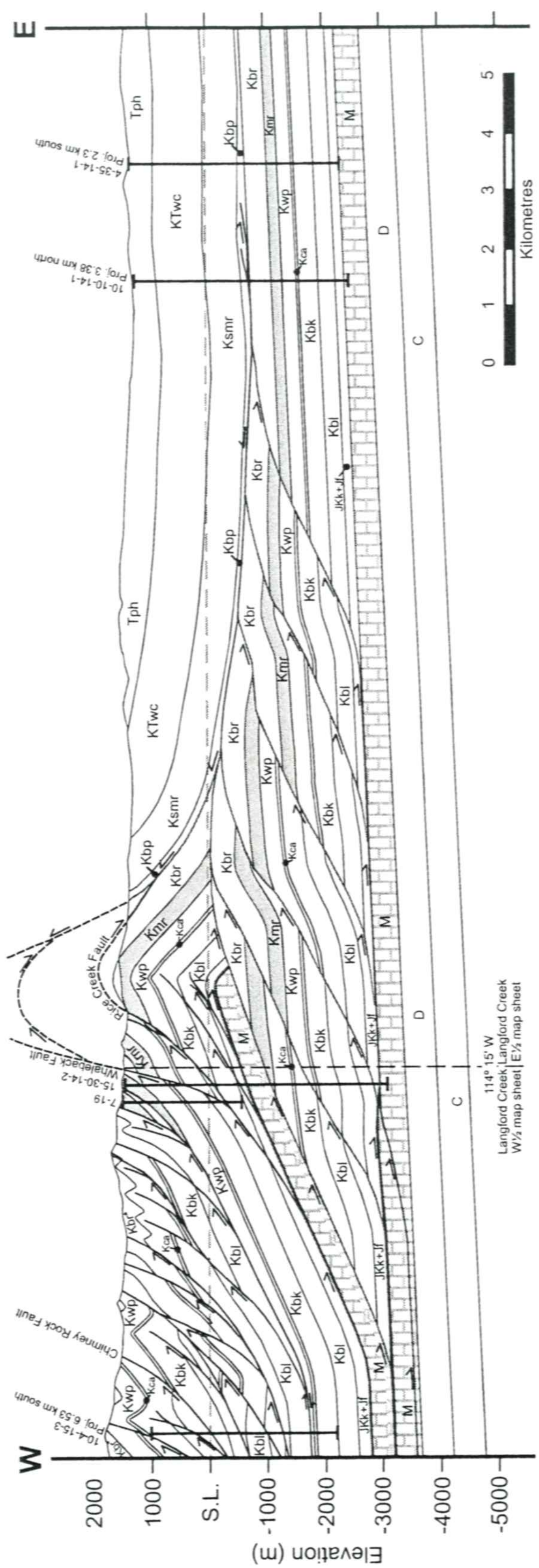


Figure 1-3-3: Geological cross section across the Langford Creek map sheet, constrained by well and seismic data. Overall, the triangle zone takes the form of a simple "passive roof duplex". Note the slice of Mississippian carbonates inserted into the triangle zone above the blind Outwest Thrust.

South of Rice Creek (Figure 1-3-6), the trace of the Big Coulee Fault takes a smooth but abrupt excursion to the west, at the latitude of Chaffen Creek. The Big Coulee Fault and deformation within the Bearpaw and lowermost St. Mary River intervals is reasonably well exposed in Chaffen Creek. This swing in the trace of the upper detachment coincides with the southerly plunge-out of the Rice Creek Anticline (Figure 1-3-6). Figure 1-3-7 is a south view down the plunging axis of the anticline, showing the swing in the trace of the Big Coulee Fault.

Figure 1-3-8 is a time-structure map on the top of the Mississippian carbonates at depth, showing a lateral hanging wall ramp carried on the blind Outwest Thrust (the "Highwood Structure", compare with cross section, Figure 1-3-3). There is a clear spatial coincidence of this lateral ramp with the abrupt swing in the trace of the upper detachment and the rapid plunge of the Rice Creek Anticline and its associated antiformal stack. In addition, above the upper detachment, the degree of deformation increases markedly, expressed by a near-doubling of the apparent thickness of the St. Mary River Formation and associated hinterland-vergent folds and faults within the Willow Creek Formation (Figure 1-3-6). This spatial coincidence suggests that the lateral hanging wall ramp within the blind Outwest Thrust, cutting out the "strong beam" of carbonates, influences the structure within the overlying Cretaceous section.

Road Log:

Retrace route past the Administration Building to Highway 22.

Reset odometer to ZERO

0.00 km Junction with Highway 22, turn south (right); view to east through Willow Creek valley

0.45 km Bridge across Willow Creek

0.85 km **Turn west** onto gravel concession road **for <u>optional</u> stop**

2.20 km **Stop 3b** – outcrop of St. Mary River Formation in road cut on crest of low ridge; good view to north along upper detachment

Stop 3b (optional): St. Mary River Formation outcrop, approximately 1.3 km west on gravel road immediately south of Chain Lakes Park

Distance: 2.20 km from entrance to Chain Lakes Provincial Park

Access: Drive to the crest of the low ridge, and park on the shoulder beside the outcrop.

Themes: Stratigraphic succession of the Foreland Basin, and triangle zone structure.

Purpose: To view the tilted St. Mary River Formation in the immediate hanging wall of the Big Coulee Fault (triangle zone upper detachment).

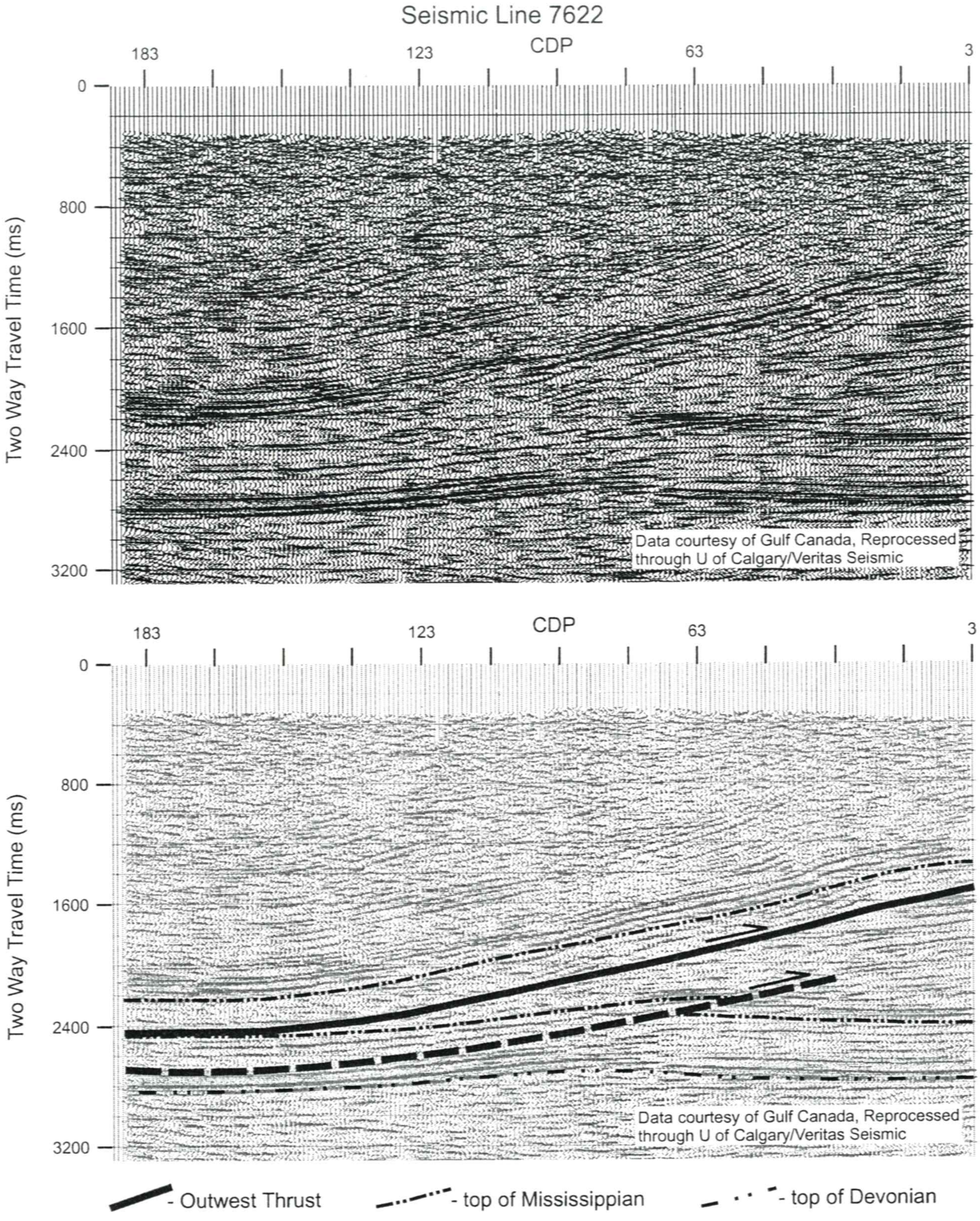


Figure 1-3-4. Seismic reflection data (dynamite source, 21-fold, acquired 1976) reprocessed through the University of Calgary in support of the southeastern Cordillera NATMAP Project. Line is located along the line of the cross section, and clearly images the Mississippian carbonates carried on the Outwest Thrust and a small footwall splay.

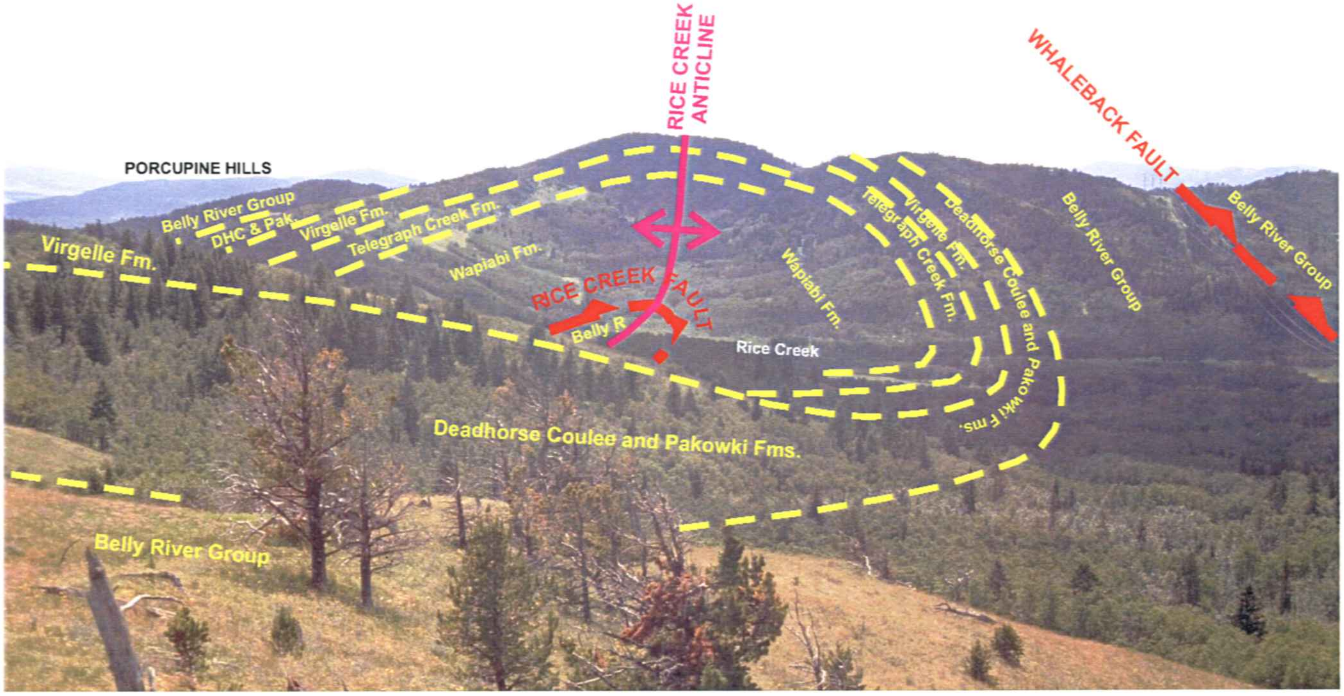


Figure 1-3-5. Slightly oblique-to-strike, annotated view to the south-southwest across Rice Creek showing the Rice Creek Fault folded across the trace of the Rice Creek Anticline. Viewpoint indicated in Figure 1-3-1 (lower left camera icon).

Geology: This outcrop occurs in a shallow road cut at the crest of a low ridge underlain by the St. Mary River Formation, lying in the immediate hanging wall of the triangle zone upper detachment (Big Coulee Fault) (Figure 1-3-1). The moderately east-dipping dipping strata (56°) reflect the approximate dip of the upper detachment. The low ridge reflects the relative resistance of the St. Mary River Formation in relation to the Bearpaw Formation below and the Willow Creek Formation above. This low ridge is one of a long series of ridges which grow in topographic expression from north to south, perhaps reflecting an overall increase in the sand/shale ratio.

At this location, approximately 15 metres of St. Mary River Formation is exposed. The outcrop consists of approximately 40% fine grained sublitharenite, variably current rippled, cross bedded, or massive, and 25% very fine grained sublitharenite, current rippled or cross bedded. These sandstones weather light to medium brownish gray, and display small scale channels and characteristic rootlets. Lesser percentages of dark gray mudstone (15%) and siltstone (10%), and rooted, massive and well fractured, light orange-brown weathering argillaceous limestone (probably lacustrine) are present. Bed thicknesses range from roughly 1 metre down to 20 centimetres.

Road Log:

Return along gravel road to Highway 22

Reset odometer to ZERO

0.00 km Highway 22 junction, turn south (right); views to west into south-plunging antiformal stack

3.30 km Crest of hill; view west to Livingstone Range through Rice Creek drainage; to southwest St. Mary River Formation ridge in near distance

5.70 km View toward 1:00 to far distant cliff exposure of the Virgelle Formation, south end of Chimney Rock Ridge

As we drive south, note the every increasing elevations attained by the ridge of St. Mary River Formation in the immediate hanging wall of the upper detachment. The St. Mary River Formation becomes sandier to the south, suggesting that the increase in elevation may be a crude proxy for the change in sand/shale ratio.

9.00 km Cross Langford Creek

9.65 km Chimney Rock Road turnoff; **reset odometer to zero to accommodate side trip to optional St. Mary River and Bearpaw exposures, but <u>for main trip continue south on Highway 22</u>**

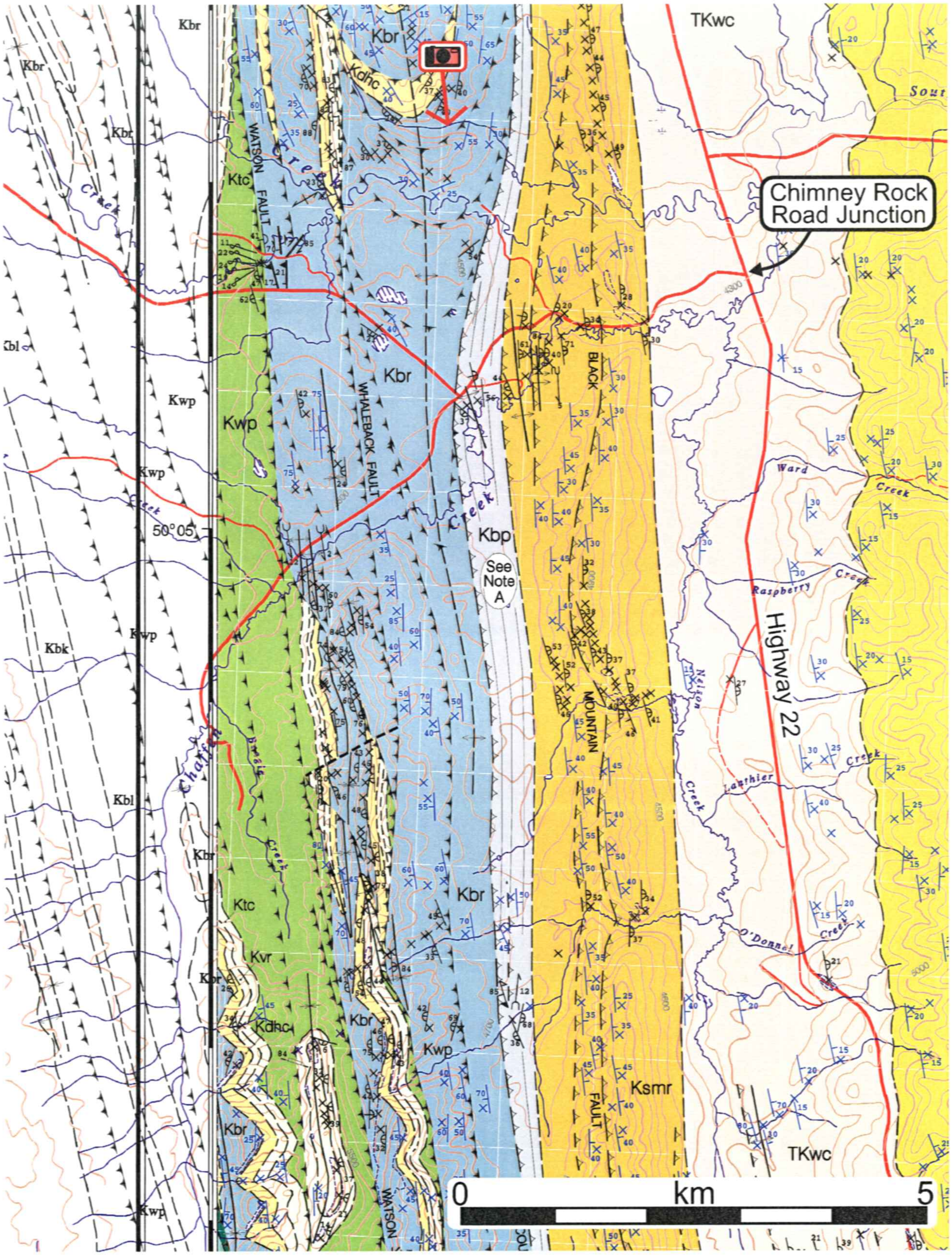


Figure 1-3-6. Detail of GSC Open File #3568, map of Langford Creek east half (Stockmal, 1997), and line work of GSC Map 1837A (Norris, 1993), centred approximately on 50°04'30"N, 114°12'30"W. Optional stop described in guide book is off Chimney Rock Road. Camera icon and red arrow indicate photo location and view direction.

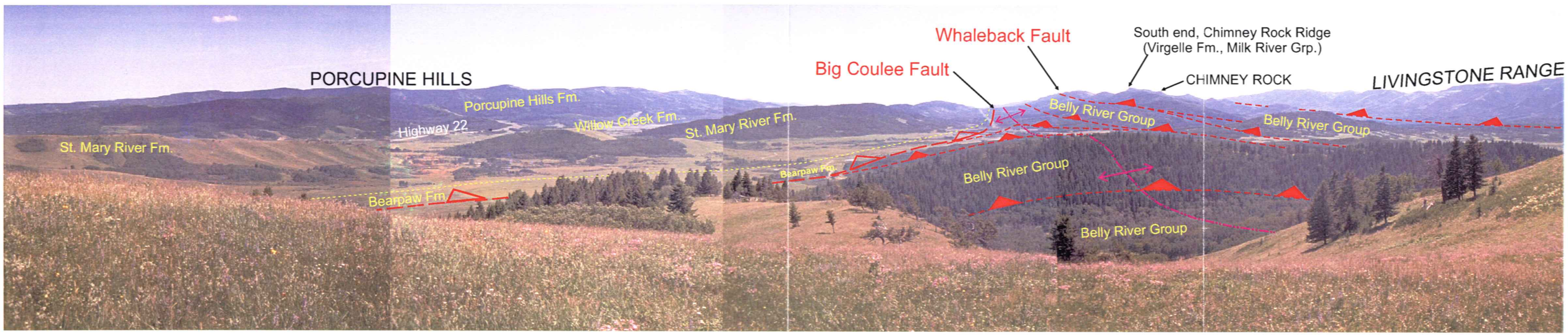


Figure 1-3-7. Panoramic, annotated, along-strike view to the south from location indicated in Figure 1-3-6. View is along the axis of the triangle zone, as defined by the trace of the south-plunging Rice Creek Anticline. Compare the swing in the trace of the Big Coulee Fault with the map (Figure 1-3-6).

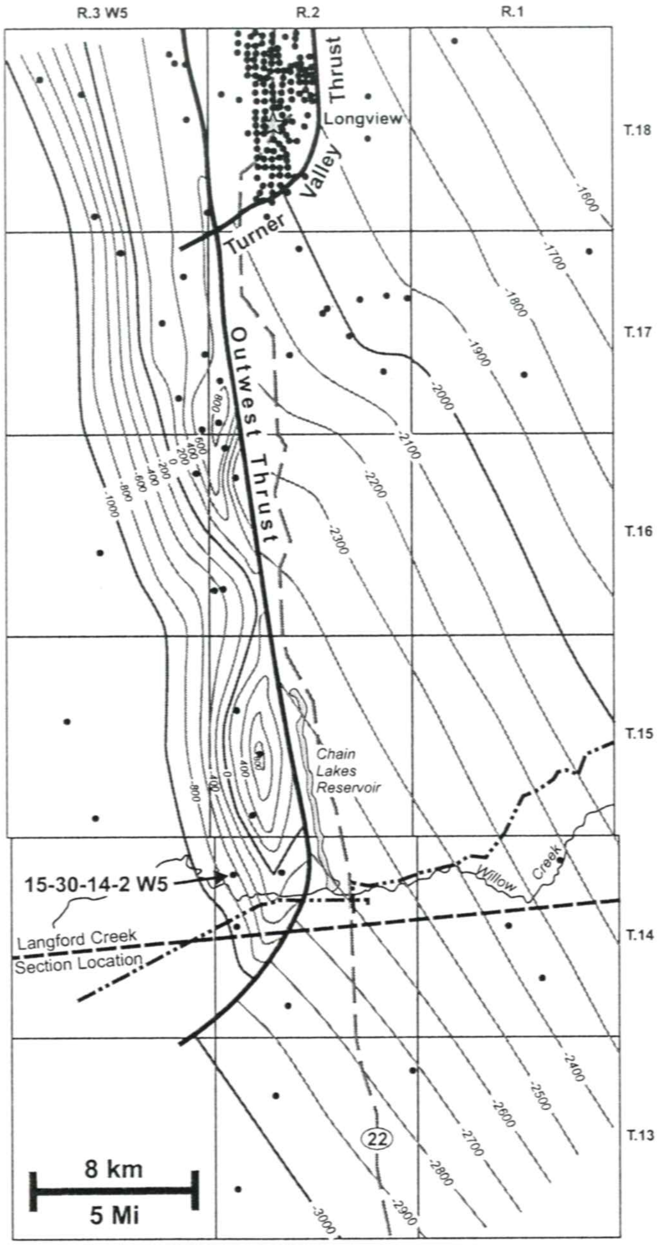


Figure 1-3-8. Structure contour map (metres relative to sea level) on the top of the Mississippian section (modified after MacKay, 1996). Subsurface locations of the Outwest Thrust and the Turner Valley Thrust are at the hanging wall cutoffs of the Mississippian section.

Road Log for optional outcrop stops:

0.00 km **Reset to zero** at the Chimney Rock Road turnoff; **turn west (right)**

1.30 km St. Mary River Formation outcrop; east-facing and east-dipping

2.15 km St. Mary River Formation outcrop

2.60 km St. Mary River Formation outcrop along Chaffen Creek; vertical and east-facing

2.90 km Bearpaw Formation outcrop; above/within upper detachment zone

3.65 km Junction with Saddle Mountain Road; cross trace of Big Coulee Fault; view down road to southwest of west dipping Belly River Group strata; view south along Breeding Valley along the upper detachment (following path of power line)

Return to Highway 22, and proceed south (right)

Reset odometer to ZERO at Chimney Rock Road junction

0.00 km Junction with Chimney Rock Road

0.20 km Cross Chaffen Creek; to east Langford and Chaffen creeks merge to form South Willow Creek; Porcupine Hills Formation outcrops to southeast, St. Mary River Formation ridge to west

3.20 km View through St. Mary River ridge to Chimney Rock Ridge and exposures of the Virgelle Formation

6.10 km View through Ropeo Gap to Chimney Rock Ridge

7.80 km Maastrichtian-Paleocene Willow Creek Formation exposed in long road cut; above K-T boundary at this location

8.50 km Highway 22 crosses gas pipeline; view due west to south end of Chimney Rock Ridge; Willow Creek exposures in gullies on either side of road

13.50 km Uphill grade; view west to Whaleback Ridge (underlain by Belly River and Milk River group strata)

13.90 km Willow Creek Formation outcrop in road cut

15.40 km Opposite gas pipeline compressor station (to west)

16.45 km Junction with Highway 520 to Claresholm

17.10 km **Stop 4** at road cut of Willow Creek Formation

Stop 4 (Provisional): Outcrop of Willow Creek Formation, Highway 22, just south of junction with Highway 520, Maycroft map sheet

Distance: 17.10 km from turnout to Stop 3b

Access: Park anywhere off the highway shoulder.

Theme: Stratigraphic succession of the Foreland Basin, and triangle zone and Foothills structure.

Purpose: Possible stop to view Willow Creek Formation outcrop, and discuss the view across the triangle zone into the Outer Foothills.

Geology: This long road cut exposes a 40 metre section of the upper Willow Creek Formation, on both sides of Highway 22 (Figure 1-4-1). At this level within the Willow Creek, we are above the Cretaceous-Tertiary boundary (T. Jerzykiewicz and A. Sweet, pers. comm., 1993). The outcrop is dominated by rubbly, medium brownish gray weathering, muddy siltstone, with approximately 10% light to medium gray, silty, very fine grained sublitharenite forming massive, rubbly weathering beds 10 to 30 cm thick, approximately 5%

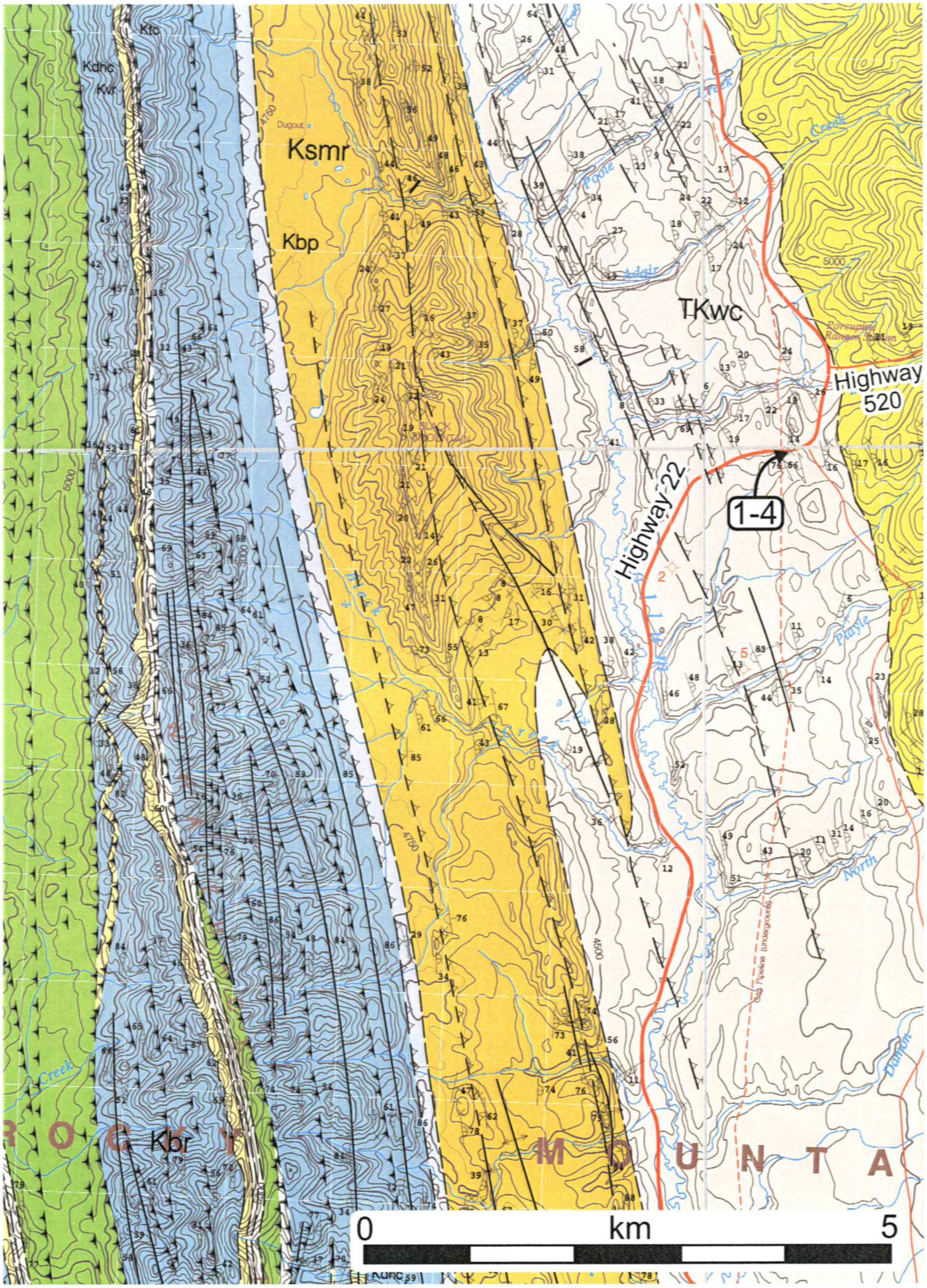


Figure 1-4-1. Detail of GSC Open File #3275, map of Maycroft east half (Stockmal, 1996), centred approximately on 49°56'30"N, 114°10'00"W, showing location of Stop 1-4.

very light grey, current rippled to cross bedded fine grained sublitharenite in beds approaching 1 m in thickness, and minor 10 to 30 cm thick beds of medium reddish-brown calcareous mudstone with caliche nodules and lime concretions. The Willow Creek Formation is generally very recessive, with exposures limited to stream and road cuts. The environment of deposition was likely in distal, semiarid "alluvial fans", periodically violently flooded leaving ephemeral lakes.

Looking west from this locality, downslope toward Callum Creek, the nearest prominent ridge is underlain by the St. Mary River Formation, structurally thickened by and folded above a series of overlapping backthrusts (Stockmal, 1996). Similar faults are inferred within the topographically low Willow Creek Formation, also (Figure 1-4-1). Note the relatively high relief attained by this ridge underlain by the St. Mary Formation, in relation to that attained in the vicinity of Chain Lakes Reservoir (relief may be a proxy for sand/shale ratio). Looking west-southwest, through the gap in the St. Mary River Formation ridge formed by Black Creek, the prominent ridge on the skyline is Whaleback Ridge, underlain by Belly River and Milk River group strata. These ridges are separated by a long, continuous valley (note the powerline) occupied by the triangle zone upper detachment, localized within and near the base of the Bearpaw Formation shales (Figure 1-4-1).

Road Log:

17.10 km From Stop 4 – proceed west and south along Highway 22

17.50 km Increasing views to the south along Callum Creek drainage; good views north along upper reaches of Callum Creek to heavily treed dip-slopes of St. Mary River Formation; possibly near the K-T boundary

20.20 km Turnout to west; on north side of the gravel road are exposures of the basal Willow Creek Formation (characteristic red mudstones)

20.60 km Lower Willow Creek outcrop to east, just north of ranch

21.80 km String of small Willow Creek outcrops to east along Callum Creek; hummocky hills to west underlain by St. Mary River Formation

26.00 km Good views to east of the Porcupine Hills, underlain by the Porcupine Hills Formation; thick sandstones of the Porcupine Hills Fm retain moisture and are relatively well-treed; good views to the far south to the Precambrian section in the Lewis Thrust sheet

28.00 km Due east: fire tower on top of Porcupine Hills.

31.80 km Gas pipeline right-of-way seen at 1:00 p.m.

32.80 km View south along straight west edge of Callum Creek, caused by thrust juxtaposition of St. Mary River Fm over Willow Creek Fm

34.30 km Willow Creek Fm outcrop on far side of Callum Creek, in the footwall of the unnamed thrust

35.30 km Cross trace of east-directed Bridge Fault

35.60 km View to south, slightly east of the highway direction, of the trace of the Bridge Fault across the Oldman River, where resistant beds of the St. Mary River Formation are thrust over recessive beds of the Willow Creek Formation; note the syncline in the hanging wall of the fault

36.40 km Turn west (right) onto gravel road, immediately north of the Oldman River bridge

36.50 km Turn south (left) onto gravel access road leading to the primitive campground and picnic area; park on the side of the road for **Stop 5a**

Stop 5a: Junction of turnoff to Oldman River campground from unnumbered gravel road, adjacent to Highway 22, immediately north of the Oldman River bridge.

Distance: 36.50 km from turnout to Stop 3b

Access: Turn west (right) from Highway 22 onto the gravel road immediately north of the Oldman River bridge, and take the first left. Proceed a few tens of metres and park at the side of the road.

Theme: Triangle zone structure.

Purpose: Overview of the triangle zone and discussion of map-scale structures in the hanging wall of the upper detachment.

Geology: Looking north are a series of low hills underlain by the St. Mary River Formation, in the hanging wall of the upper detachment (Figure 1-5-1). The apparent anticline (Figure 1-5-2) is in fact a south-plunging syncline, the plunge of which is steeper than the hillside slope. The small hill on which this fold is exposed is underlain by a folded foreland-directed thrust, the Bridge Fault (Figure 1-5-1). A second, unnamed, thrust is also folded in a similar fashion. These faults are well constrained on the Oldman River, and their traces can be mapped to the north where they are folded and eventually merge with the trace of the hinterland-directed Co-op Fault. In cross section (Figure 1-5-3, constrained by seismic data, e.g. Figure 1-5-4) this synclinal structure is seen to be one-half of a kilometre-scale, hinterland-vergent fold pair involving both hinterland- and foreland-directed thrusts, all above the upper detachment. In a palinspastically restored section (Figure 1-5-3), the two folded foreland-directed thrusts appear to be part of a smaller hinterland-directed triangle zone developed above the larger, principal, foreland-directed triangle zone.

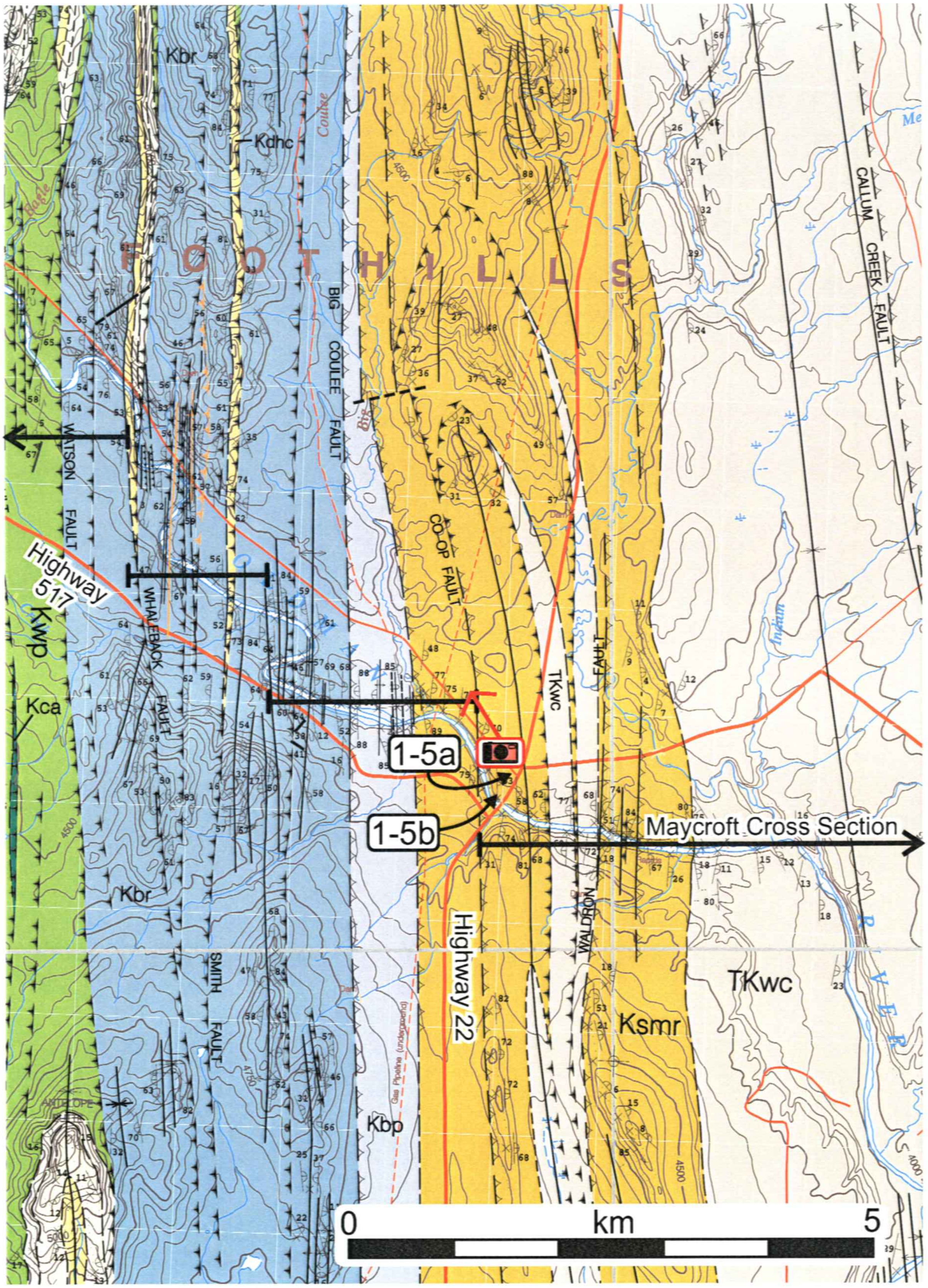


Figure 1-5-1. Detail of GSC Open File #3275 map of Maycroft east half (Stockmal, 1996), centred approximately on 49°48'30"N, 114°09'00"W, showing locations of Stops 5a and 5b, and cross section.

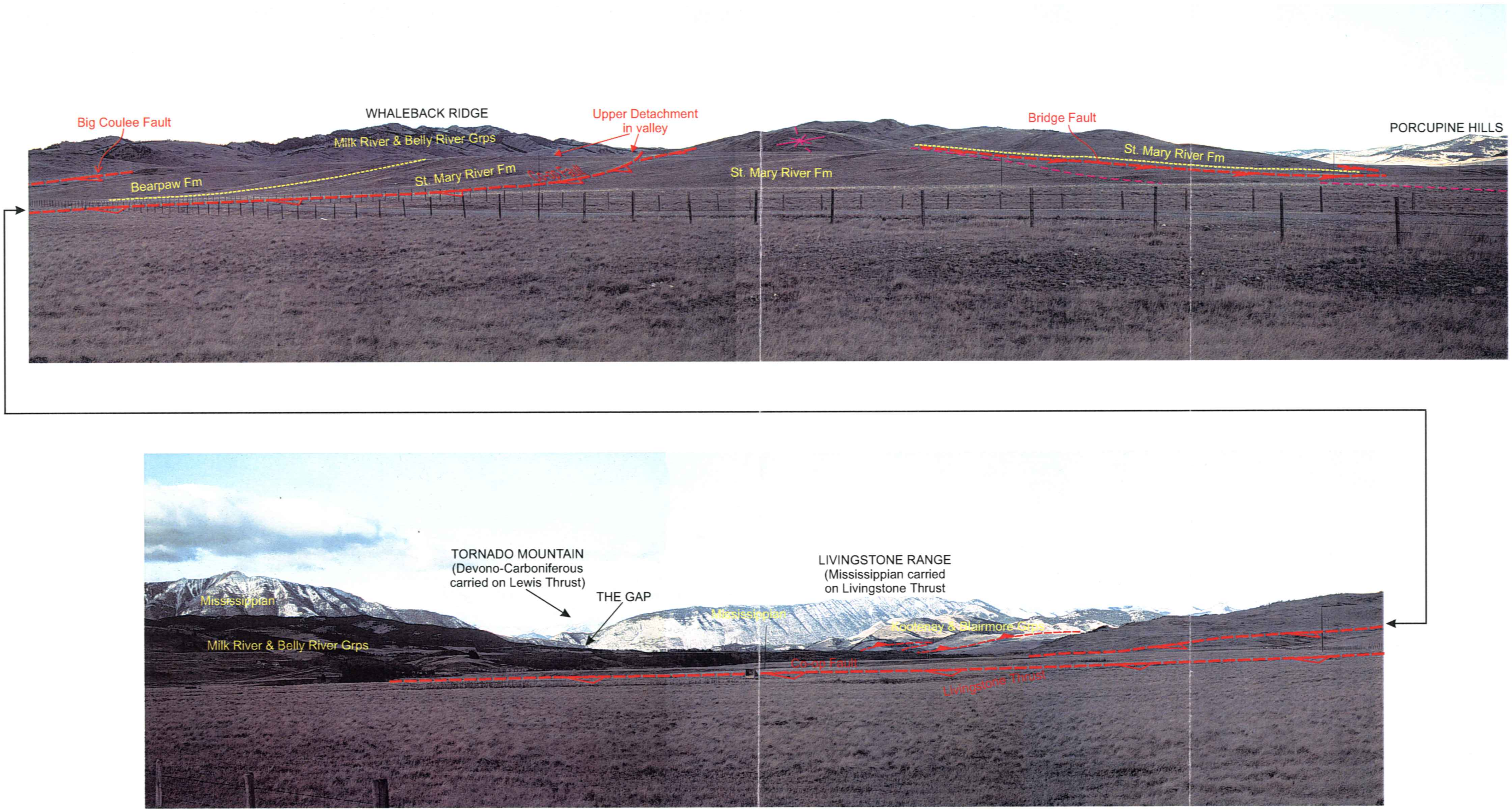


Figure 1-5-2. Panoramic, annotated view to the north and west from the north side of the Oldman River, west of Highway 22. A south-plunging syncline involving folded foreland-directed thrusts (Bridge Fault and unnamed fault) is mapped in the hanging wall of the upper detachment (the Big Coulee Fault zone), above a hinterland-directed thrust (the Co-op Fault). To the west are ridges underlain by thrust slices of Upper and Lower Cretaceous and Jurassic strata. In the distance are Mississippian carbonates carried on the Livingstone Thrust and, visible through The Gap, Devono-Carboniferous strata carried on the Lewis Thrust.

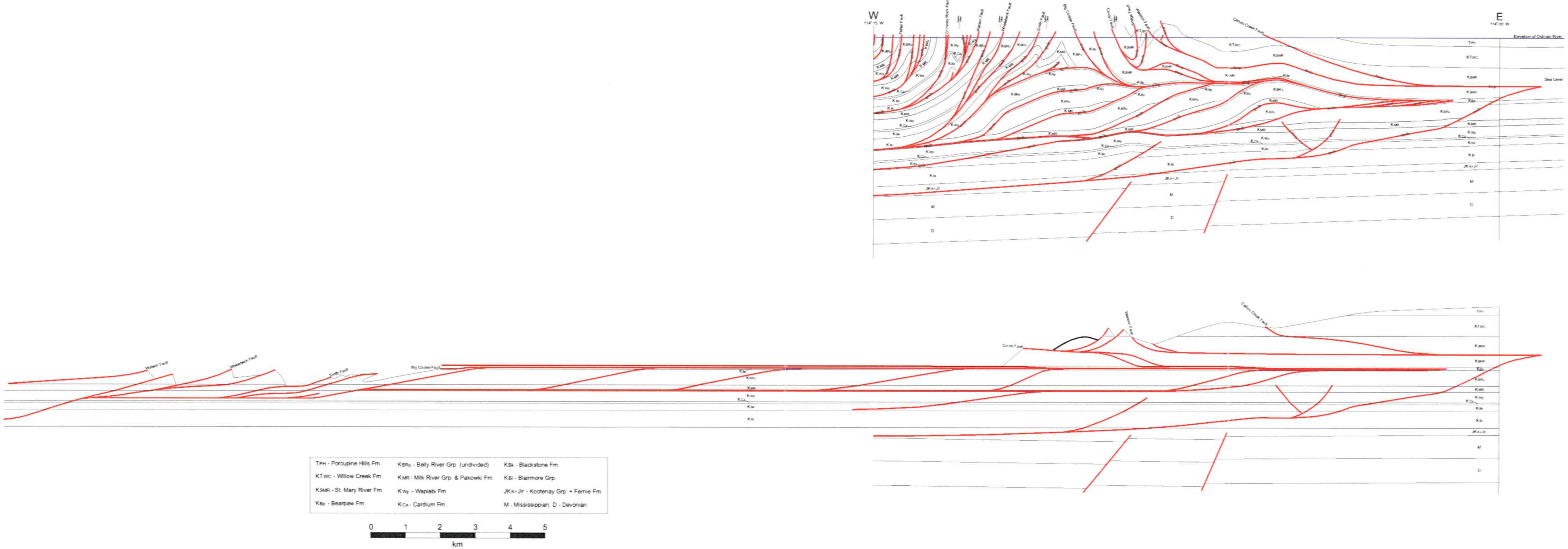


Figure 1-5-3. Geological cross section and palinspastic restoration across the Maycroft (east half) map sheet, constrained by seismic data. Milk River Group and Pakowki Formation shaded gray as a visual aid. Note the degree of hinterland-vergent deformation present above the upper detachment, including a faulted, kilometre-scale anticline-syncline pair. The Maycroft triangle zone comprises two "nested" triangle zones, with basal detachments in the Wapiabi and Fernie formations, respectively. Restoration indicates that significant motion on the Watson Fault must be "out of sequence" (modified from Stockmal et al., 1996).

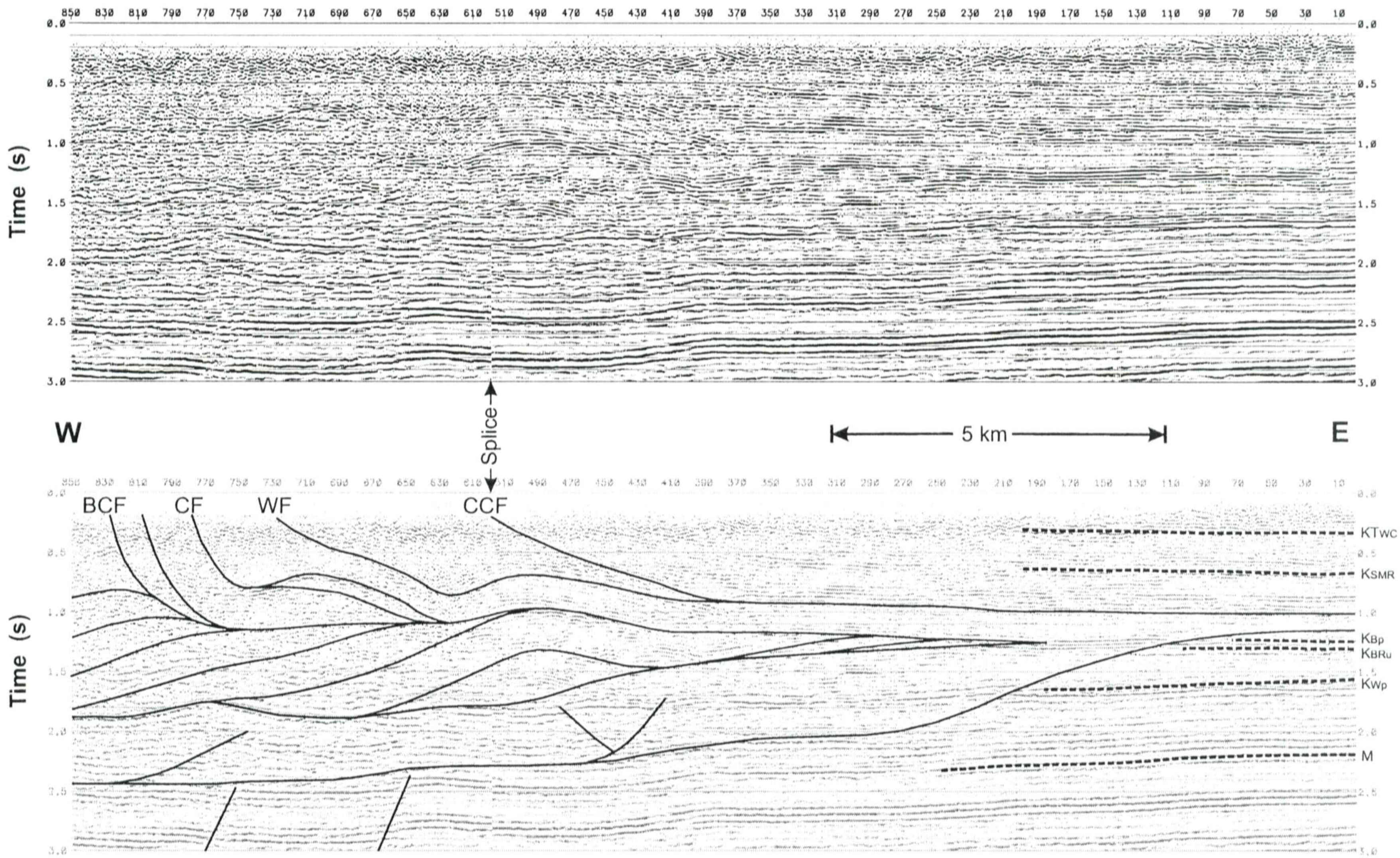


Figure 1-5-4. Reinterpretation of VibroseisTM seismic reflection data originally interpreted by Lawton et al. (1994), used to constrain interpretation of Maycroft geological cross section. BCF = Big Coulee Fault; CF = Co-op Fault; WF = Waldron Fault; CCF = Callum Creek Fault.

These structures and others developed to the east all lie above the upper detachment, and represent a significantly different structural style in comparison with the simpler passive-roof duplex triangle zone we discussed at the latitude of Chain Lakes Reservoir. Figure 1-5-5 presents the Turner Valley, Langford Creek, and Oldman River cross sections aligned along structural strike, allowing easy comparison of the inferred changes in structural style.

The Bearpaw Formation is greatly thickened structurally and very deformed in exposures along the Oldman River, approximately 1 km to the west. Scaly fabric, similar to that described along the Highwood River, is very common. The magnitude of deformation is very apparent where light-coloured bentonitic clays contrast with the dark gray shale (Figure 1-5-6).

Road Log:

36.50 km From Stop 5a, continue down access road toward Oldman River and campground
36.8 km **Stop 5b**, campground and picnic area

Stop 5b: Oldman River campground, adjacent to Highway 22, immediately north of the Oldman River bridge.

Distance: 36.8 km from turnout to Stop 3b
Access: Continue south on the access road to the parking lot.
Theme: Triangle zone structure and stratigraphic succession of the Foreland Basin.
Purpose: Lunchstop/rest-stop, and casual examination of outcrops of St. Mary River Formation (including dinoturbation).

Geology: The St. Mary River Formation is very well exposed along both banks of the Oldman River, upstream and downstream of the Highway 22 bridge. Overall, the lithologies are similar to those described for Stop 3b. The section on the southwest side of the river upstream of the bridge was measured and described by Rahmani and Schmidt (1975), and that downstream of the bridge on the northeast side was measured and described by Lerand (1982). The St. Mary River Formation dips approximately 60º to the west at the campground. It is partly duplicated by the Co-op Fault, about 300 m to the west, and it folded across a syncline (the same structure observed from Stop 5a, but now with very shallow plunge) approximately 400 m downstream, in the immediate hanging wall of the Bridge Fault (Figure 1-5-1).

Participants are encouraged to casually examine the outcrops during or following lunch. Watch for interesting sedimentary structures that exhibit characteristics similar to load structures, or irregular ball-and-pillow structures. However, many of these features occur at or near sand-on-sand bedding surfaces. In some cases, these features clearly appear to be footprints (*dinosaurs?!*), leading one sedimentologist to (tongue-in-cheek) refer to these deformed beds as being "dinoturbated" (G. Nadon, pers. comm., 1990).

Road Log:

Retrace route back to Highway 22.
Reset odometer to ZERO.
0.00 km Highway 22 junction. Turn south (right) and proceed across Oldman River bridge.
0.30 km Oldman River bridge
0.50 km Turnoff to The Gap (alternate route to stops on Day 3)
0.60-1.00 km St. Mary River Formation outcrops to east of road; these strata are in the hanging wall of the upper detachment, and are near-vertical and east-facing
3.40 km Views east of St. Mary River outcrop along crest of ridge
3.80 km View west across low ridges underlain by Belly River Group to the well-treed Antelope Butte, underlain by the Milk River Group and carried in the hanging wall of the Watson Fault; Mississippian section carried by the Livingstone Thrust in far distance
5.40 km View toward 2:00 to Virgelle Formation (Milk River Group) sandstone at Chapel Rock; view east to "porcupines" (east-dipping treed ridges) of the Porcupine Hills, and view south to the Lewis thrust sheet
7.00 km Just after bend in the road, good view to 3:00 of the south plunging syncline along the crest of Antelope Butte – thick sandstone outcrops are the Virgelle Formation
8.30 km Cross Todd Creek
9.00 km Willow Valley Road to west; view south to Chief Mountain klippe of the Lewis thrust sheet in Montana
13.00 km Cross Cow Creek
13.10 km Chapel Rock Road turnoff to west
20.00 km View of Oldman Reservoir at 10:00; views to south of ridges of Cretaceous in middle distance, and Proterozoics of Lewis thrust sheet in far distance
24.40 km Road cut through Virgelle Formation; belt of outcrop continues across the Crowsnest River to Stop 6
24.70 km T-junction with Highway 3; view to south of Wapiabi and Milk River group outcrop on south side of the Crowsnest River; **TURN WEST (RIGHT) ONTO HIGHWAY 3**
24.90 km Virgelle Formation outcrop

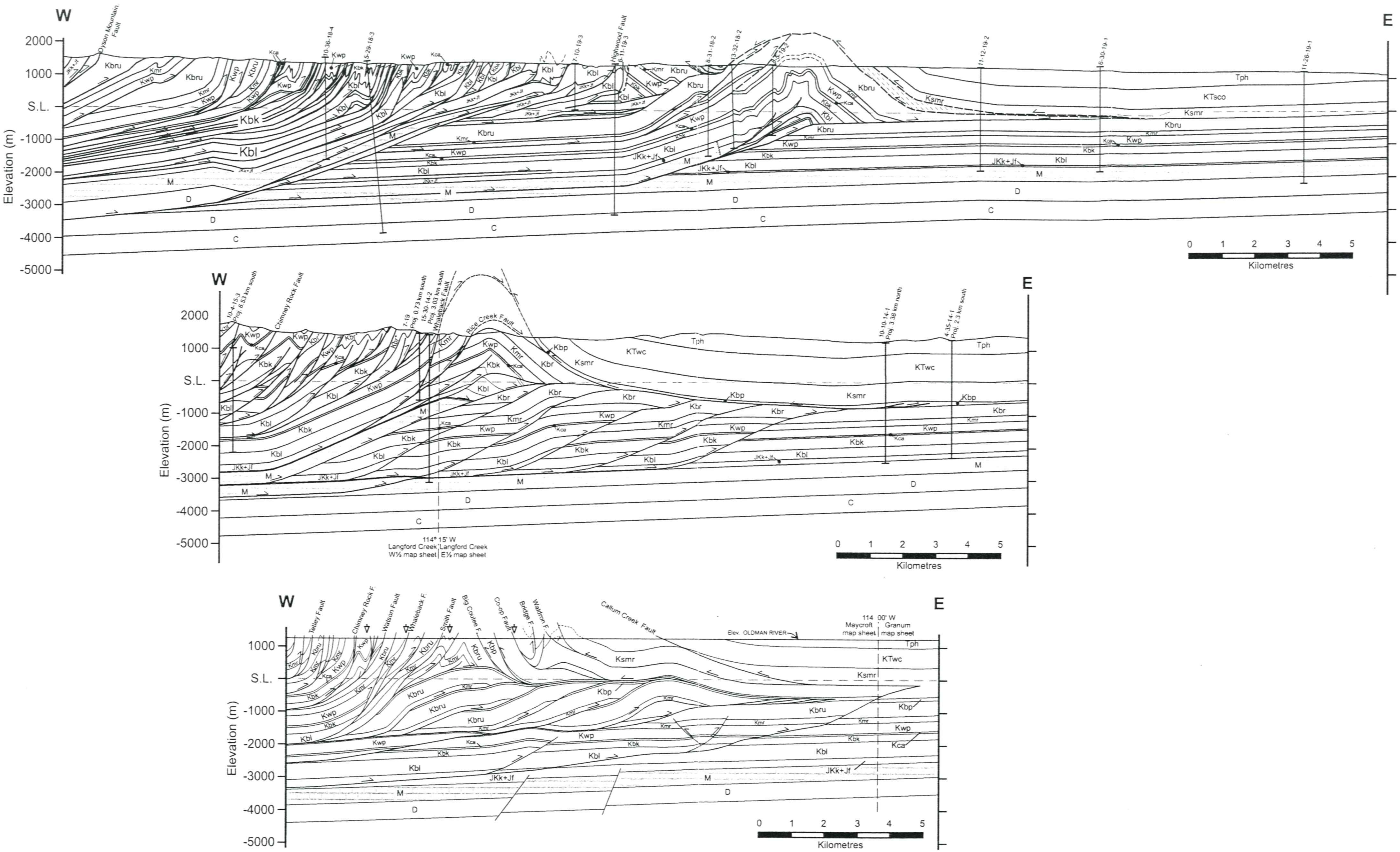


Figure 1-5-5. Turner Valley, Langford Creek, and Maycroft cross sections aligned along structural strike, illustrating changes in structural style.

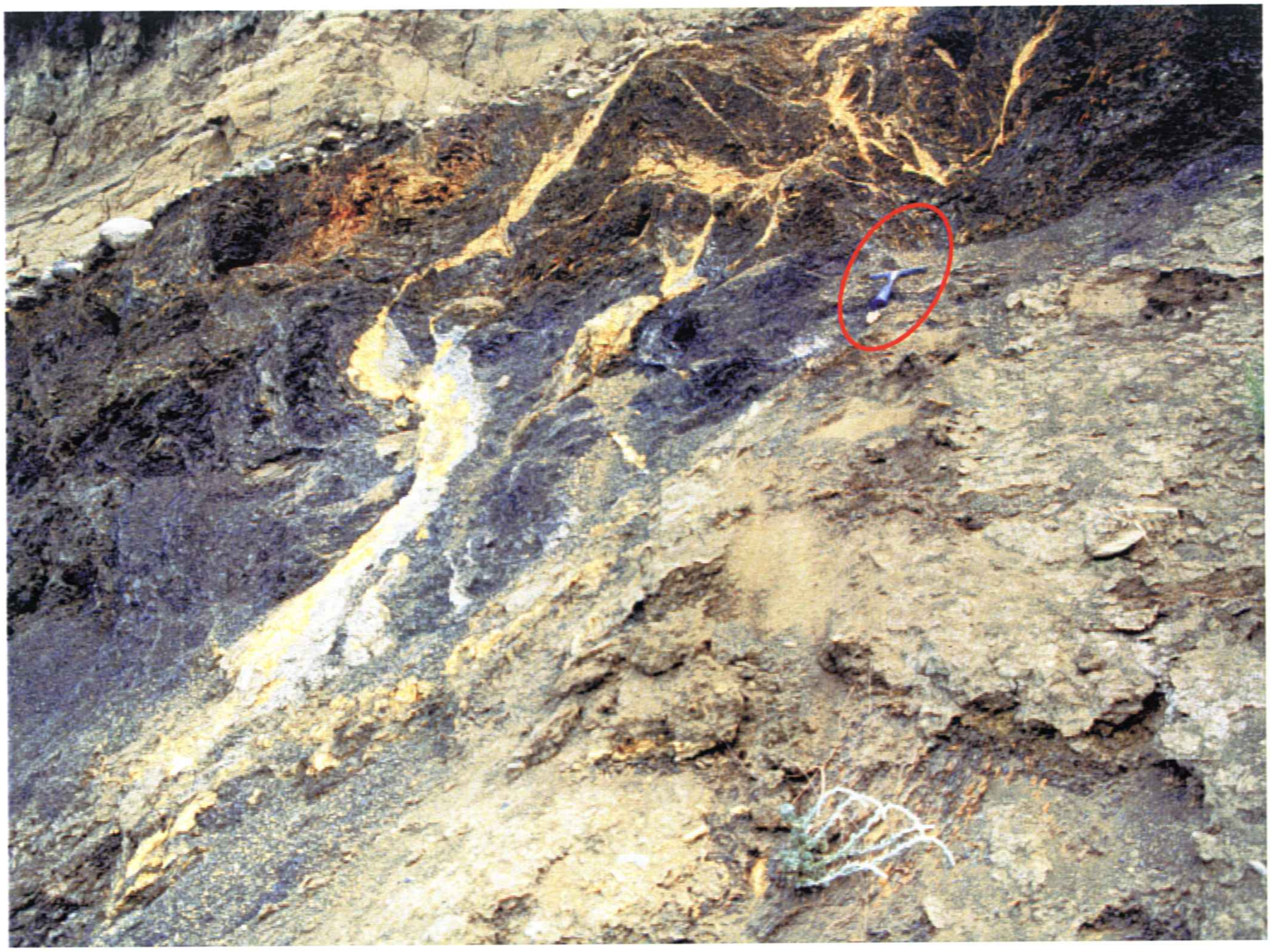


Figure 1-5-6. Outcrop of deformed Bearpaw Formation shale, south bank of Oldman River. Degree of deformation is highlighted by one or more bentonitic shale horizons (yellow-orange). Hammer for scale (circled).

25.20 km Lundbreck Formation outcrop, Belly River Group
26.50 km Belly River Group outcrop
26.80 km Junction with Highway 3A, to Lundbreck Falls Recreation Area, **TURN SOUTH (LEFT) ONTO HIGHWAY 3A**
27.30 km Virgelle Formation outcrop
28.00 km Parking lot at Lundbreck Falls viewpoint; spectacular outcrop of Virgelle Formation
28.05 km Crowsnest River Bridge
28.10 km Access to parking lot on south side of Crowsnest River
29.30 km **Stop 6**; Milk River Group outcrop to north at crest of hill; park on shoulder

Stop 6: Milk River Group outcrop, downstream of Lundbreck Falls Provincial Recreation Area, on Highway 3a near junction of Highway 3 and Highway 22.

Distance: 29.30 km from turnout off Highway 22 to Stop 5a

Access: From Highway 3, take the west access onto Highway 3A to Lundbreck Falls Recreation Area. Drive 2.5 km, passing the falls and continuing over a bridge to the crest of a hill. Park at the side of the road opposite the flat top of a prominent, large outcrop of east-dipping cliff-forming sandstones. Carefully cross the barbed-wire fence to a viewpoint near the cliff edge **(caution!)**.

Theme: Stratigraphic succession of the Foreland Basin

Purpose: Overview of the Upper Cretaceous stratigraphic succession from the uppermost Wapiabi Formation, through the Milk River Group, and view the lowermost Belly River Group strata.

Geology: This is the frequently visited "Lundbreck transition" outcrop on the Crowsnest River west of Lundbreck (Figure 1-6-1). This unit has also been

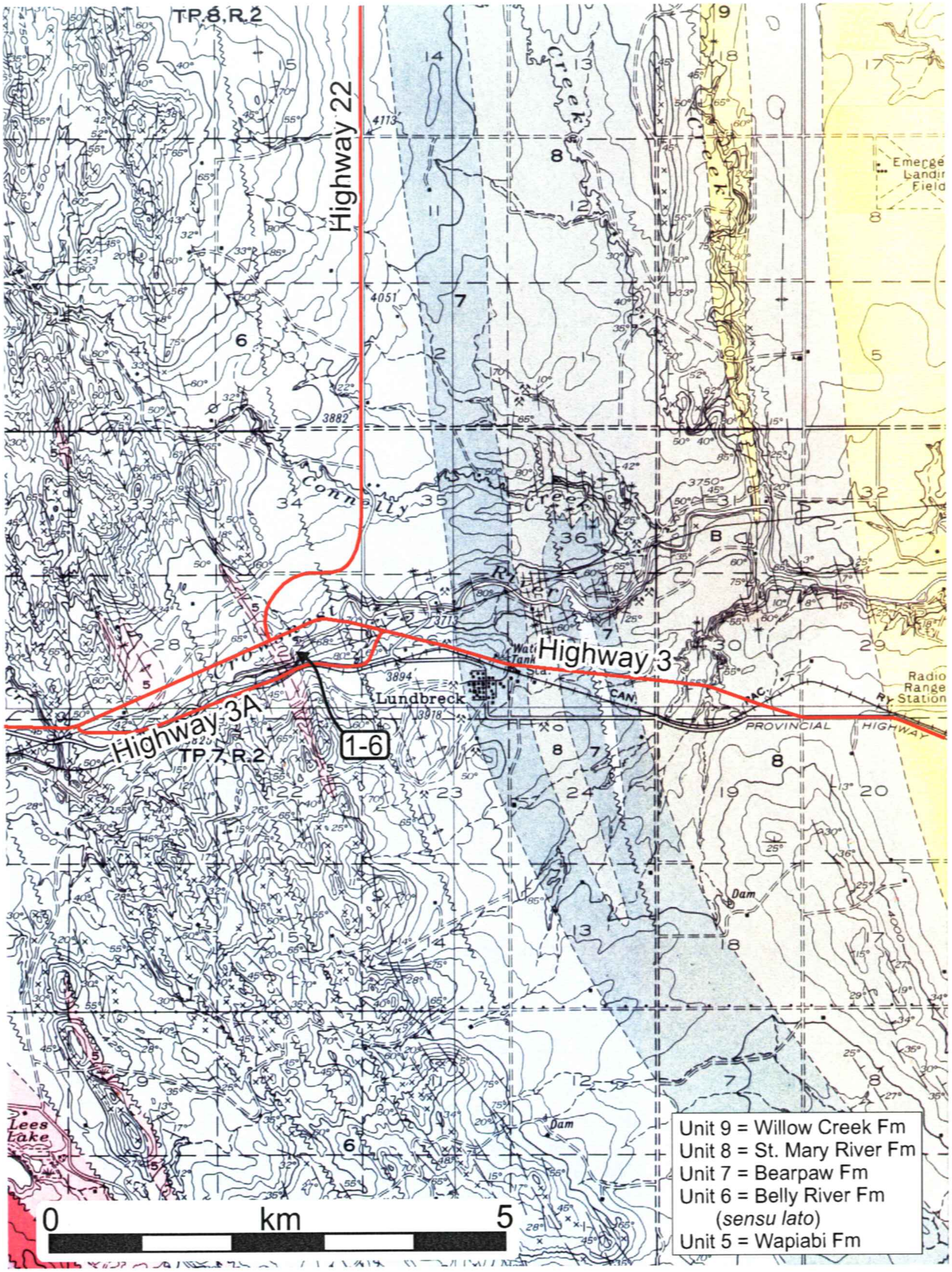


Figure 1-6-1. Detail of GSC Map 816A (Hage, 1945), centred approximately on 49°35'30"N, 114°10'00"W, showing location of Stop 1-6.

known as the Chungo Member of the former Belly River Formation, that is now mapped as part of the Milk River Group (Stockmal, 1995, 1996, 1997.; Lebel and Kisilevsky, 2000). The Milk River Group consists of the Telegraph Creek, Virgelle, and Deadhorse Coulee formations (Figure 1-6-2). It is underlain by the Wapiabi Formation and overlain by the Pakowki Formation (formerly Nomad Member), both marine shales. The Pakowki is overlain in turn by the Belly River Group, mappable locally at the formation level.

At the viewpoint overlooking the Crowsnest River, we are standing on the Virgelle Formation, a shoreface sandstone. The Telegraph Creek Formation presents the lower shoreface transition from the marine Wapiabi Formation, whereas the Deadhorse Coulee Formation is a nonmarine interval above the Virgelle. The description of this outcrop by Lerand and Oliver (1975) is excellent, and very useful for a detailed examination (Figure 1-6-3). The Telegraph Creek Formation corresponds to Lerand and Oliver's units 2 through 9, and the Virgelle Formation corresponds to their units 10 through 13 (the top is not exposed). Four coarsening upward cycles (units 2-3, 4-5, 6-7, and 8-9) are seen in the Telegraph Creek Formation, where the lower unit of each cycle consists of thinly interlaminated shale, siltstone and very fine grained sandstone, and the upper unit consists of very fine to fine grained sandstone with minor siltstone and shale. Bioturbation structures occur throughout the Telegraph Creek. The Virgelle Formation consists of fine to medium grained sandstone with subordinate silty and shaly beds displaying platy to flaggy parting. Soft-sediment deformation features (some spectacular!), massive and chaotically fractured beds, and hummocky cross stratification (HCS) are characteristic of units 10 through 12, whereas low-angle to trough cross bedding characterize unit 13.

Figure 1-6-4 is an annotated view facing north from the viewpoint on top of the Virgelle outcrop. These Milk River, Pakowki, and Belly River units are mappable across the grassy hills. Note how the thick Virgelle sandstone can crop out as discrete, narrower bands, rather than as a single unit, complicating correlation especially on aerial photographs. Figure 1-6-5 is an annotated view of the outcrop from the north, facing south, from Highway 3. The approximate locations of the formation boundaries are marked, including the location of the Pakowki Formation marine shale, and the overlying prominent shoreface sandstone at the base of the Belly River Group (Connelly Creek Formation).

Structurally, we are on the east limb of the Tower Anticline (Figure 1-6-1), in the hanging wall of the east-directed Watson Fault (Jerzykiewicz and Norris, 1993). The interpreted upper detachment of the triangle zone is ~3 km to the east-northeast. To the south, the deformation front swings markedly to the southeast (Price, 1962). The triangle zone continues at least as far south as the Waterton River (township 4), where it was interpreted by Shell Oil Company geologists (as reported in Gordy et al., 1977, where the term "triangle zone" was first used in publication). However, the triangle zone is not expressed at the surface farther to the south in the Cardston map sheet (Lebel, 1994).

Road Log:

29.30 km From Stop 6, continue south on Highway 3A
30.20 km Junction with Highway 3
Reset odometer to ZERO, and turn east (right)
0.00 km North of the junction of Highway 3A and Highway 3 is an excellent, though deformed, exposure of the Lundbreck Formation of the Belly River Group. Here, the Lundbreck is characterized by pale green shale, caliche, and calcrete horizons.
0.60 km To the north are scrappy outcrops of the Drywood Creek Formation, the uppermost subdivision of the Belly River Group. Evidence of coal mining in this formation can be seen in the linear successions of subsidence cavities leading away from the north bank of the Crowsnest River and from sparse piles of slack coal. Two seams of high volatile A and B bituminous coal were mined intermittently between 1903 and 1954.
1.90 km Turnoff to Lundbreck; at this point we cross the upper detachment of the triangle zone and essentially pass out of the east-vergent structures of the Foothills and into structures lying above the upper detachment. The upper detachment appears to be internally complex here, with a west-directed repetition involving the St. Mary River Formation.
2.60 km View at 1:30 of the 52 wind power turbines on Wind Ridge, south of Cowley
4.20 km Willow Creek outcrop, north of highway
4.40 km Willow Creek outcrop, north of highway
5.00 km Cross train tracks
8.60 km Enter west side of Cowley
9.50 km Turnoff to Oldman Dam (north); views to north of Porcupine Hills, and to south of Lewis thrust sheet
12.10 km Willow Creek Formation outcrop
13.60 km Bridge over arm of Oldman Reservoir, Cretaceous-Tertiary boundary exposed in Willow Creek Formation in bank in low water
14.00 km To the north and east, resistant sandstone beds of the Paleocene Porcupine Hills Formation form a series of cuestas along the west side of the Porcupine Hills. This is the west limb of the Alberta Syncline which dips east due to the underlying triangle zone structure.

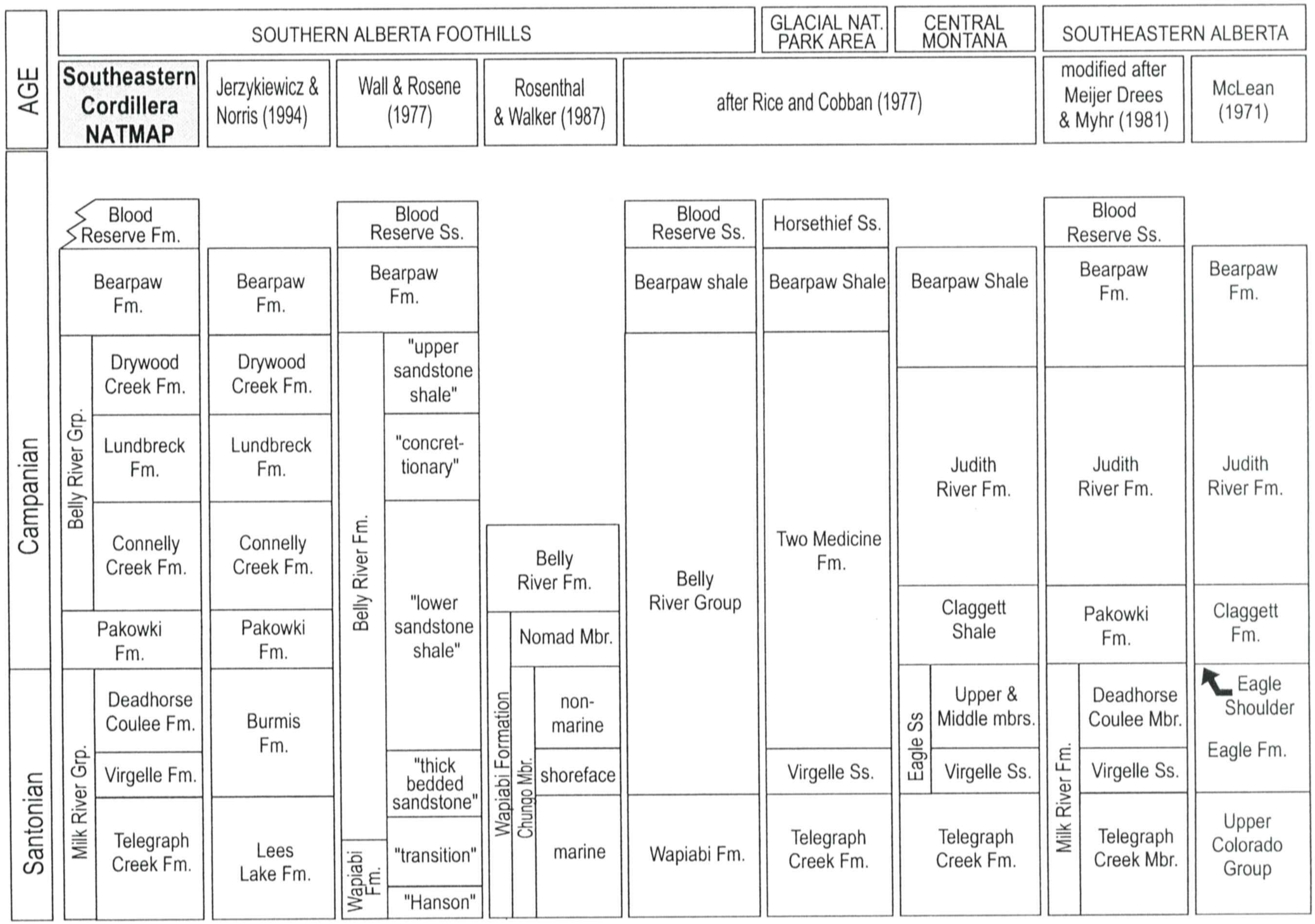


Figure 1-6-2. Lithostratigraphic units applied to Santonian-Campanian strata in southern Alberta and adjacent Montana.

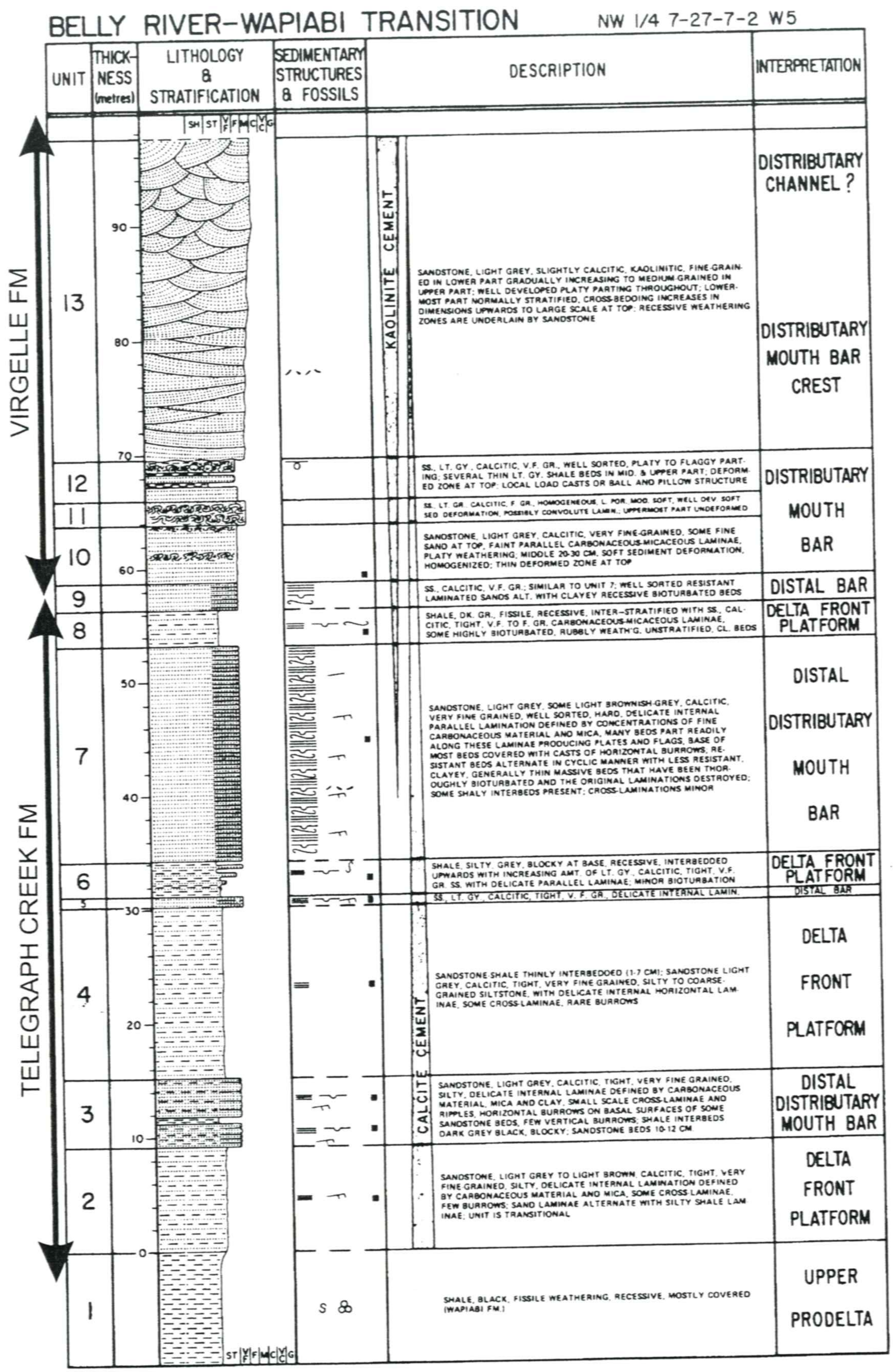


Figure 1-6-3. Measured section, Crowsnest River (from Lerand and Oliver, 1975).

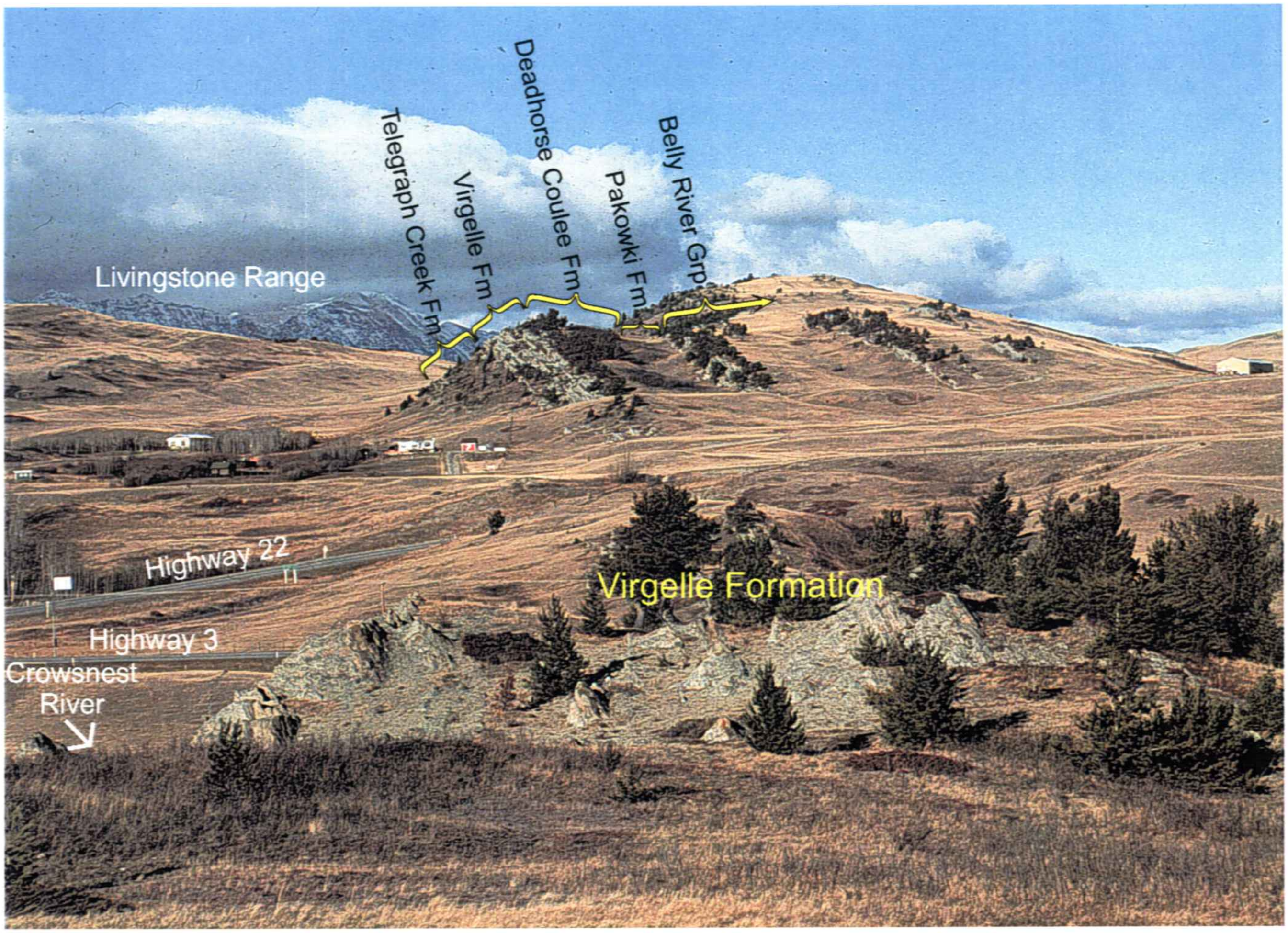


Figure 1-6-4. Annotated view north from top of Virgelle Formation outcrop at Stop 1-6, south side of Crowsnest River. Units along strike on distant ridge are labeled. Mississippian carbonates exposed in the Livingstone Range in far distance.

20.00 km Pincher Junction. **Turn south (right) onto Highway 6 to Pincher Creek.**

In the Pincher Creek area, the leading edge of the Foothills continues to approximate a triangle zone geometry with both wedge and duplex characteristics. Shortening across the wedge area is estimated at approximately 35%, most of the displacement having occurred across low-angle thrust ramps and flats that offset Jurassic to Upper Cretaceous-age strata. Folded Tertiary-age strata indicate that triangle zone development continued through Paleocene time. Other "abandoned" wedge geometries have been identified west of the leading edge of the deformation suggesting that triangle zone development may have been a ubiquitous feature of the Laramide Orogeny. Locally, no commercial hydrocarbon production occurs from the triangle zone; however, both source and clastic reservoir rocks are carried in the wedge, with potential trapping geometries.

Interesting, Hiebert (1992) states that a seismic image of a subtle duplex structure is seen 16 km northeast of the triangle zone in the Pincher Creek area, and suggests that shortening on the Monarch Fault Zone, along the Oldman River near Lethbridge 65 km into the Interior Platform, is due to Laramide compression – food for thought!

Road Log (continued):

22.90 km Turn east (left) on Pincher Creek Bypass (by the A&W restaurant); follow the main road.

24.00 km Bridge across Pincher Creek

25.60 km Leave Pincher Creek, driving south on Highway 6

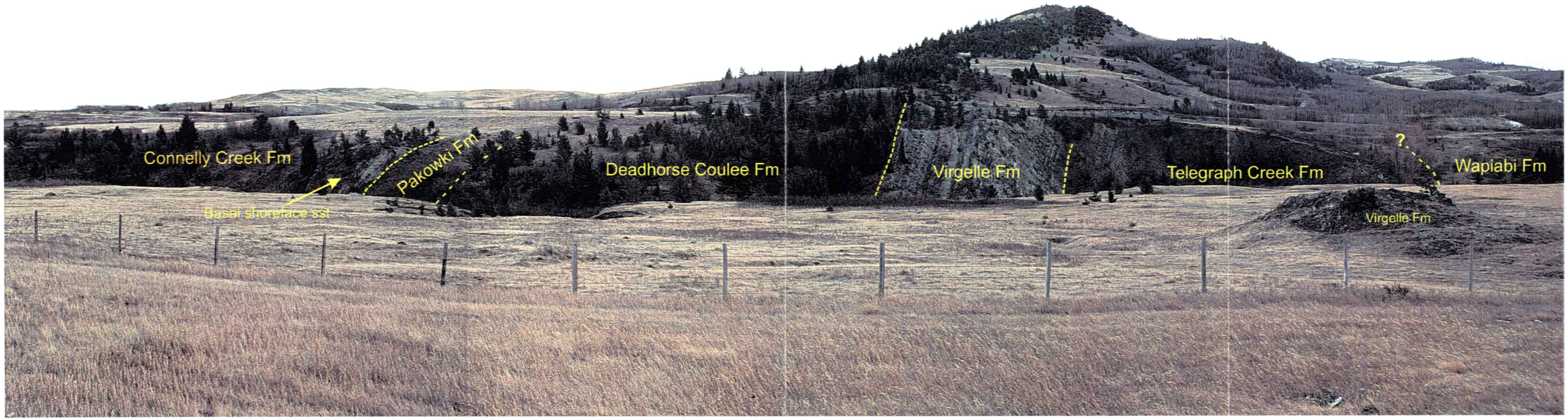


Figure 1-6-5. Panoramic view facing south of Milk River Group outcrop at Stop 1-6, viewed from Highway 3, north side of Crowsnest River. This east-dipping section is complete from the uppermost Wapiabi Formation (marine shale), the Telegraph Creek (lower shoreface), Virgelle (upper shoreface), and Deadhorse Coulee (non-marine) formations of the Milk River Group, the marine Pakowki Formation shale, through to the Connelly Creek Formation of the Belly River Group, the basal unit of which is a prominent shoreface sandstone similar to but thinner than the Virgelle.

26.90 – 27.20 km Gully and road outcrops of east-dipping St. Mary River strata, hanging wall of the upper detachment
27.80 km St. Mary River Formation outcrop

The prominent ranges to the west, which we will discuss in more detail at the last stop today and the first stop tomorrow, consist of Proterozoic rocks carried in the Lewis Thrust sheet. East of the Lewis Thrust in its footwall, new regional stratigraphic subdivisions in the Upper Cretaceous succession have facilitated a new round of structural mapping, as we have already seen to the north. The outcrops of St. Mary River Formation we have just passed lie in the hanging wall of the triangle zone upper detachment, as indicated by studies by Hiebert and Spratt (1996), and Lebel et al. (1997). Along the straight stretch of highway to the south we cross the upper detachment followed by a series of imbricates involving Bearpaw, Belly River, and Milk River strata, eventually encountering a series of Belly River, Milk River, and Wapiabi imbricates that overlies the subsurface Pincher Creek gas field (a culmination of Rundle Group strata). Outcrop through this area is limited and widely scattered, although exposures along Indianfarm Creek and especially the Waterton River and the Belly River are good to excellent.

Road Log (continued):
34.50 km View at 1:00 of the stack at the Shell Canada Waterton Gas Plant
38.90 km Creek crossing
40.10 km Creek crossing
43.50 km Cross beneath railway trestle
44.50 km Junction with Highway 505; **TURN EAST (LEFT) TO WATERTON DAM**
44.60 km View east at 12:30 of the stack at the Pincher Creek Gas Plant
47.60 km Marr Lake to north
50.60 km Turnoff to Palmer Ranch and Pincher Creek Gas Plant
52.90 km Cross abandoned rail bed; outcrop of Connelly Creek Formation
57.80 km Intersection; in immediate hanging wall of the Ockey Thrust; view of Waterton Reservoir at 1:00
61.10 km Cross onto Waterton Reservoir earth dam; views south to Chief Mountain and Waterton Park; to north are exposures of Belly River Group
61.90 km **Turn north (left)** just west of the concrete spillway; follow the road downhill
62.50 km Park at the bottom of the hill, as near the outcrops on the west side of the Waterton River (**Stop 7**) as reasonable (caution if muddy!)

Stop 7: Waterton Reservoir Dam Site
Distance: 62.50 km from east junction of Highway 3 and Highway 3A
Access: After crossing the Waterton Reservoir earth dam, turn down the gravel road just west of the concrete spillway. Proceed to the bottom of the hill, parking as close to the outcrops on the west side of the river as reasonable.
Theme: Triangle zone and Foothills structure.
Purpose: View deformation within Bearpaw, Blood Reserve, and lower St. Mary River strata in the footwall of the Hillspring Thrust.

Geology: The excellent exposures on the west side of the Waterton River, immediately downstream from the Waterton Reservoir Dam, include spectacularly deformed strata of the lower St. Mary River, Blood Reserve and Bearpaw formations in the footwall of the Hillspring Thrust, and upper formations of the Belly River Group in the hanging wall (Figure 1-7-1; Lebel et al., 1997). Figure 1-7-2 is an annotated view of the outcrop, showing the principal structures. These structures include backthrusts, suggestive of a structural history involving sequential development of triangle zones, which may be progressively abandoned as a new frontal triangle zone evolves. These abandoned wedges would be modified by later "out-of-sequence" deformation, uplifted, and partly eroded, leaving behind only vestiges of the original structure for us to examine (and argue over!).

At this latitude, the Bearpaw Formation is imbricated at map scale by foreland-directed thrusts, along with overlying and underlying strata, in contrast to its role in forming the upper detachment to the north (compare northern cross sections with the section adjacent to the Waterton Dam locality shown in Figure 1-7-3) Hinterland-directed backthrusts are mapped a few kilometres to the east, however (Lebel et al., 1997), within the lower St. Mary River Formation. This character is gradually lost southward toward the International Border.

Road Log:
Retrace the route back along Highway 505 to Highway 6.
Reset odometer to ZERO. Turn south (left) onto Highway 6 toward Waterton Park.
0.00 km Junction of Highway 6 and Highway 505
0.85 km Turnoff to Shell Canada Waterton Gas Plant
2.80 km Drywood Creek bridge
5.80 km Yarrow Creek bridge
7.20 km Twin Butte General Store

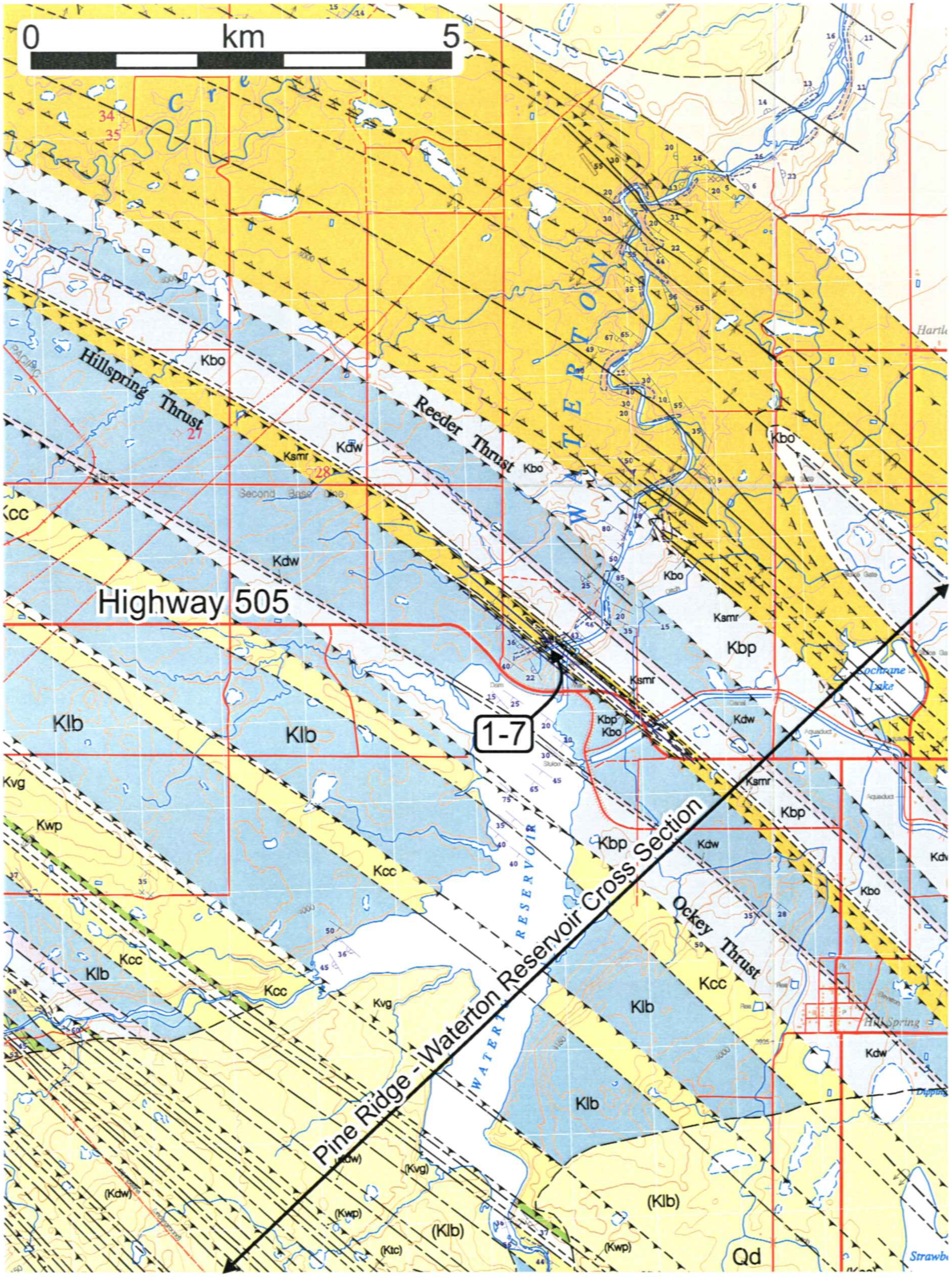


Figure 1-7-1. Detail of GSC Open File #3543, map of Pincher Creek (Lebel et al., 1997), centred approximately on 49°20'00"N, 113°40'30"W, showing location of Stop 1-7 and Pine Ridge-Waterton Reservoir cross section.

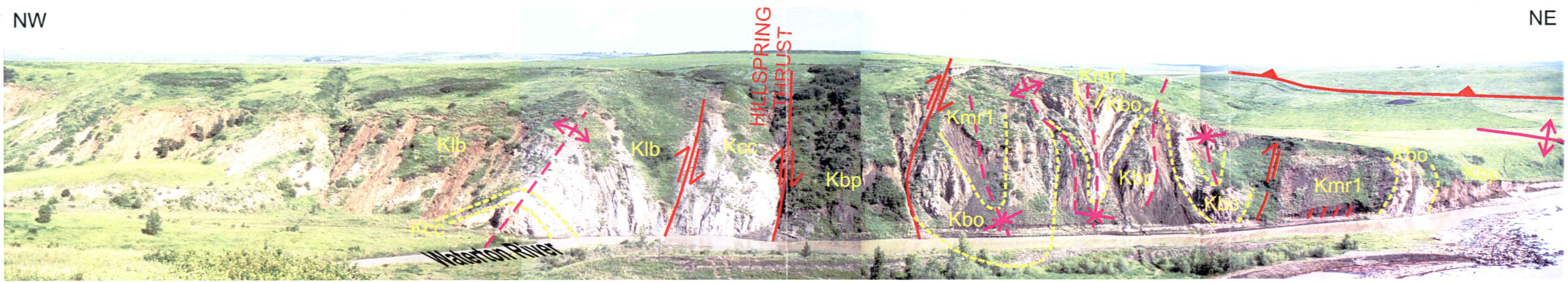


Figure 1-7-2. Panoramic view of outcrop of the Hillspring Thrust, north bank of the Waterton River, immediately downstream (east) of the Waterton Reservoir Dam. The Hillspring Thrust places lowermost Belly River Group strata on Bearpaw Formation. Deformation in both the hanging wall and footwall is very well exposed. Kcc = Connelly Creek; Klb = Lundbreck; Kbp = Bearpaw; Kbo = Blood Reserve; Kmr = St. Mary River.

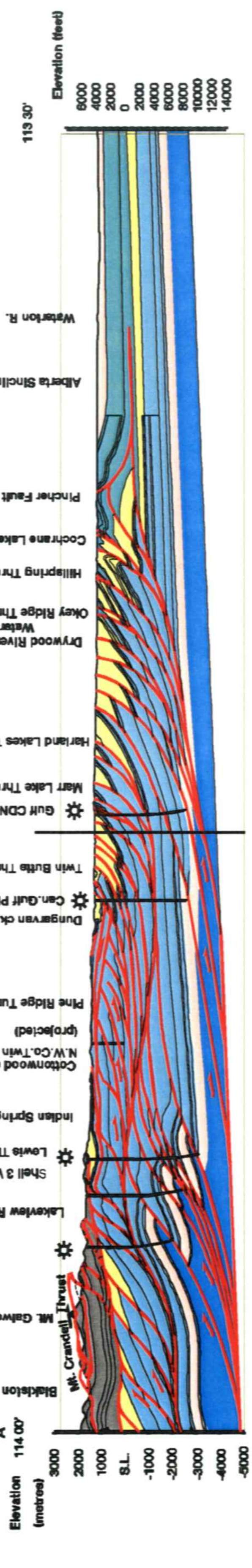


Figure 1-7-3. Pine Ridge - Waterton Reservoir cross section through the Waterton, Pincher Creek, and Raley map areas (D.K. Norris, modified by D. Lebel, preliminary).

13.00 km View at 10:00 to valley of Dungarvan Creek, and northeast end of Pine Ridge

16.60 km **Stop 8** – official viewpoint overlooking Waterton Lakes

Stop 8: Waterton Lakes viewpoint, Pine Ridge, Highway 6

Distance: 16.60 km from the junction of Highway 6 and Highway 505

Access: Pull off and park at the designated and signed observation point.

Theme: Foothills structure.

Purpose: Overview of Lewis thrust sheet and Waterton Lakes National Park, and discussion of structural setting of the Pine Ridge Fault in relation to the Foothills

Geology: This spectacular viewpoint affords an unparalleled opportunity to enjoy some of the world's best scenery (on a clear day) and consider some extremely interesting structural geology. To the south are the three Waterton Lakes in Waterton National Park. The Front Ranges within view from this point are imbricated, exclusively Proterozoic rocks, carried by the great Lewis Thrust (displacement just south of here on the order of 115 km). We will discuss the Proterozoic stratigraphy, and the structural geology of the Lewis Thrust sheet, in more detail on the morning of Day 2.

Note that the topographic break between "mountains and prairies" that Waterton National Park and the surrounding area illustrates as a vital physiographic and ecological contrast is not a reflection of the geological structure. As we have seen between here and Pincher Creek, beneath the "flat prairie" are the Foothills structures of the Cordillera. What we will see at surface in the "Inner Foothills" on Days 2 and 3 lies beneath us here at Waterton.

As seen in Figure 1-8-1, the view point is located in the hanging wall of a significant Foothills thrust, the Pine Ridge Fault, which is interpreted to form the roof thrust, localized at the top of the Wapiabi Formation (upper Alberta Group), of a duplex involving Kootenay, Blairmore, and Alberta Group strata (Figure 1-7-3). The Pine Ridge Thrust crops out along Dungarvan Creek (4 km to the NW) as a northeast-directed but slightly northeast-dipping folded thrust. It underlies the Milk River Group, with the Virgelle Formation sandstone forming the crest of Pine Ridge. Between the Castle River to the north, and the North Belly River to the south, the upper Wapiabi Formation forms an important bedding-parallel detachment, as observed and interpreted along the Dungarvan, Yarrow, Drywood, Pincher, Mill, and Gladstone creeks, and

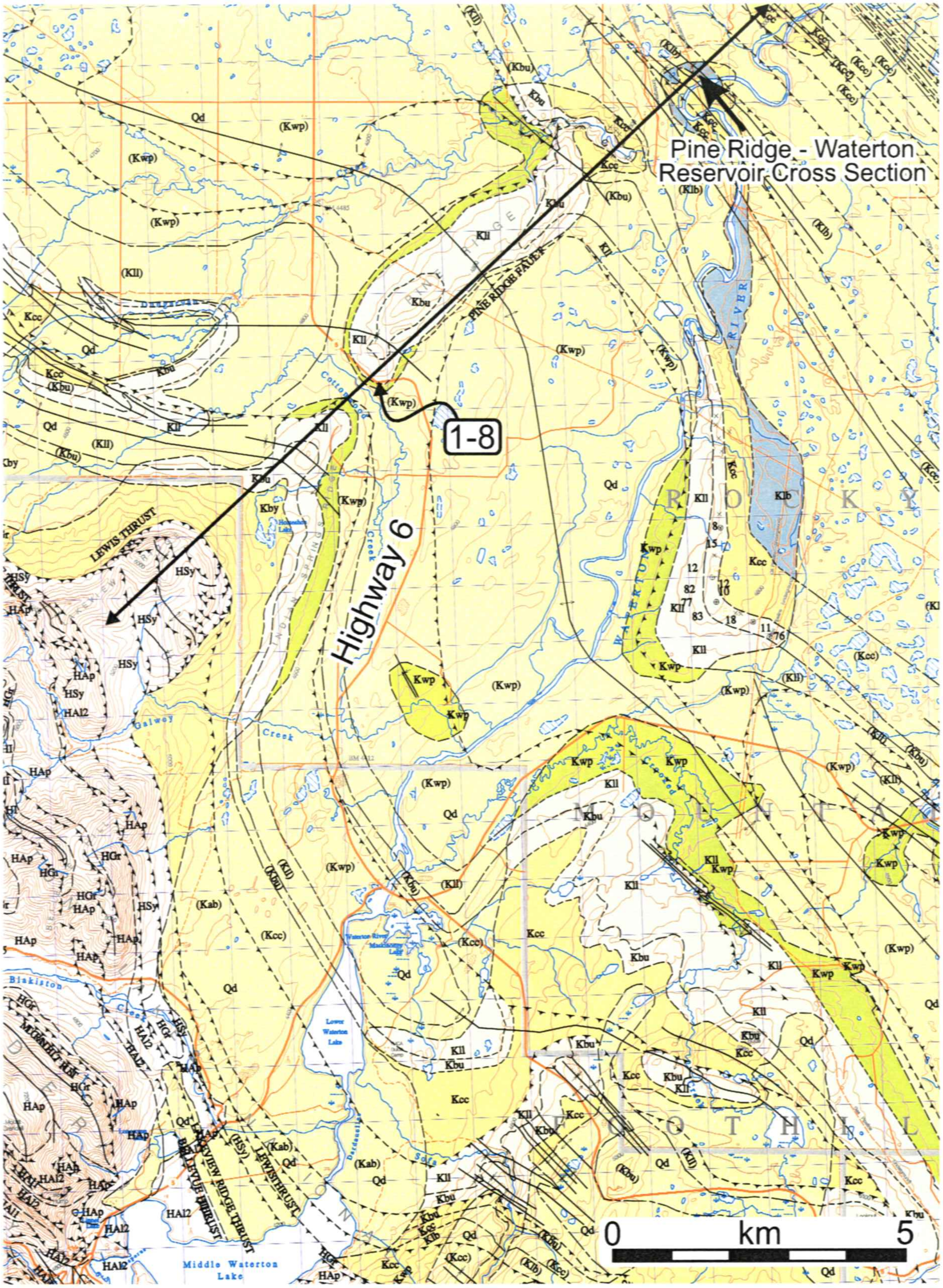


Figure 1-8-1. Detail of GSC Open File #2855, map of Waterton Lakes (Lebel et al., 1994), centred approximately on 49°09'00"N, 113°49'30"W, showing location of Stop 1-8 and Pine Ridge - Waterton Reservoir cross section.

near the headwaters of the North Belly River. At most of these localities, the Wapiabi is also tectonically thickened. The structural style across the Foothills at this latitude, involving relatively flat-lying thrust slices, and the virtually horizontal Pine Ridge roof thrust, contrasts markedly with the structure north of Crowsnest River, where thrusts are commonly rotated by underlying structures to near-vertical attitudes. As suggested by the cross section through Pine Ridge and Waterton Reservoir (Figure 1-7-3), this may have been a consequence of having the thick, competent, Lewis thrust sheet overlying this portion of the Foothills during deformation. At this position we are approximately 10 km west of the south end of the Pincher Creek gas field (Figure 1-8-2) and approximately 10 km east of the south end of the Waterton gas field (Figures 1-8-2 and 1-8-3).

Foothills geology south to the International Border: To the south, Foothills structure is inferred largely from two relatively well exposed cross-strike outcrop sections along Lee Creek and the Belly River. In between these two sections, few outcrops are present and only a few sandstone ridges can be traced through an area of relatively low relief. The section along Lee Creek shows a series of structural repeats of formations in the Belly River Group and uppermost Wapiabi Formation. Most strata are moderately inclined in thrust sheets striking NW-SE, up to about 5 km north from the international border where strata are broadly folded. A few of the sandstone ridges of the Virgelle Formation can be traced throughout the outer Foothills to the Belly River and the Waterton River. These ridges provide a basis for inferring extensions of structures mapped along Lee Creek. Seismic data suggests that most of these thrust faults merge into a detachment one kilometre below the surface. This detachment occurs near or below the base of the Alberta Group shales and it separates Upper Cretaceous rocks from the older succession. Only a few of the surface faults can be traced into Lower Cretaceous Blairmore Group and older rocks.

New work by Lebel suggests a significantly different Foothills structural style as the Front Range is approached. A few, broadly folded thrust sheets compose the overall surface structure of the area. Beneath these thrust sheets, the Wapiabi Formation is more deformed locally and generally by extension (Lebel et al. 1994). In the upper reaches of Lee Creek section, strata and faults dip shallowly and are involved in broad folds. Along the escarpments situated on both sides of the valley at the head of the Belly River, the Virgelle Formation is nearly flat lying, where it is cut by no significant thrusts – a similar geometry to that mapped near Pine Ridge and in Dungarvan Creek. In contrast, in exposures along the North Belly River (west branch of the headwaters of the Belly River), the underlying Wapiabi Formation is folded and faulted and thickened by several moderately to steeply inclined, south-west dipping thrust faults. This too suggests a detachment in the upper Wapiabi Formation below the Virgelle sandstone.

Road Log:

16.60 km From Stop 6, continue south along Highway 6

21.00 km View west to Lakeview Ridge of multiduplex structure in Mesoproterozoic rocks of the Lewis thrust sheet (Siyeh Formation)

24.50 km Entering Waterton Lakes National Park

26.50 km Turnoff from Highway 3 to Waterton Village – **turn south (right)**

27.00 km Entrace gate; to the southeast (left) is Vimy Peak, in the immediate hanging wall of the Lewis thrust (to be discussed in detail at the first stop on Day 2)

31.00 km View south-southwest of the spectacularly situated Prince of Wales Hotel, and west to Mt. Crandell

31.60 km Creek crossing, and turnoff to Red Rock Canyon

33.00 km Mesoproterozoic Altyn Formation outcrop

34.50 km Turnoff to Prince of Wales Hotel

34.70 km Mesoproterozoic Altyn Formation outcrop

34.90 km Turnoff to Cameron Lake

Proceed to motel.

Overnight Accommodation and Dinner in Waterton Lakes Town Site

N.B. In late afternoon and early evening, it is advantageous to view aspects of the surrounding geology, which will be discussed on Day 2, Stop 1. In particular, views to the east to Vimy Peak from the western shore of Upper Waterton Lake are well illuminated at this time. See discussion and annotated figures for Day 2, Stop 1. You may also wish to stroll along the western edge of the town site to Cameron Falls, where Cameron Brook falls over Waterton Formation, in the immediate hanging wall of the Lewis Thrust. Historically, Upper Cretaceous strata were exposed in the creek bed (Lewis Thrust footwall), but this is now obscured by earthworks.

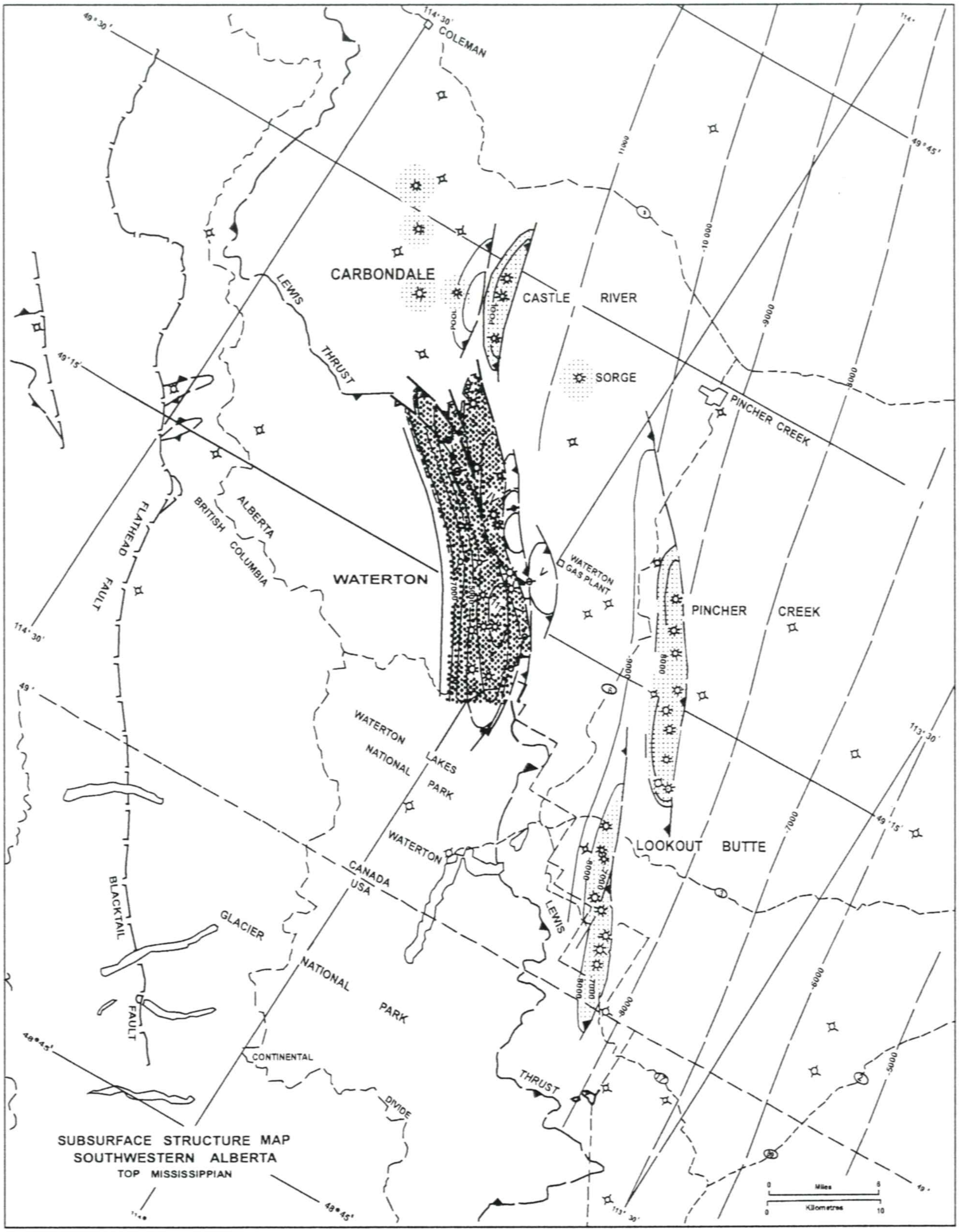


Figure 1-8-2. Subsurface structure map, southwestern Alberta (top Mississippian) (from Gordy et al., 1977).

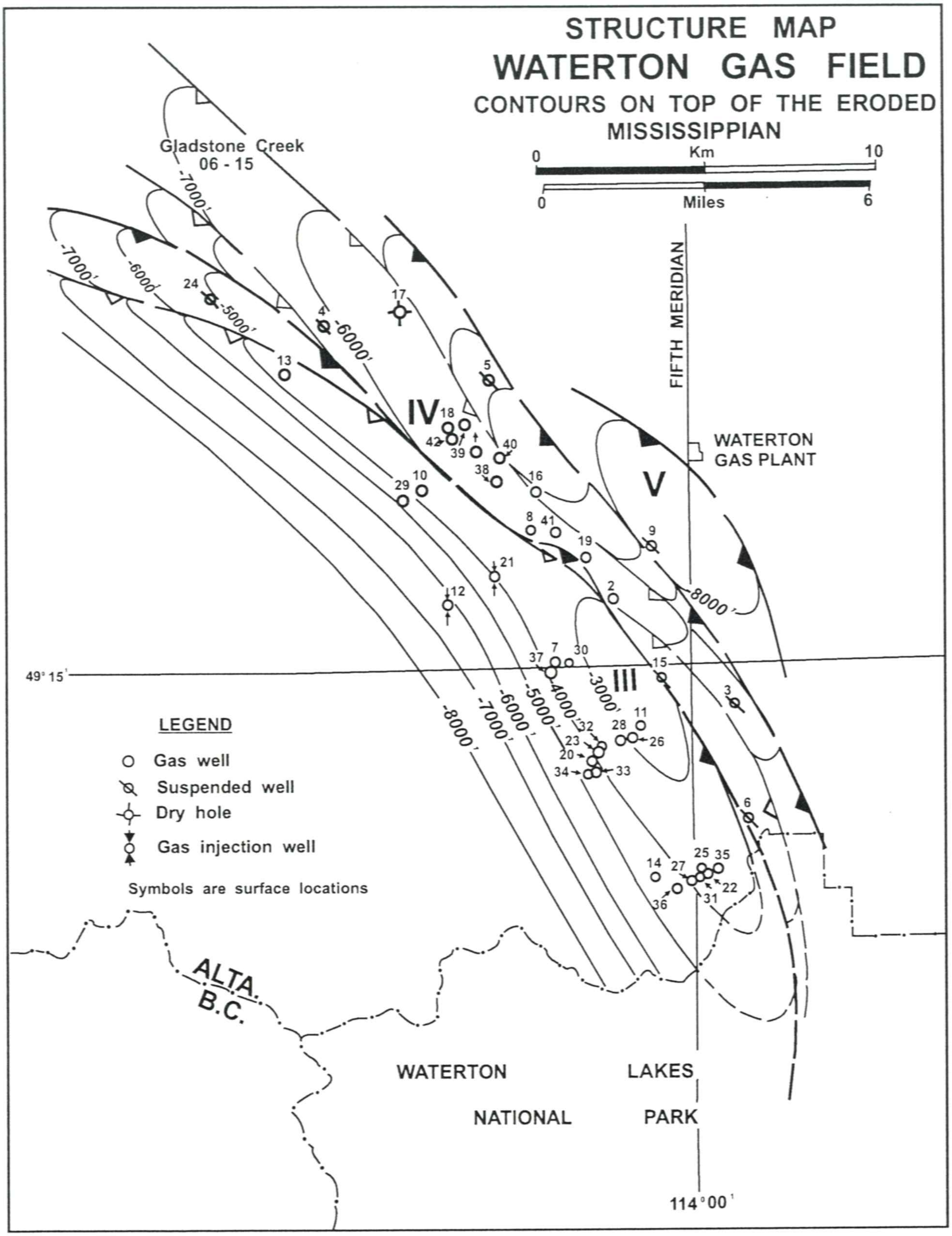


Figure 1-8-3. Structure map of the Waterton Gas Field, top of Mississippian (from Gordy et al., 1977).

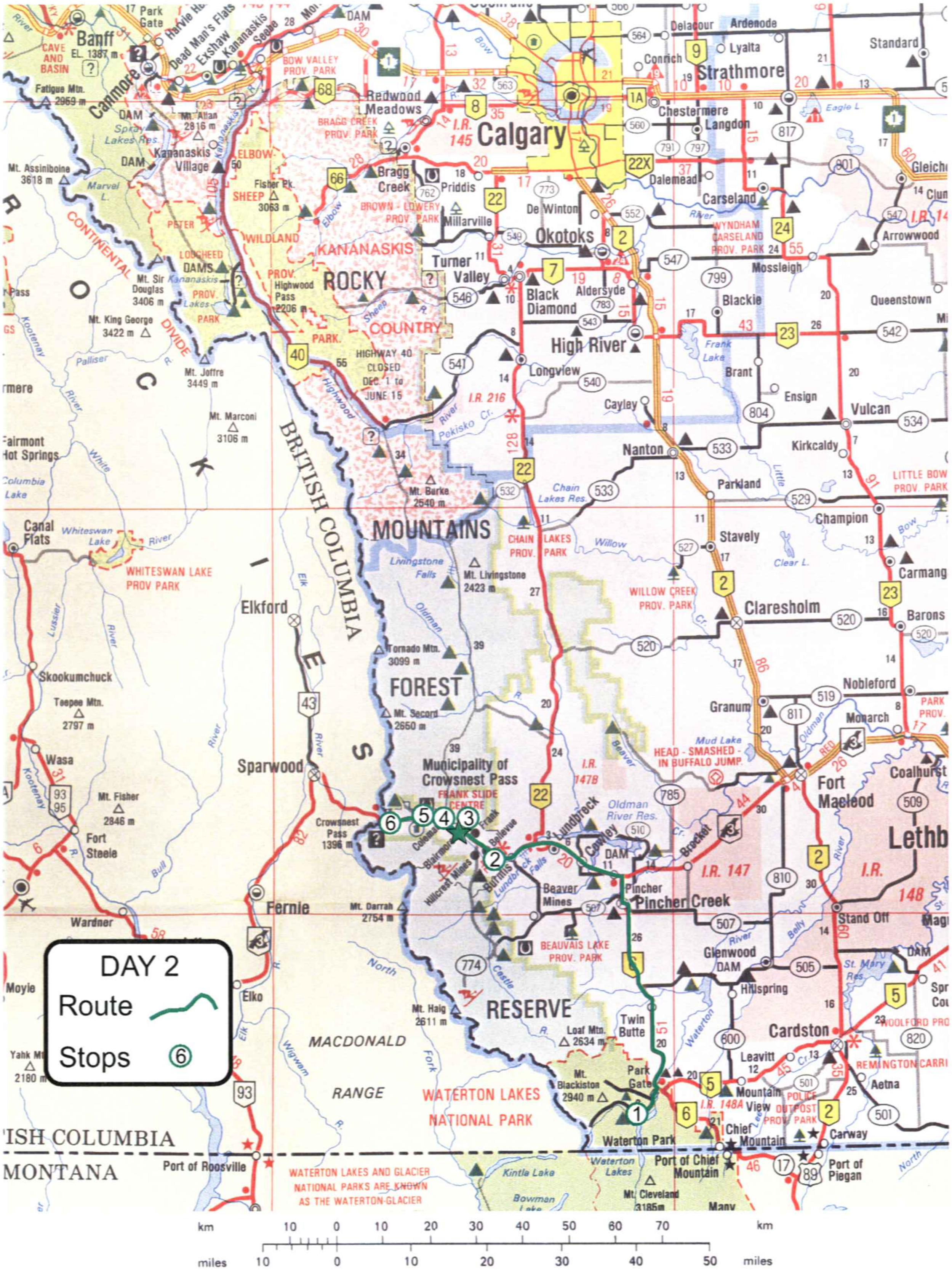


Figure 2-0-1. Road map of southern Alberta showing the route and stop locations for Day 2.

DAY TWO

Lewis Thrust Sheet and Crowsnest Reentrant

(refer to Figure 2-0-1)

Road Log:

Retrace route back through town to the turnoff to the Prince of Wales Hotel, turn east (right) up the access road and park in the parking lot.

Stop 1: Waterton National Park, Prince of Wales Hotel

Distance: 0.0 km at junction of access road to hotel and main road to town.

Access: Turn up the access road to the hotel, and park in the parking lot. Walk around the hotel to a viewpoint on the south side.

Theme: Introduction to the Lewis thrust sheet.

Purpose: View of Lewis thrust sheet structure and stratigraphy, and overview of Day Two.

Geology: The Prince of Wales Hotel lies within Waterton National Park which overlaps the southern Alberta Foothills and the Rocky Mountain Front Ranges immediately north of the Canada-USA border. The western part of the park and surrounding area is marked by the Lewis thrust sheet (carrying the Mesoproterozoic Purcell Supergroup), while the Foothills belt occupies the eastern part (only Upper Cretaceous strata exposed at the surface; Figure 2-1-1). A generalized stratigraphic diagram of the Crowsnest Pass area, including Proterozoic units, is shown in Figure 2-1-2. A stratigraphic table of the Purcell Supergroup only is shown in Figure 2-1-3. The northeastern corner of the Waterton 1:50,000 map sheet is within 5 kilometres of the edge of the Foothills belt (triangle zone).

The structural complications on the west face of Vimy Peak (to the southeast; Figure 2-1-4), Mount Crandell (to the northwest; Figure 2-1-5) and the Bear's Hump (smaller flank of Mount Crandell to the west-northwest) are best viewed in the morning light. The viewpoint by the hotel overlooking the Upper Waterton Lake is a kame terrace deposited by the Cordilleran ice sheet.

The Proterozoic rocks of Waterton Lakes National Park and the surrounding region are now referred to as the Purcell Supergroup (Figure 2-1-3) and have recently been dated as having accumulated during a short interval around 1440 Ma to 1470 Ma (Aleinikoff et al., 1996; Anderson and Davis, 1995). Originally the oldest part of the succession was believed to be present at Waterton, but recent study of the multiduplex structures at the base of the Lewis thrust sheet (Fermor and Price, 1987) has shown that older stratigraphic units underlie the Waterton Formation in the western Clarke Range. These older strata have been named the Tombstone Mountain Formation, which underlies Waterton Formation, and Haig Brook Formation, which underlies Tombstone Mountain Formation, although the base of the Purcell succession is faulted away. The Purcell Supergroup succession consists of 3300 m (11,000 feet) of shallow water and intertidal clastics and carbonates accumulated on the margin of Belt Basin. This thick sequence of varicoloured sediments can be divided into upper and lower successions by a 60 m (200 feet) thick volcanic formation now known as the Nicol Creek Formation (a.k.a. Purcell Lava) located in the upper half of the succession. In the region of the Park and the Crowsnest Pass the Cambrian succession is characteristic of the Montania depositional realm, a positive paleotectonic element discussed in the Introduction, above.

Two thrust faults are of major importance in the immediate area of Waterton Lakes. They are the Lewis Thrust, at the base of the Purcell succession, and the Mount Crandell Thrust (Figures 2-1-4, 2-1-5, and 2-1-6). The Lewis Thrust forms a large salient of superficially flat-lying, but intensively deformed and far transported strata of the Belt-Purcell Supergroup that has been displaced eastward along the Lewis Thrust. This immense thrust sheet forms the skyline to the south and west as the Park is approached. In some places it is possible to glimpse Windsor Mountain whose castellated turrets are carved from Mississippian and Upper Devonian strata underlain by a thin Cambrian and Devonian succession. Lewis thrust reaches its maximum stratigraphic separation in the vicinity of the International Boundary. The horizontal displacement on the Lewis Thrust sheet is estimated to be in the order of 115 km, with 70 km of displacement on Lewis Thrust itself, and an additional 45 km of transport on underlying thrusts involving the Paleozoic succession. The Lewis Thrust is more than 425 km long. We will examine spectacular structures in the immediate hanging wall in detail later this afternoon near Crowsnest Lake. There, however, the stratigraphic relationships in the hanging wall are significantly different than those observed in the Park.

Sandstones of the Upper Cretaceous Belly River Group generally occur in the footwall at the leading

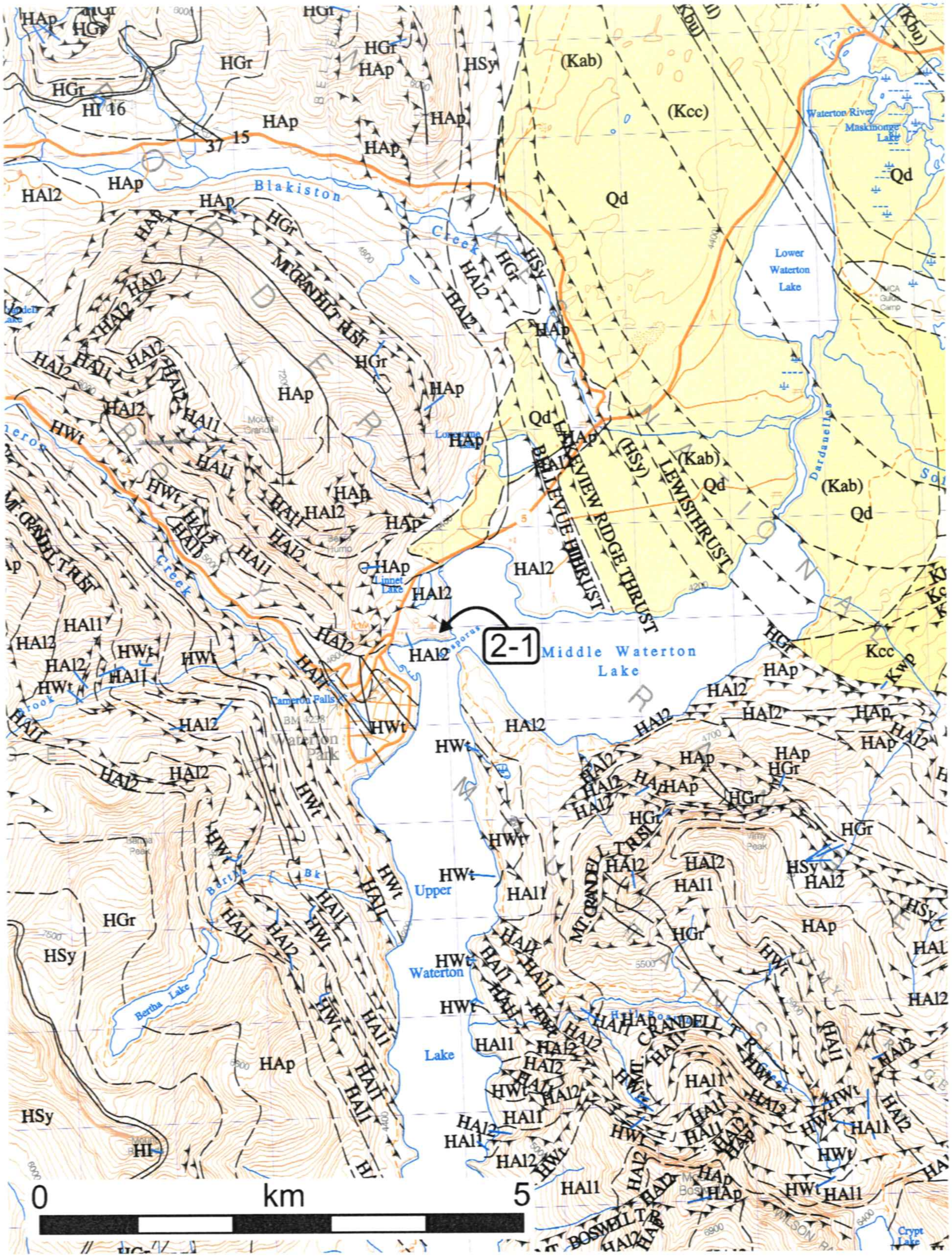


Figure 2-1-1. Detail of GSC Open File #2855, map of Waterton Lakes (Lebel et al., 1994), centred approximately on 49°03'30"N, 113°54'00"W, showing location of Stop 2-1.

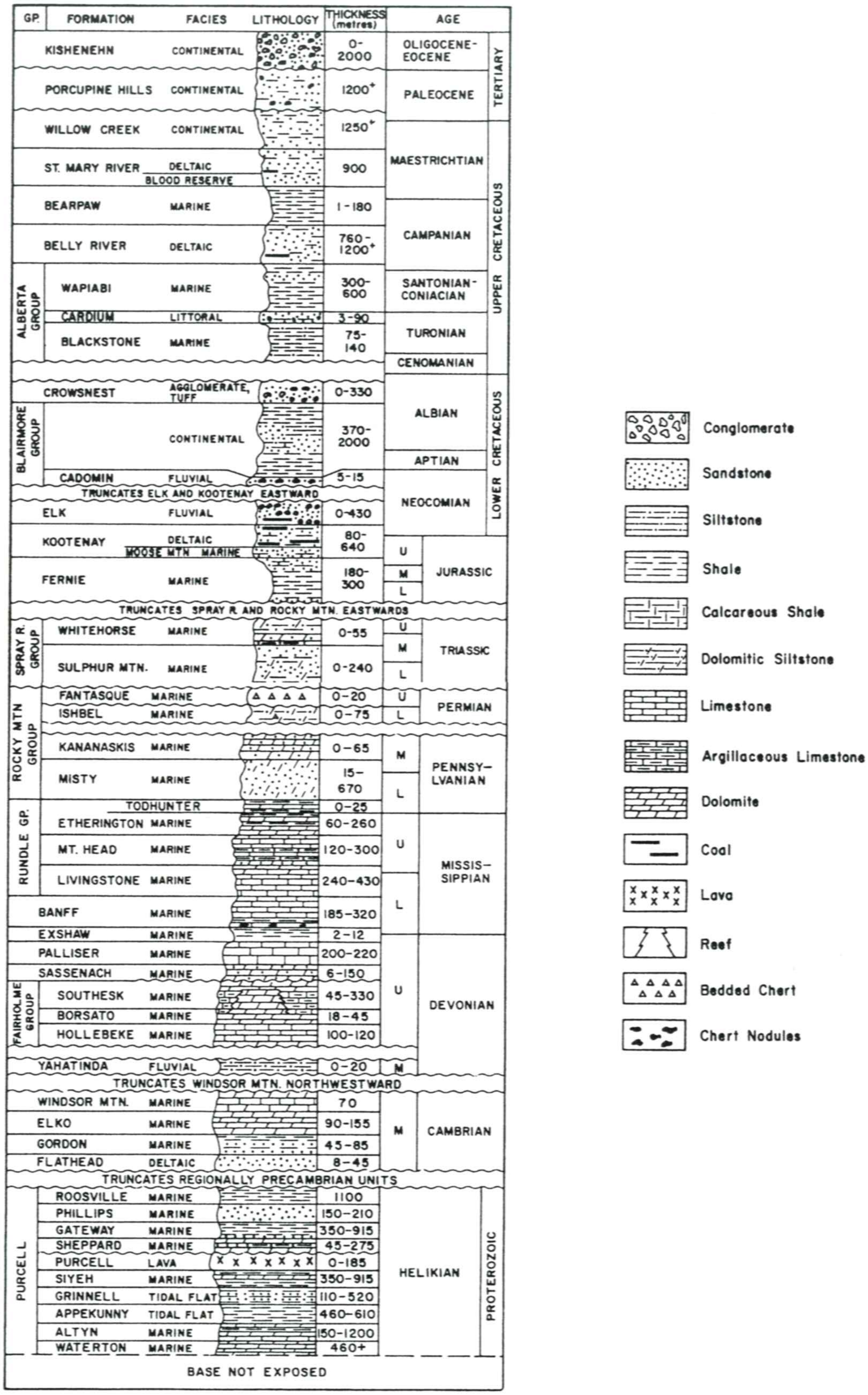


Figure 2-1-2. Stratigraphy of the Crowsnest Pass area, SW Alberta and SE B.C. (from Norris and Bally, 1972, XXIV IGC Field Excursion Guidebook A25-C25).

	thickness	lithology	
gabbro		sill intrusions	
KINTLA	3000 feet (900 m)	red, green and grey argillite and quartzite { Roosville, Phillips, Gateway	
SHEPPARD	600 feet (180 m)	grey dolomite and dolomitic argillite; recessive, brown weathering	
PURCELL LAVA	200 feet (60 m)	dark purplish green, amygdaloidal; resistant, dark grey weathering	
SIYEH	2000 to 3000 feet (600 to 900 m)	Upper (600 feet, (180 m)	interbedded dolomite, quartzite, algal limestone, green argillite; three bands of red argillite
		Middle (900 feet, 275 m)	massive to thickly bedded dolomite, molar tooth and algal limestone, grey argillite; resistant, cliff forming, grey weathering
		Lower (500 feet, 150 m)	interbedded grey dolomite, quartzite, green and black argillite; recessive, buff weathering
GRINNELL	750 to 1000 feet (230 to 300 m)	recessive, bright red argillite at the base, inter-bedded with green argillite and white, green and red quartzite and conglomerate in resistant upper part	
APPEKUNNY	1100 to 1600 feet (330 to 500 m)	Upper (600 to 1000 feet, 180 to 300 m)	massive, green laminated argillite and thinly bedded green quartzite; with maroon and red argillite in the northeast
		Lower (500 to 600 feet, 150 to 180 m)	interbedded green quartzite, dolomite and quartz pebble conglomerate, green and red argillite; grading southwestward into massive, green, laminated argillite
ALTYN	500 to 1400 feet (150 to 425 m)	Upper (100 to 200 feet, 30 to 60 m)	thinly bedded, sandy, gritty dolomite, algal dolomite, black argillite
		Middle (200 to 400 feet, 60 to 120 m)	massive, cliff forming, sandy dolomite, algal dolomite, dolomite and quartz pebble conglomerate; light grey weathering; in the northeast brown weathering gritty dolomite at the base
		Lower (200 to 800 feet, 60 to 250 m)	thinly bedded, laminated, grey dolomite; light buff weathering, recessive
WATERTON	600 feet (180 m)	red, green grey dolomite and limestone	

Figure 2-1-3. Stratigraphic table of the Purcell Supergroup in Waterton Lakes National Park (modified after Gordy et al., 1977).

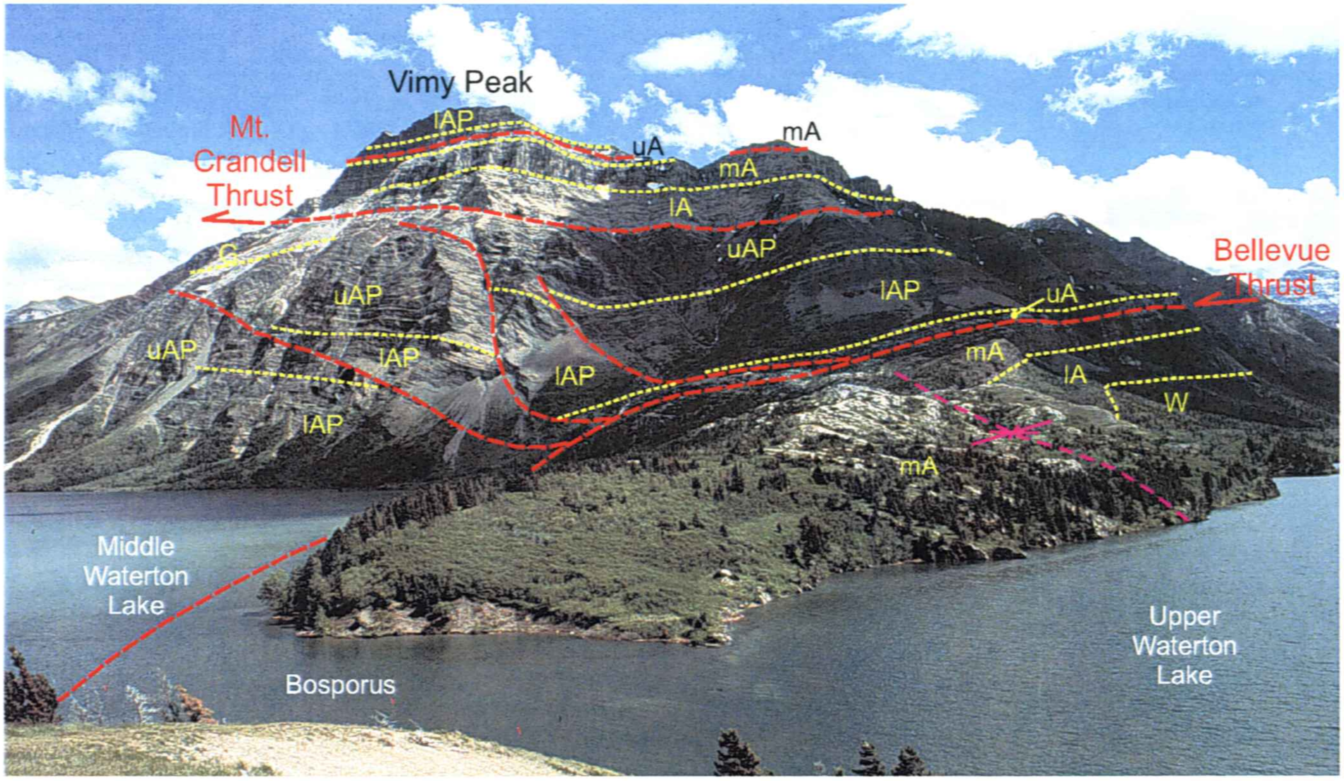


Figure 2-1-4. Annotated view of Vimy Peak, Waterton Lakes National Park, from the Prince of Wales Hotel (geology after D.K. Norris *in* Gordy et al., 1977).

edge of the Lewis Thrust, where it generally follows a major footwall flat. At the Waterton town site historical drilling shows that Upper Cretaceous Wapiabi Formation shales that underlie the Belly River Group (*sensu lato*), locally lie in the immediate footwall of the Lewis thrust.

The Mount Crandell thrust sheet, a major imbricate of the Lewis Thrust, is easily identified on Vimy Peak, across the lake to the southeast (Figure 2-1-4). It can be mapped throughout the Waterton area and may well be the middle thrust on Chief Mountain, the klippe of Lewis thrust sheet 7 km south of the International Boundary in northwestern Montana. Only the four lowest formations of the Belt-Purcell Supergroup present in this area can be seen. To the southeast, on the flanks of Vimy Peak, the lowest beds are Waterton Formation – brown, red and grey limestones and dolomites in excess of 180 m (600 feet) thick. The Altyn Formation – buff and light grey, cliff-forming gritty and algal stromatolitic dolostones – gradationally and ?conformably overlies the Waterton Formation. Altyn Formation occurs near both the bottom and the top of Vimy Peak because of repetition by the Mount Crandell Thrust. The Appekunny Formation – green argillite with green quartzitic interbeds – forms the central band of the mountain above Altyn Formation The Appekunny Formation caps Vimy Peak above the Mt. Crandell Thrust, although these beds are difficult to see from this location. On the extreme northwest flank of Vimy Peak the brilliant red argillite and mudstones of the Grinnell Formation gradationally and ?conformably overlie Appekunny Formation. Grinnell Formation – white and red quartzite with conglomerate interbeds, displaying abundant ripple marks, mud cracks and salt hopper casts – is cut out below the Mount Crandell Thrust to the southwest.

Mount Crandell thrust is exposed on Mount Crandell to the northwest of the viewpoint (Figure 2-1-5). As on Vimy Peak, resistant, light grey Altyn Formation dolostones are thrust over the green Appekunny Formation argillite. Just to the left of the gully two small thrusts offset the Mount Crandell Thrust. East of the gully, the Mount Crandell Thrust is folded about a northwest-trending axis and cuts rapidly up section in the transport direction, in both its hanging wall and footwall, so that the Appekunny Formation above the thrust is in contact with red argillite of the Grinnell Formation below it on the northeastern slopes of the mountain. The Mount Crandell Thrust circles Mount Crandell to form a klippe (Figure 2-1-6). The thrust is folded over the antiformal duplex structure of Altyn and Waterton strata, the culmination of which is indicated by the valley of Cameron Creek. These repeats produce the stack of east-dipping slices of Altyn Formation dolostones that form the Bear's Hump and the southern ridge on Mount Crandell. The Mount Crandell Thrust has a horizontal displacement of about 3 km and a stratigraphic throw of 300 to 600 m.

The Oil and Gas Resources of the Cordillera: Waterton Park includes the discovery well of Waterton oil and gas field and the first production of oil from the Fold and Thrust Belt. What you see in topography is a rough proxy for the structure in the subsurface. The buried and obscured structures of the Foreland Belt anticlinal oil and gas province are comparable in scale to the mountains you see from the viewpoint.

Environment vs. Development: The Waterton park reserve, originally significantly larger, was first identified in 1895. The Canadian National Parks system originated out of an economic motivation to establish tourism and provide passenger load for the railways. The parks were originally conceived as "recreational playgrounds" in the middle of a "wilderness". Numerous activities, now completely forbidden, were not just tolerated but encouraged. In Canadian Glacier National Park, near Revelstoke, B.C., a unique Alpine caribou herd was hunted, to extinction. Changing perceptions and values have led to changing policies and regulations in the Parks, which are now considered "wildernesses" in the middle of a "recreational playground". These changes have been rapid and the vestiges of the old park policies with their obvious conflicts among access, use and preservation are obvious from this viewpoint. In the 1980's the Canadian Park Service, responding to an article in Canadian Geographic magazine entitled "Islands of Extinction" introduced a new more aggressive policy of park management known as "Ecosystem Integrity". Through this policy the interests of preservation in the parks were seen to extend beyond their legal boundaries into the surrounding regions that bordered them. The change in park policy accompanied a time of tension over federal-provincial economic and taxation issues that added to the adversarial nature of an environmentally and territorially aggressive policy, especially in Alberta.

Waterton Park borders the largest producing sour gas field in the Canadian Cordilleran Structural Province (Figure 1-8-3) and it is adjacent to an active region of two provincial forests. These features highlight the competing interests for the use of the eastern slopes of the Rocky Mountains. The resilience of Canadian regulation and legislation serves as an example as to how these competing interests were compromised. They are especially a credit to the foresight and stewardship of the Alberta provincial government and its agencies. The policy of the eastern slopes shows that with the correct legislative and social framework the best interests of the economy and the environment can be compromised. This does not mean that they there is not conflict, and it is not to say that there are not those who believe that certain principals cannot be compromised. It is only a "wealthy society that can afford to have an environmental conscience" (Wm. Fyfe, president the Royal Society of Canada, 1992). Recent changes in public focus, the emphasis on the economy and jobs, and quicker financial recovery of certain provincial governments compared to the federal government, have all taken much of the inertia away from the Parks Service. The reality of the situation is that the Federal Government has voted with its pocket book and the old uneasy compromise between preservation and development hobbles on.

***Road Log*:**

Proceed from the parking lot back out to the main road. **Reset odometer to ZERO**. Turn north (right) onto the main park road.

0.00 km Turnoff to Prince of Wales Hotel; From the Hotel we retrace our steps from yesterday north to Pincher Creek on Provincial Highway 6.

1.50 km Mesoproterozoic Altyn Formation outcrop

2.90 km Creek crossing, and turnoff to Red Rock Canyon

7.50 km Entrance gate; approximately 6 km west of the Lookout Butte (Rundle Group) gas field.

8.00 km Junction with Highway 6 – **turn north (left)**

10.00 km Leaving Waterton Lakes National Park

13.50 km View west to Lakeview Ridge of multiduplex structure in Mesoproterozoic rocks of the Lewis thrust sheet (Siyeh Formation); As we leave Waterton Lakes National Park note the prominent, light grey weathering algal biostromes and the dark grey diabase sill in the middle Siyeh Formation in the Clarke Range, to the west. The Purcell Lava forms prominent castellated peaks above the Siyeh on Cloudy Mountain and Mount Dungarvan. Chief Mountain of the Clark Range, to the south, is separated from the Lewis Range in the north by Lower and Upper Waterton Lakes. An appreciation of the folding and faulting there may be obtained from attempting to trace the bright red argillite of the Grinnell Formation from west to east across the face of the range between Vimy Peak and Sofa Mountain. The deformation is intimately associated with displacements on several major splays from the Lewis Thrust, including Lakeview Ridge and Bellevue Hill Faults. The light buff-weathering cliffs on Lakeview Ridge, are formed by dolostones and

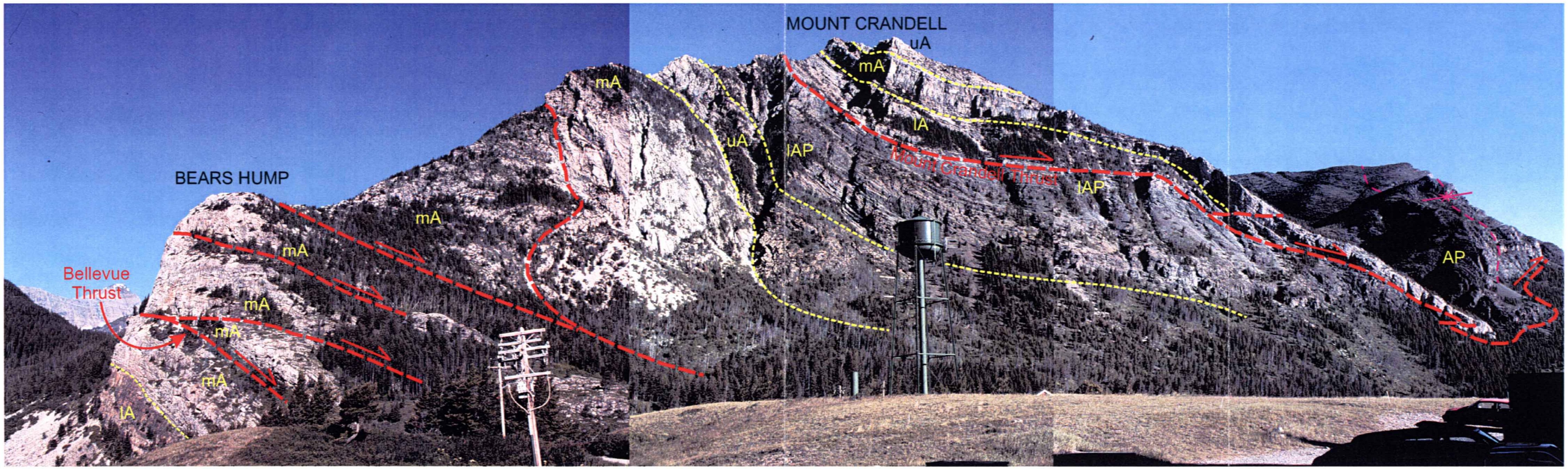


Figure 2-1-5. Annotated view of Mt. Crandell and Bears Hump, Waterton Lakes National Park, viewed from the Prince of Wales Hotel (geology after R.J.W. Douglas and D.K. Norris *in* Gordy et al., 1977).

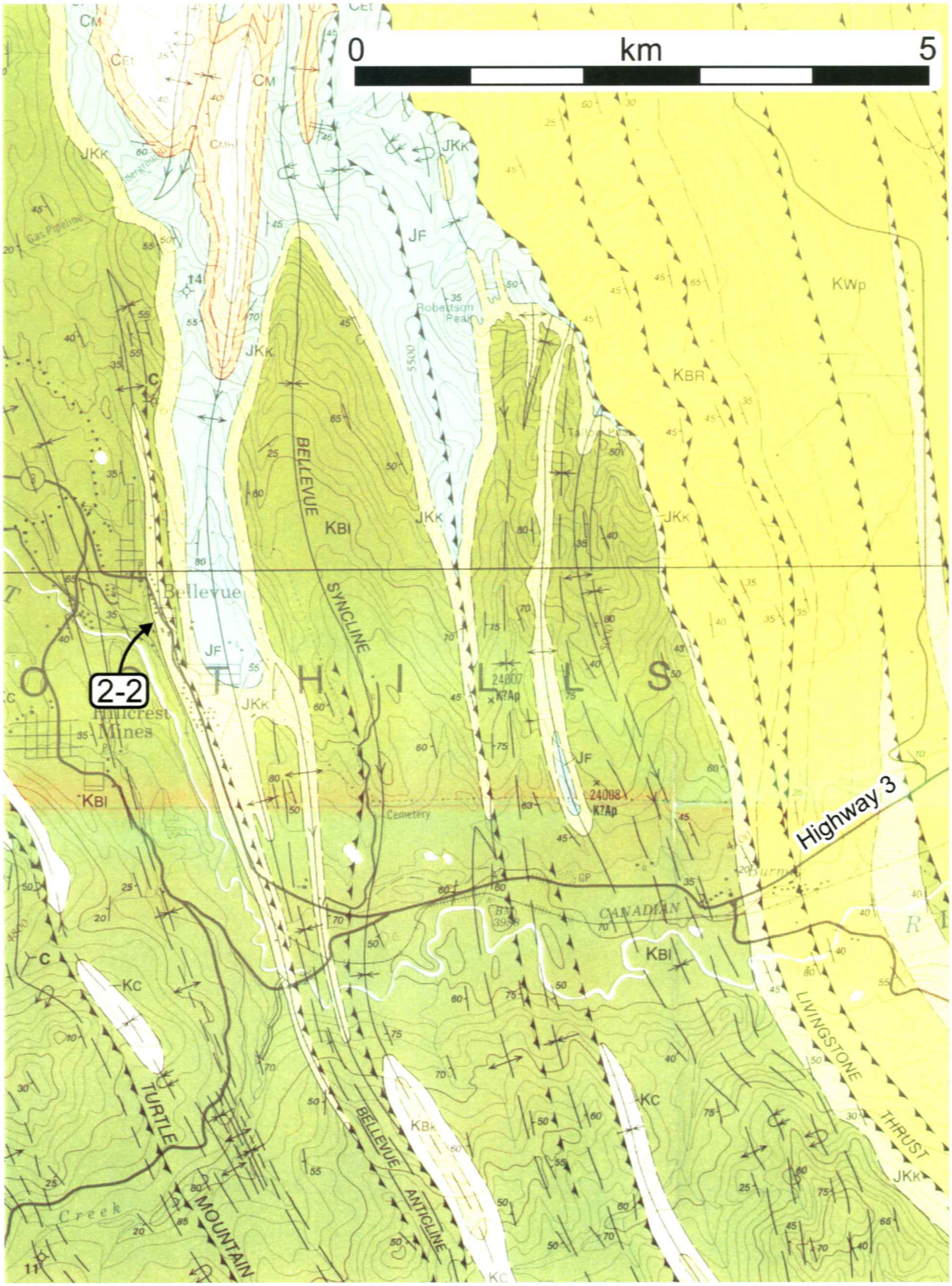


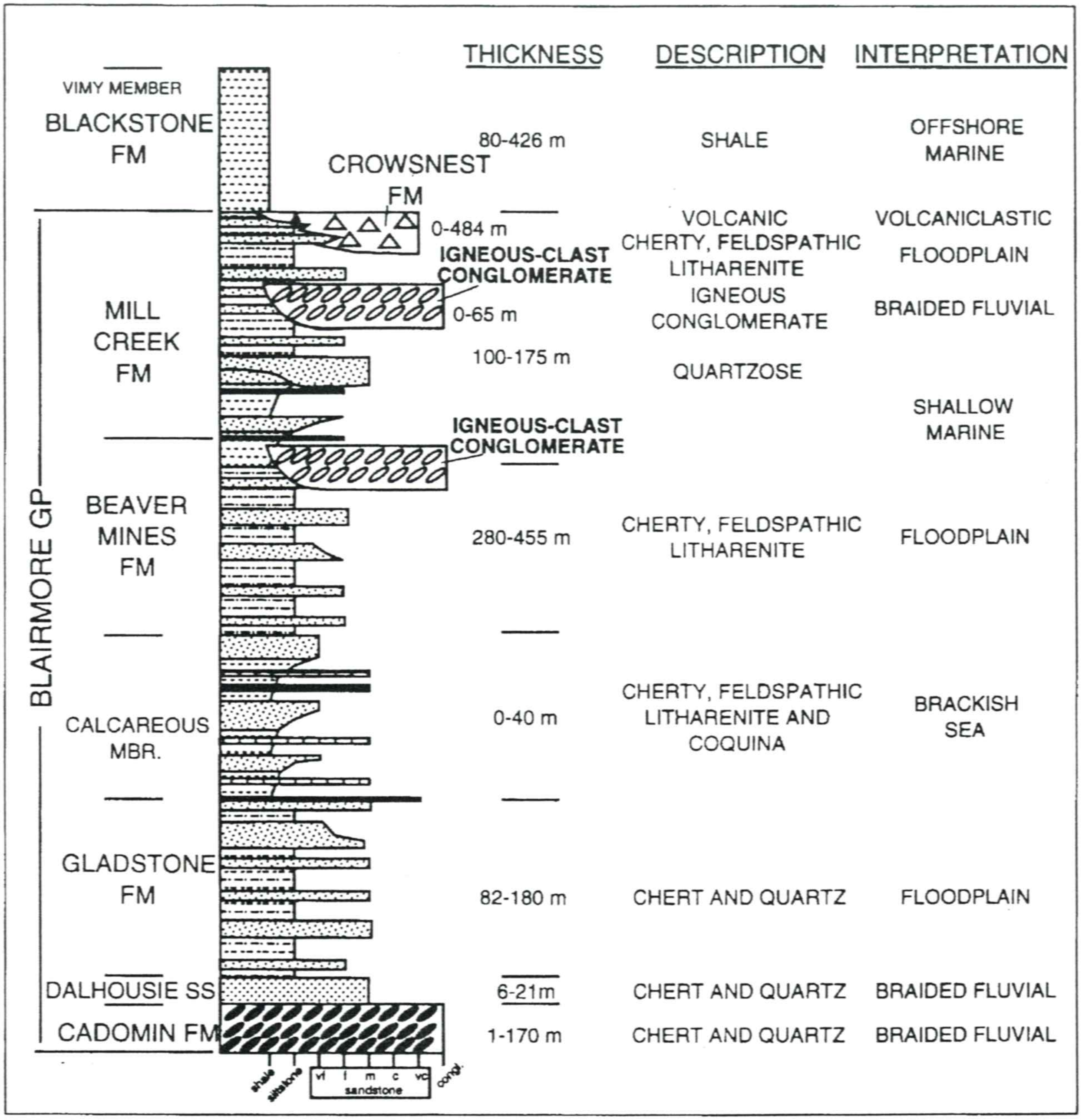
Figure 2-2-1. Detail of GSC Map 1829A (Norris, 1993) of Blairmore (west half), centred approximately on 49°34'30"N, 114°19'30"W, showing location of Stop 2-2 in the hanging wall of the Livingstone Thrust.

Figure 2-2-2. Outcrop at Stop 2-2. The Dalhousie Sandstone, at the base of the Blairmore Group, rests unconformably on the Mist Mountain Formation of the Kootenay Group (conglomeratic Cadomin Formation is absent).

pebble conglomerates characteristic of the Cadomin Formation. This facies is commonly referred to as the "Dalhousie Sandstone" particularly in the subsurface around Turner Valley (Figure 2-2-3). There is a prominent colour contrast near the base of the cliff-forming sandstone, which unconformably overlies coal, sandstone and siltstone of the Lower Cretaceous Mist Mountain Formation, Kootenay Group (Figure 2-2-4). The lithology, bedding style and colour changes within the sandstone succession marks the contact. A similar contact relationship may be viewed approximately 2 km south along Highway 3.

Stratigraphy of Columbian Clastic Wedges: The Upper Jurassic and Lower Cretaceous succession (Figures 2-2-3 and 2-2-4) encountered from Bellevue west comprises the two clastic wedges inferred to be indicative of the Columbian orogenic phases. The lowest part of this succession is the Jurassic Fernie Formation, a succession predominantly composed of brownish-grey to black shales with interbeds of sandstone, siltstone, and limestone. The lower part of the formation includes interbeds of phosphatic limestones and sandstones and black cherty limestone overlain by a well-bedded sandstone, siltstone, and black oolitic limestone, concretionary bands, and shell accumulations; the upper part is characterized by interbeds of glauconitic sand, brown weathering siltstone and sandstones, and concretionary bands, fraught with complex stratigraphic relationships and a confusing stratigraphic nomenclature. The lower and middle portions of the formation shows clear evidence of a cratonic source, while the uppermost portion of the formation, where preserved, exhibits a coarsening upward succession that passes into the Kootenay Group of the first Columbian clastic wedge. The Fernie forms a major regional structural detachment above the Paleozoic carbonate succession (Figure 1-1-2).

Late Jurassic/Cretaceous Kootenay Group (Gibson, 1979) gradationally and conformably overlies Fernie Formation. The Kootenay Group comprises three formations (Figure 2-2-4; Gibson, 1979, 1985). The basal Morrissey Formation is predominantly a cliff-forming sandstone; the middle Mist Mountain Formation is characterized by interbedded sandstone, siltstone, mudstone, shale, rare conglomerate and economically important coal seams; and the upper Elk Formation contains interbedded sandstone, siltstone, mudstone and shale with thin coal seams and local chert-pebble conglomerate, and only occurs west of the Lewis thrust fault, outside of the study area (Gibson, 1979). Kootenay Group extends throughout the Rocky Mountain Foothills, and parts of the eastern Front Ranges of southeastern British Columbia and southwestern Alberta, from just north of the International boundary to the North Saskatchewan River. The Kootenay Group reaches a maximum thickness of 1100 metres near Sparwood, British Columbia and thins to the east beneath the disconformably overlying Blairmore Group.



Stratigraphic context of the igneous–clast conglomerate. Most occurrences of the conglomerate are in the Mill Creek and upper Beaver Mines formations of the Blairmore Group. Note that multiple, stacked occurrences of the igneous–clast conglomerate are extremely rare. In any given section, the conglomerate occurs in either the Mill Creek or upper Beaver Mines Formation.

Figure 2-2-3. Stratigraphic context of the igneous-clast conglomerate in the Mill Creek and upper Beaver Mines formations of the Blairmore Group (from Leckie and Krystinik, 1995).

Blairmore Group is the second Columbian clastic wedge. It is about 2000 metres thick in the Fernie Basin and it thins to 300 metres in the eastern Foothills (McLean, 1982). It is the stratigraphic equivalent of the Mannville Group in the Interior Platform. It is composed of a distinctive succession of predominantly coarse clastic formations (Figure 2-2-3; Mellon, 1967; McLean, 1982). At the base is the Cadomin Formation, a chert pebble and cobble conglomerate, 0-170 metres thick in the Foothills, showing the first appearance of green cherts derived from allocthonous terranes; it is well indurated and forms a prominent structural marker because of its distinctive lithology and propensity to form resistant ridges. The overlying Gladstone

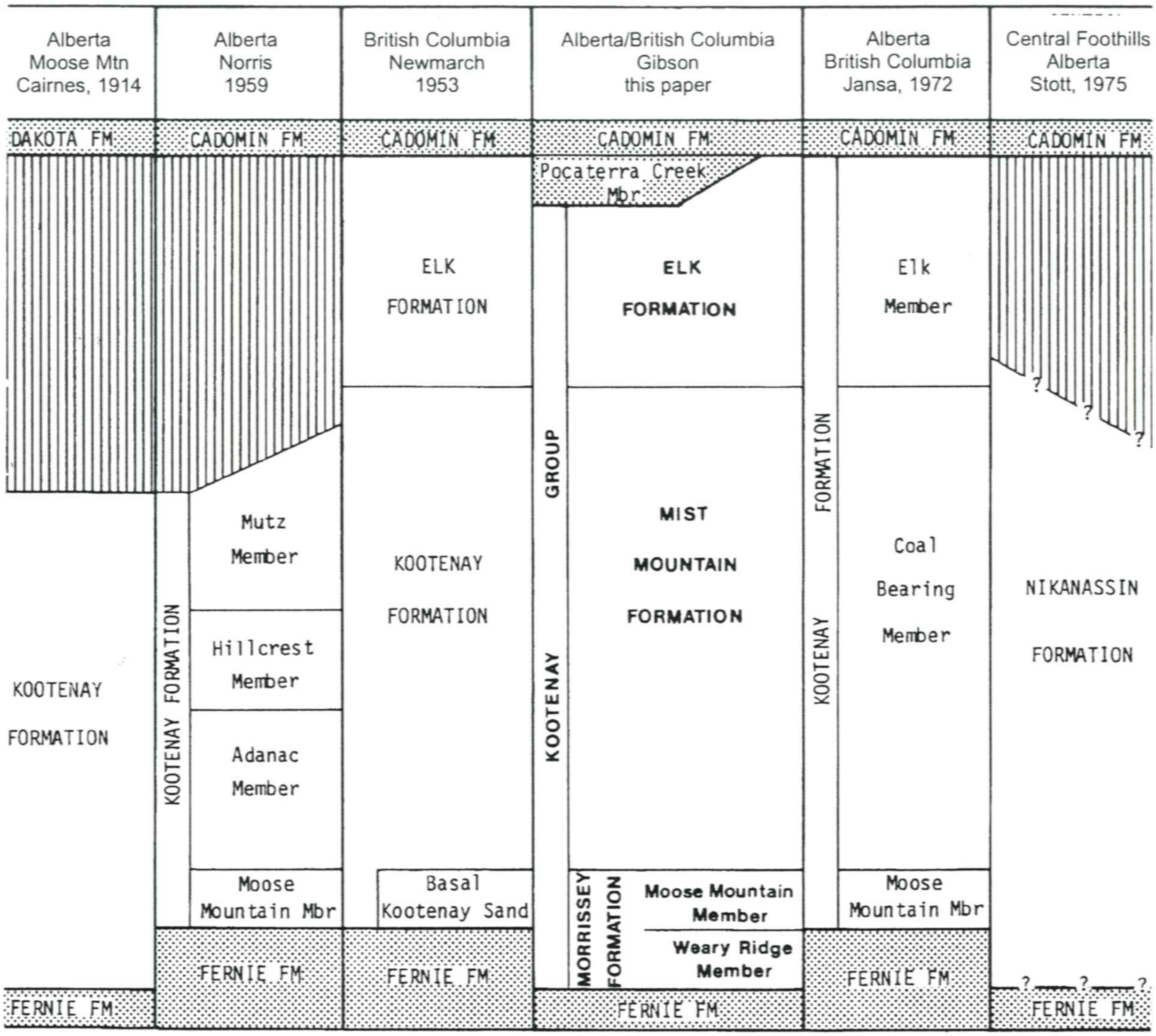


Figure 2-2-4. Nomenclature chart illustrating the Jurassic-Cretaceous members and formations of the Kootenay Group, and their comparison with proposals of earlier workers. The Kootenay Group is overlain unconformably by the Blairmore Group (Figure 2-2-3) (from Gibson, 1979).

Formation has a lower member consisting of quartzose sandstone layers interbedded with siltstone, mudstone and claystone (82-180 m thick), and an upper member, predominantly limestone and calcareous mudstone (0-40 m thick). The overlying Beaver Mines Formation, greenish-grey weathering, pre-dominantly interbedded very fine grained felspathic sandstone and mudstones with subordinate coarse grained thick bedded sandstones and minor conglomerate beds (280-455 m thick), is disconformably overlain by Mill Creek Formation, upward coarsening cycles of sandstone below nonmarine quartzose sandstone (100-175 m thick) and, commonly igneous pebble conglomerates (0-65 m thick). Within both the Beaver Mines and Mill Creek formations there are conglomerates of igneous and volcanic clasts, chert, quartzite, and argillite.

Stratigraphic Section In the Vicinity of this Outcrop: At this location a partially exposed stratigraphic succession, approximately 310 metres thick, can be measured. It comprises approximately 11 metres of Kootenay Formation at its base. The overlying Blairmore Group consists of Dalhousie Formation sandstone (41 m), Gladstone Formation (128 m), and Beaver Mines Formation (170 m). The Mill

Creek Formation is not exposed here, but will be seen at the next stop.

Road Log:

14.60 km From Stop 2; continue west along Highway 3.
15.10 km Beaver Mines Formation outcrop
15.60 km Beaver Mines Formation (?) outcrop
16.20 km Beaver Mines Formation outcrop
16.50 km Turnout to Hillcrest Mines; enter Frank Slide debris field
18.50 km Turnoff to Frank Slide Interpretive Centre; **TURN NORTH (RIGHT)**; watch for several outcrops of the Mill Creek Formation (120 metres thick), shallowly dipping at this location. Drive up the access road to the parking lot (**Stop 3**). Proceed first toward the Interpretive Centre for an overview of the slide.

Stop 3: Frank Slide Interpretive Centre
Distance: 18.50 km from junction of Highway 3 and Highway 22 to Frank Slide Interpretive Centre access road
Access: Drive up the Frank Slide Interpretive Centre access road to the parking lot. We will first walk to the Interpretive Centre to an observation point to discuss the slide and its structural setting. We will then walk back to the parking lot and proceed up the hill to the north to the prominent conglomeratic outcrops; a path from the northeast corner of the parking lot leads to a stile crossing the barbed wire fence.
Theme: Depositional patterns in foreland basins and proximal-distal relationships; and structure of Turtle Mountain (preview of *Day Three*).
Purpose: Views of the Frank Slide and discussion of its structural setting, and outcrop examination of the conglomeratic facies in the Mill Creek Formation (Blairmore Group).

Geology: Most southern Albertans are familiar with the Frank Slide and know at least the general outline of its history. At about 4:10 a.m. on April 29, 1903, part of the eastern side of the summit of Turtle Mountain broke free and plummeted into the Crowsnest Valley, partially obliterating the south side of the young town of Frank, burying the railroad and highway to depths of 30 metres or more, and rushing across the valley floor to climb 100 metres or more up the opposite slope; 70 lives were lost, though none in the coal mine that may have contributed to the instability. An estimated 90 million tons of rock were involved in the slide, making it one of the largest to have occurred on Earth in the past few thousand years. Although this spectacular event happened more than 80 years ago, the appearance of the debris on the valley floor is remarkably fresh. Boulders as large as 15 metres in diameter are found in the slide, but the average size of the fragmental debris is considerably smaller.

Turtle Mountain (Figure 2-3-1) is composed of Mississippian Banff, Livingstone, Mount Head and Etherington formations folded into an asymmetric and faulted anticline with a vertical to overturned panel on its east flank. The anticlinal is seen in outcrops near the southern limit of the slide scar (Figure 2-3-2). Most of the boulder field about the viewpoint (Figure 2-3-2) is composed of Carboniferous Livingstone Formation limestone. The Turtle Mountain Thrust truncates the fold low on the mountain side. Beneath it is the asymmetrical Hillcrest Syncline in which, until the slide, there was extensive coal mining including in the nearly vertical seams immediately beneath the thrust fault.

Turtle Mountain has been interpreted as the surface sheet of an antiformal stack of Paleozoic thrust sheets developed in the hanging wall of the Livingstone Thrust (Figure 2-3-3; Jones, 1993). The Turtle Mountain Thrust is interpreted by Jones (1993) to be one of the faults within the stack, with some "late" displacement affording thrusting of the folded Mississippian section seen here above the Juro-Cretaceous section in the footwall of the thrust. This basic geometry, of an eroded antiformal stack with a very steep forelimb, is considered fundamental to the instability of the mountain side. A prehistoric slide, only 6 km along strike to the north along the Turtle Mountain Anticline and termed the Bluff Mountain Slide by Jones (1993), is much larger than the Frank Slide. Several en echelon structural culminations occur in the vicinity as a consequence of duplex and antiformal stack structures within the Mississippian section. Although this lower set of sheets has been penetrated by a number of wells, only the Coleman Field 13 km north of Turtle Mountain has established production.

Conglomeratic Facies of the Mill Creek Fm.: On the small hill just north of the Interpretive Centre is an example within the Mill Creek Formation of the Albian-aged igneous pebble to cobble conglomerate channels (Figure 2-3-4) that are incised into finer-grained sediments at various places in the Rocky Mountain Foothills and Front Ranges in southwest Alberta and southeastern British Columbia (Leckie and Krystinik, 1995). These channels occur in both the Mill Creek and Beaver Mines formations (Blairmore Group; Figure 2-2-3).

Here, the average clast size is 3-4 cm with cobbles up to 20 cm. Clasts are well imbricated, indicating east-southeasterly flow. The poorly defined bedding is decimetres thick and parallel, with a dip less than 10

Figure 2-3-1. Detail of GSC Map 1829A (Norris, 1993) of Blairmore (west half), centred approximately on 49°36'00"N, 114°24'30"W, showing location of Stop 2-3 and the outline of the Frank Slide (red line). The access road to the Frank Slide Interpretive Centre is not shown.

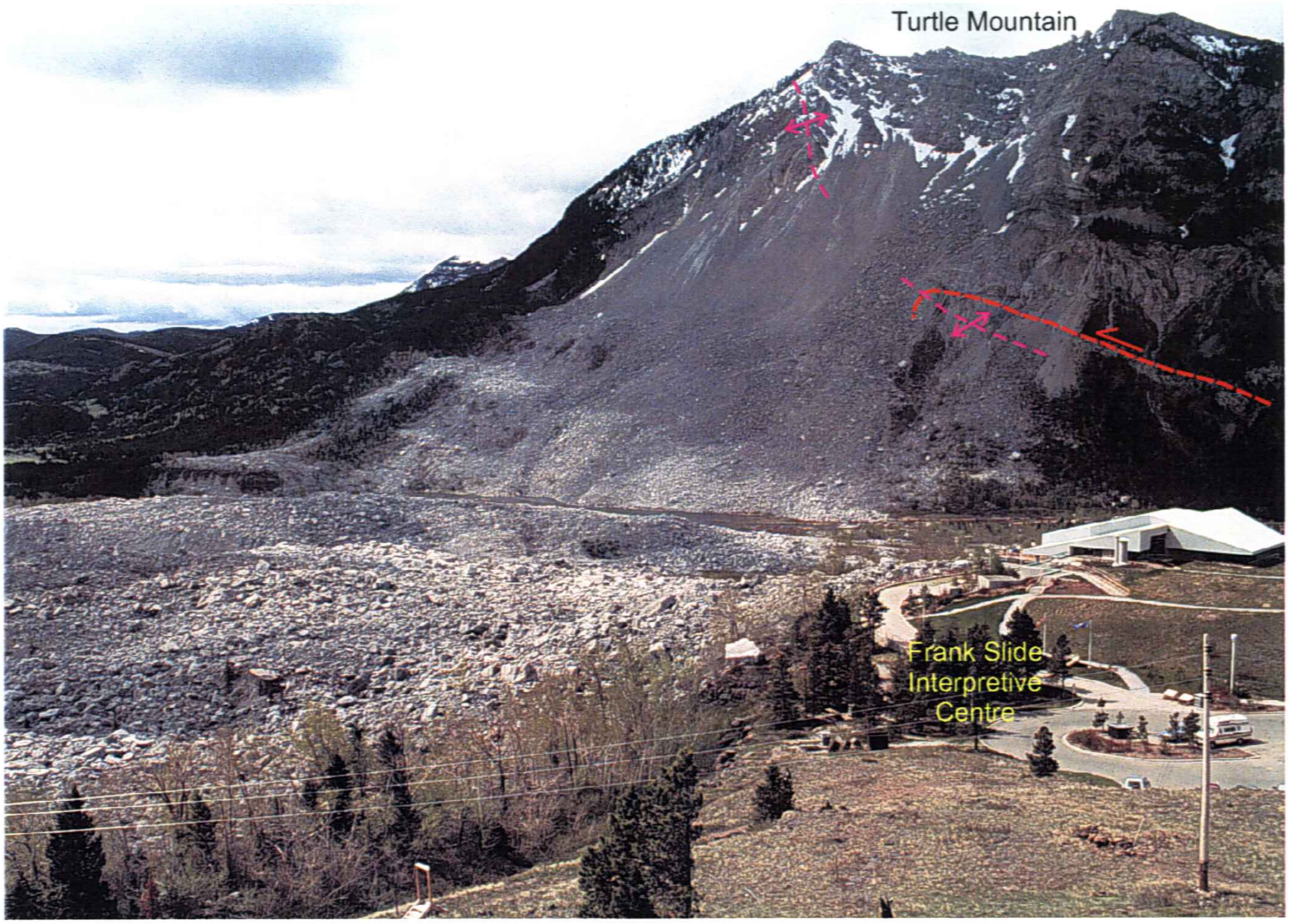


Figure 2-3-2. View of Frank Slide and Turtle Mountain. Note the exposure of the Turtle Mountain Anticline and an interpreted folded thrust.

degrees. The conglomerate becomes sandier upwards and is overlain by 12 metres of medium-grained chloritic sandstone. The sandstone is trough cross-bedded and parallel laminated. Note that clasts also characteristically display surface pitting, due to pressure solution at clast-clast contacts (Figure 2-3-4).

Regionally, these channels can be traced intermittently along easterly trends for up to 66 km in several adjacent thrust slices. Correlative units in the Alberta subsurface occur in the Bow Island Formation of the Colorado Group. In the Foothills and Front Ranges, the conglomerate was deposited in a series of ten east-flowing, sub-parallel channels that flowed into the foreland basin perpendicular to the paleo-mountain front. Based on age and mineralogical similarities, Urbatt (1965) interpreted the McDougall-Segur conglomerates to have been sourced from the Kuskanax and Nelson batholiths, in the Omineca Belt to the west (Leckie, 1993). However, at the time of the deposition of the conglomerates these sources were up to 400 km from the restored locations of these channels. The conglomerates are interpreted to have been deposited in low-sinuosity braided streams incised into regional finer-grained flood plain deposits of the upper Beaver Mines and Mill Creek formations (Leckie and Krystinik, 1995). Individual conglomerate bodies are up to 60 m thick (probably composite) and can be traced laterally for up to 3 km. The largest conglomerate-filled valley, Bruin Channel, is 22 km wide. Crowsnest Channel is the likely reservoir for the Blood Pool in the Bow Island Formation south of Lethbridge.

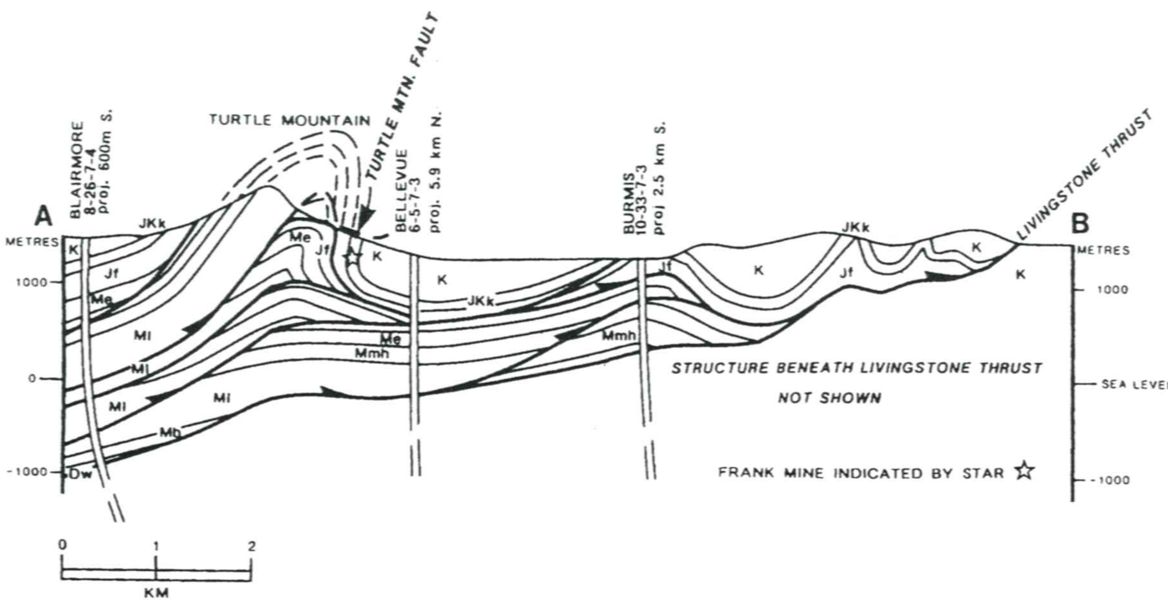
Road Log:

From the parking lot, return down the access road to the junction with Highway 3

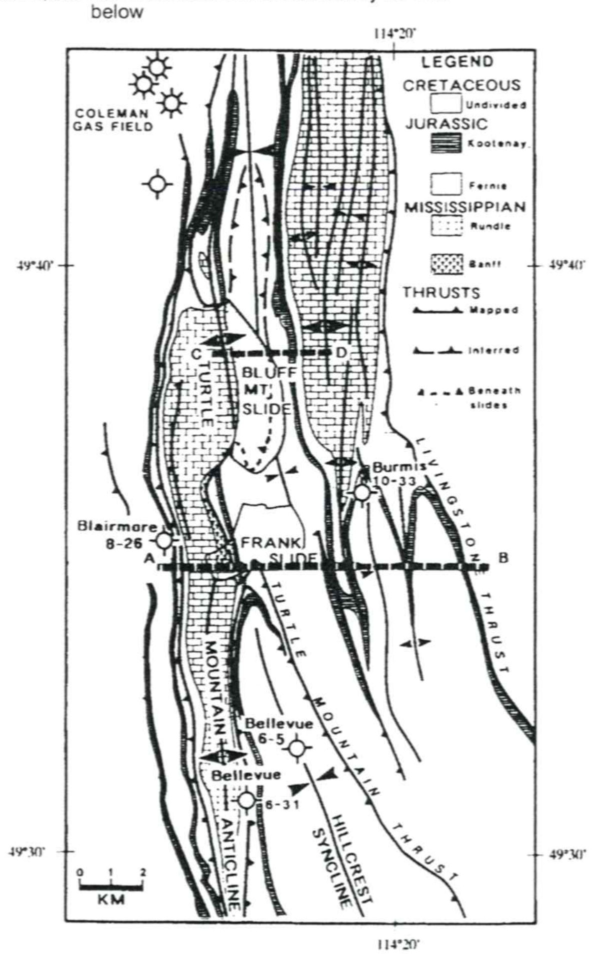
Reset odometer to ZERO

0.00 km Junction of Highway 3 and Frank Slide Interpretive Centre access road; **continue west (right)**

1.00 km Crowsnest River bridge



West-east cross-section through Blairmore and Livingstone ranges. Structure beneath the Livingstone thrust is omitted. F
2. For location of cross-section, see Figure 3. Frank Mine is indicated by the star.
below



Simplified geological map of the Crowsnest area, showing location of cross-sections A-B and C-D (modified from Norris, 1955, 1959, 1989).

Figure 2-3-3. Geological cross section and simplified map of the Turtle Mountain structure (interpreted by Jones, 1993, Bull. Can. Petrol. Geol. v. 41, p. 232-243).

Figure 2-3-4. Igneous Cobble Conglomeratic Facies in the Mill Creek Formation, Blairmore Group (on hill north of Frank Slide Interpretive Centre).

1.30 km Approximate trace of the Turtle Mountain Thrust
2.00-2.95 km Carboniferous outcrop (Stop 1, Day 3)
2.20 km East access to Blairmore
3.20 km Central access to Blairmore
5.00 km West access to Blairmore
6.40 km Blairmore outcrop
6.70 km Blairmore outcrop
7.00 km Blairmore outcrop
7.80 km Turnoff to north (right) to the Forestry Trunk Road, east side of Coleman; continue west along Highway 3
8.45 km Virgelle Formation outcrop, large road cut in Coleman
9.00 km Junction: **TURN NORTH (RIGHT) to small park and lunch stop**; access to west Coleman to south
From the park, return to junction with Highway 3
Reset odometer to ZERO

0.00 km Junction of Highway 3 with access to lunch stop (north) and west Coleman (south), **TURN WEST (RIGHT)**
0.10 km Approximate trace of the Coleman Thrust – displacement ~16 km
0.30 km Kootenay Group outcrop - just to the north, coal was mined underground until the mid-1950s
0.50 km Cadomin Formation outcrop; **Stop 4**

Stop 4: East of Old MacGillvary Mine Office, West of Coleman, Highway 3
Distance: 0.50 km from junction leading to lunch stop; 9.5 km from junction with Frank Slide access road
Access: Park beside the outcrop, off the paved shoulder and far enough around the bend to allow oncoming traffic to react; be very cautious on this blind turn
Theme: Stratigraphic succession of the Foreland Basin and contrast to stratigraphic succession at East Bellevue.
Purpose: Kootenay Group overlain by Cadomin and Gladstone formations

Geology: Here (Figure 2-4-1) the Cadomin Formation conglomerate occurs at the base of the Blairmore Group (Figure 2-2-3), most likely unconformably below the Gladstone Formation and also unconformably above the Kootenay Group. Note the green chert clasts in the Cadomin that contain Paleozoic radiolarians that indicate a provenance in Cache Creek terrane rocks in

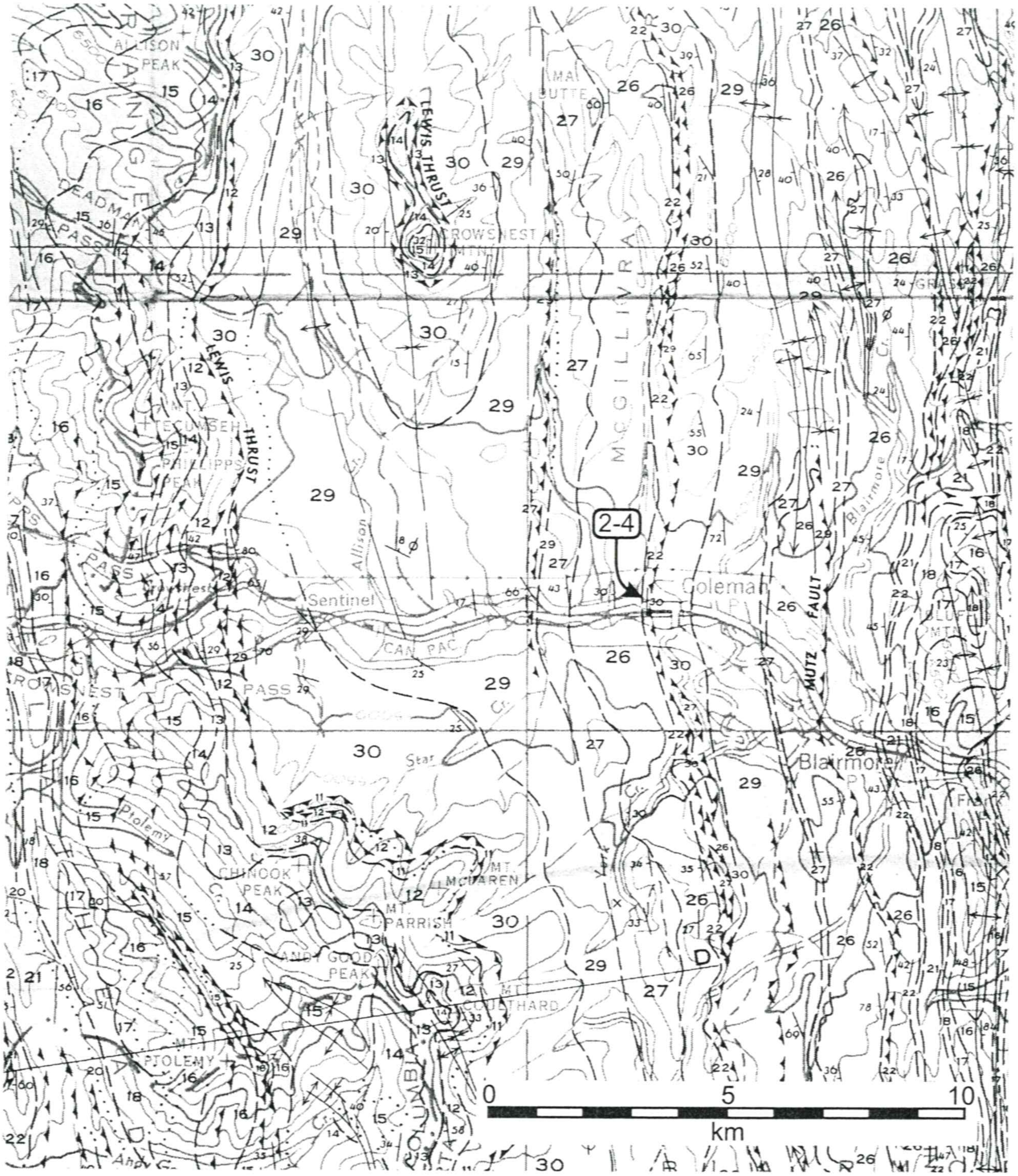


Figure 2-4-1. Detail of GSC Map 35-1961 (Price, 1962), Fernie (east half), centred approximately on 49°39'00"N, 114°32'00"W, showing location of Stop 2-4.

the interior of the Cordillera, well west of the present continental divide. The general outcrop setting is illustrated in Figure 2-4-2.

Road Log:

0.50 km From Stop 5 continue west on Highway 3
0.90-1.20 km Beaver Mines Formation
1.40 km Old MacGillvery Mine Office
2.20-2.70 km Crowsnest Volcanics outcrop, on Iron Ridge
2.60 km Roadside pullout for **Stop 5**, **SOUTH** side of Highway 3

Stop 5: Crowsnest Formation volcanics outcrop, Highway 3

Distance: 2.60 km from junction leading to lunch stop; 11.6 km from junction with Frank Slide access road

Access: Pull off into the large, paved pull-out at the west end of the outcrop on the **SOUTH** side of the highway; exercise caution driving across oncoming traffic, and crossing back to the outcrop on foot

Themes: Stratigraphic succession of the Foreland Basin; structure of the Crowsnest reentrant; and paleomagnetism – tectonic displacements and remagnetizations in orogenic terrains.

Purpose: Outcrop examination of the Crowsnest Formation volcanics, and structural overview of the Lewis thrust sheet in the Crowsnest reentrant.

Geology: The Crowsnest Formation, exposed in a long road cut where Highway 3 crosses Iron Ridge (Figure 2-5-1), is approximately 320 m thick; it is also well exposed below the road along the railway tracks. The Crowsnest Formation is a sequence of trachytic, melinite and analcime-bearing, agglomerates, tuffs, rare flows and dikes, and their epiclastic derivatives (Figure 2-5-2). It comprises a lower part, dominantly volcanic sandstone and tuff, and an upper part, predominantly agglomerates (Pearce, 1970). The contact with the underlying Mill Creek Formation is inferred to be conformable and gradational, although it is disconformably overlain by the Blackstone Formation marine shale (Upper Cretaceous Alberta Group). Away from the Coleman area, grain size, bed thickness, and total thickness of the Crowsnest Formation generally decreases (Pearce, 1970). Three main volcanic centres have been recognized. Crowsnest Formation does not occur in the Lewis thrust sheet, although there are contemporaneous intrusions of similar age and composition. Palinspastic reconstruction places the greatest thickness of these rocks in the vicinity of Cranbrook.

Sanidine recovered from this section has been dated at 90 and 94 Ma and was used to place the Albian-Cenomanian boundary at 100 Ma. Zircons recovered from the granitic fragments in the agglomerate give a fission-track age that is comparable with the earlier

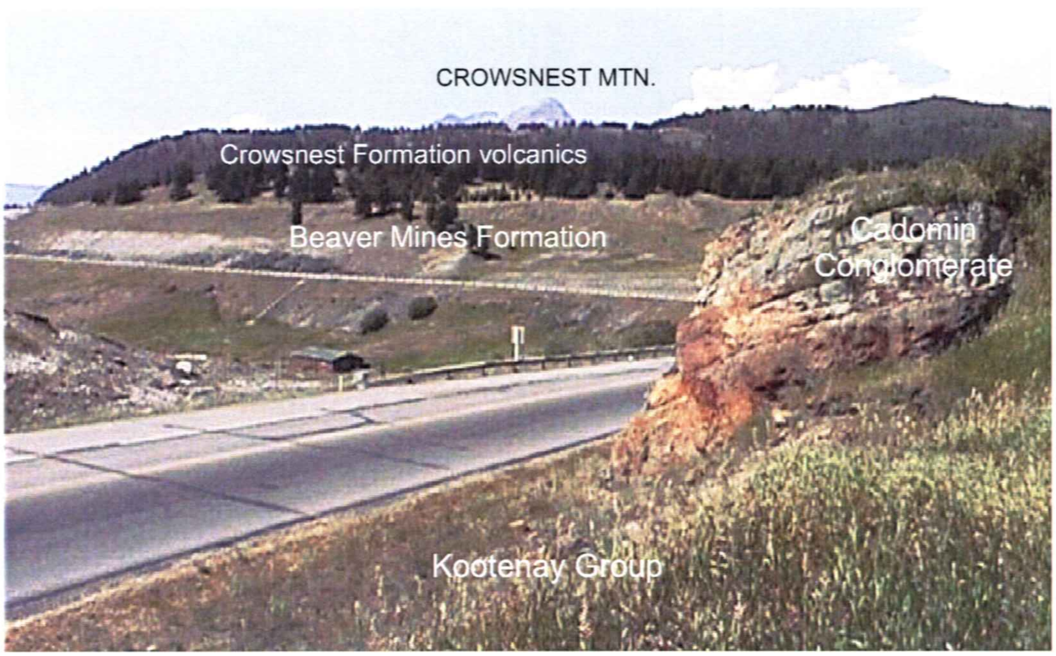


Figure 2-4-2. Outcrop view of Cadomin Formation conglomerate at Stop 2-4, where it rests unconformably on the Kootenay Group. In the distance to the west are the overlying units of the Blairmore Group, including the Crowsnest Formation volcanics (Stop 2-5). Crowsnest Mountain, a klippe of the Lewis Thrust, is visible above Iron Ridge.

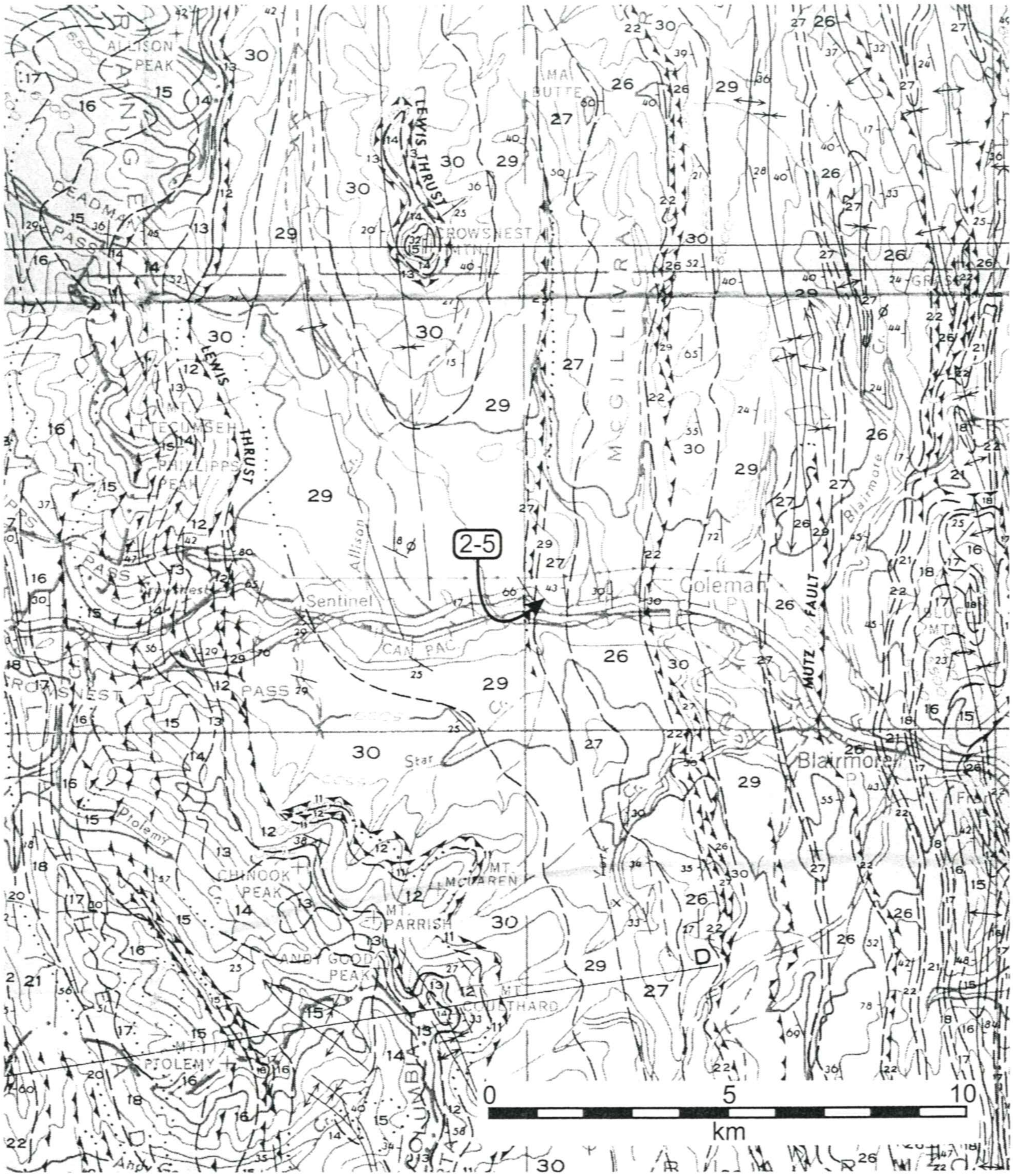
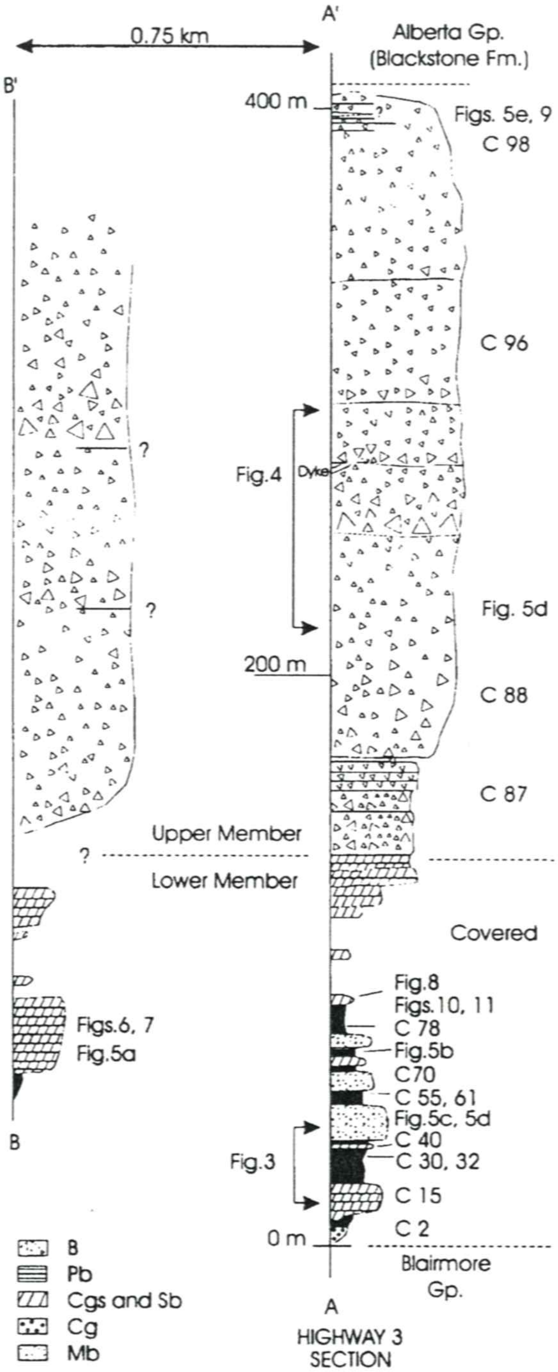


Figure 2-5-1. Detail of GSC Map 35-1961 (Price, 1962), Fernie (east half), centred approximately on 49°39'00"N, 114°32'00"W, showing location of Stop 2-5.

Stratigraphic columns measured along Highway 3 and the supplemental section after Adair (1986). Photograph locations are indicated by figure numbers. See Table 1 for sample information. B, breccia deposits; Pb, parallel-bedded deposits; Cgs, coarse-grained deposits with stratified tops (includes discrete stratified deposits Sb); Mb, massive deposits; Cg, matrix-supported, coarse-grained deposits lacking stratification. The scale of this diagram is not adequate to exhibit the full detail of the two sections. Units shown are relative to the most abundant deposit type.



Cartoon depicting flow type and related deposit. (*a*) Massive deposits emplaced by nonturbulent pyroclastic flows. (*b*) Coarse-grained deposits with stratified tops emplaced by density-stratified surges. (*c*) Stratified deposits emplaced by surges. (*d*) Breccia deposits emplaced by vent-proximal pyroclastic flows. Arrows on stratigraphic columns mark individual flow units. No scale.

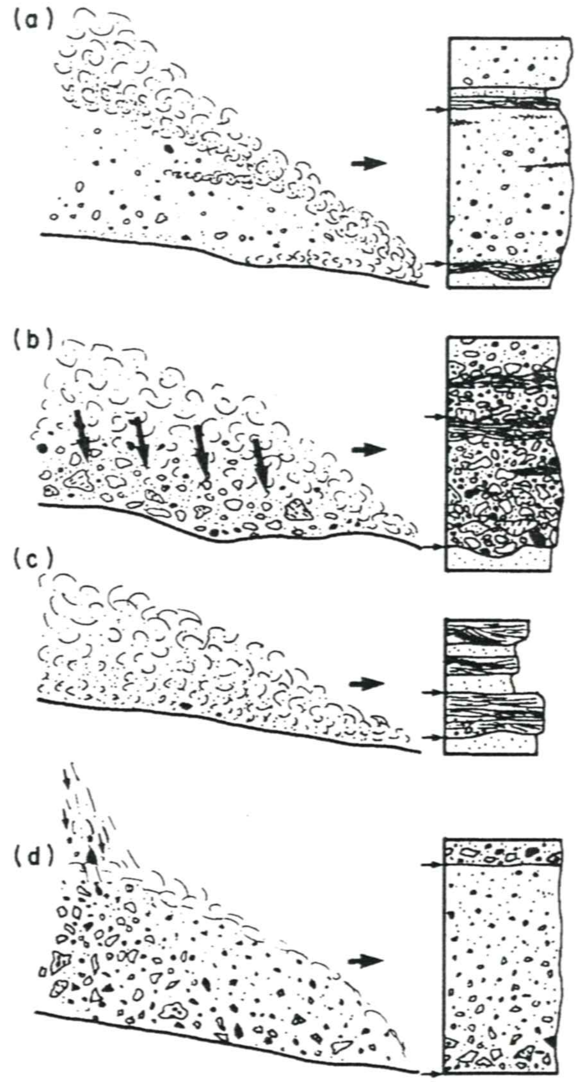


Figure 2-5-2. Measured section along Highway 3 (plus supplemental section) of the Crowsnest Formation volcanics, and a cartoon depicting types of flows and deposits present (from Adair and Burwash, 1996, CJES v. 33, p. 715-728).

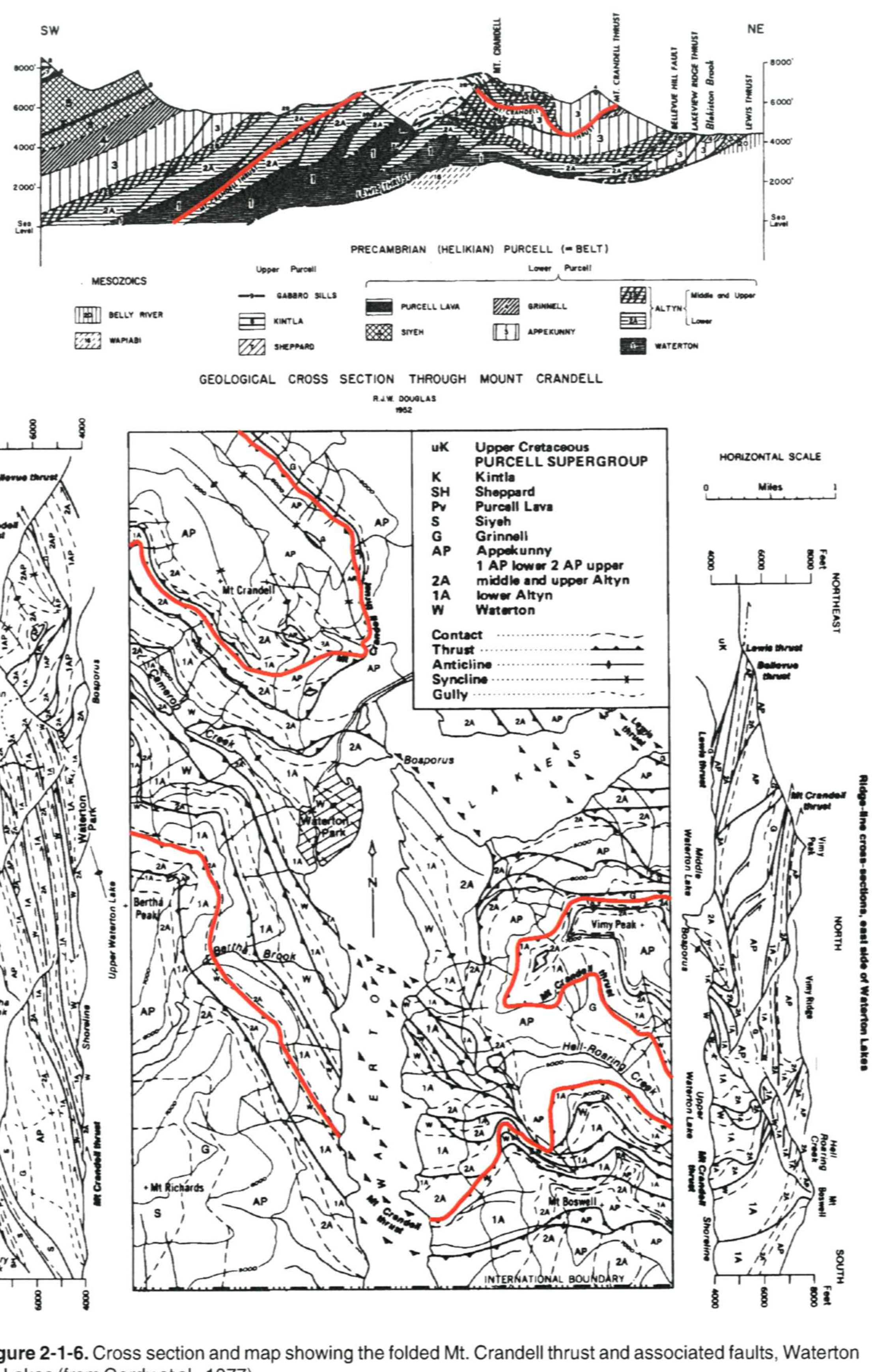


Figure 2-1-6. Cross section and map showing the folded Mt. Crandell thrust and associated faults, Waterton Lakes (from Gordy et al., 1977).

limestones of the Siyeh Formation. The Siyeh Formation is tectonically repeated several times and forms the basal imbricates of the Lewis Thrust Plate.

17.90 km Pine Ridge viewpoint (Stop 8, Day 1)

27.30 km Twin Butte General Store

28.70 km Yarrow Creek bridge

31.70 km Drywood Creek bridge

33.65 km Turnoff to Shell Canada Waterton Gas Plant

34.50 km Junction with Highway 505 (access to Stop 7, Day 1)

35.50 km Cross beneath railway trestle

45.00 km As we approach Pincher Creek, watch for westerly views to Turtle Mountain and the Frank Slide. The slide occurred on April 29, 1903 (to be viewed and discussed at Stop 3 today); the roar of the rockfall was heard here at Pincher Creek, 70 km away.

51.20 km St. Mary River outcrop

51.80-52.10 km St. Mary River outcrops; view to north of the Porcupine Hills and the Alberta Syncline – note very shallow west-dipping strata on the east flank of Porcupine Hills, and the moderate east-dipping strata (held up by the triangle zone at depth) on the west flank

53.40 km Entering Pincher Creek; continue straight through at the lights (north)

54.10 km Cross Pincher Creek, road swings to north

55.20 km Junction – turn right (north) toward Pincher Junction

58.10 km Pincher Junction – turn west (left) onto Highway 3

64.10 km Bridge over arm of Oldman Reservoir, outcrop of Willow Creek Formation containing the K-T boundary

65.60 km Lower Willow Creek outcrops

68.20 km Entering Cowley; turnoff to Oldman Reservoir; views to the 52 wind power turbines on Wind Ridge

69.10 km Exiting Cowley

72.70 km Cross train tracks

73.30 km Lower Willow Creek outcrop

73.50 km Lower Willow Creek outcrop

75.80 km Turnoff to Lundbreck (to south); cross approximate position of the triangle zone upper detachment and enter the Outer Foothills; between this point and the Livingstone Thrust, we cross a series of imbricate, east-directed thrusts duplicating Belly River, Milk River, and Alberta group strata

77.10 km Turnoff to Highway 3A (east access to Lundbreck Falls &Stop 6, Day 1)

77.85 km Junction with Highway 22

Reset odometer to ZERO

0.00 km Junction with Highway 22, continue west on Highway 3

0.20 km Virgelle Formation outcrop

0.50-2.60 km Scattered Belly River Group outcrops

2.10 km Turnoff to Highway 3A (west access to Lundbreck Falls & Stop 6, Day 1)

3.20 km Lundbreck Formation outcrop

3.30 km Lundbreck Formation outcrop

3.50 km Lundbreck Formation outcrop

5.80 km Weigh station, south side of highway

6.60 km Junction with Highway 507 (south to Lees Lake) and the North Burmis Road; as we approach Bellevue the topography becomes more pronounced and the strong west dip of thrust sheets becomes more obvious

7.20 km View due north to Virgelle Formation outcrop containing magnetite placers; prominent ridges of west dipping sandstones held up by resistant Belly River and, farther west, Lower Blairmore and Kootenay group strata appear

7.70 km Cross trace of the Livingstone Thrust, carrying Lower Cretaceous Blairmore Group through Mississippian Rundle Group strata

8.60 km "Burmis Tree" outcrop, Blairmore Group

10.00 km Blairmore Group outcrop

10.30 km Blairmore Group outcrop, and access to Leitch Collieries Historical Site – throughout the region of the Crowsnest Pass small towns like Bellevue developed around the series of coal mines that mined coal from the Mist Mountain Formation of the Kootenay Group

10.70 km Beaver Mines Formation outcrop

11.10 km Beaver Mines Formation outcrop

11.80 km Blairmore Group outcrops

12.30 km "Crowsnest Pass" sign

12.70 km Blairmore/Kootenay contact

12.90 km Kootenay outcrop

14.10 km East Bellevue access

14.20 km Blairmore Group outcrop

14.60 km **Stop 2;** Blairmore/Kootenay outcrop.

Stop 2: East Bellevue Road Outcrop, Highway 3

Distance: 12.70 km from junction of Highway 3 and Highway 22

Access: Park off the paved shoulder beside the outcrop; exercise caution beside this busy road

Theme: Stratigraphic succession of the Foreland Basin

Purpose: View Contact Between Kootenay Group and Basal Blairmore Group

Geology: This stop (Figure 2-2-1) exhibits the contrasting lithologies and the contact relationships between the upper Mist Mountain Formation, Kootenay Group, and the Basal Blairmore Group (note that Gibson suggests this is Cadomin Formation) sandstones of the Lower Cretaceous Blairmore Group (Figure 2-2-2). Here the basal sandstone is medium to coarse grained quartzose sandstone and it lacks the

K-Ar ages, as are preliminary Ar-Ar ages of samples being analysed at Queens University. A zircon U/Pb age from this outcrop is being pursued (Osadetz, in prep.).

The Lewis Thrust Sheet and Crowsnest Mountain: From the vantage point on Iron Ridge at the west end of the outcrop it is easy to identify the surface trace of the Lewis Thrust beneath the High Rock and Flathead Ranges to the west and southwest, and beneath Crowsnest Mountain to the north-northwest (Figure 2-5-3). Trachytic dykes associated with the Crowsnest Formation occur on Crowsnest Mountain as well as in the High Rock and Flathead Ranges and correspondingly must be allochthonous with respect to the Upper Cretaceous formations in the footwall of the Lewis Fault.

In sharp contrast to Waterton Park, where the Lewis Thrust carries a thick succession of Proterozoic rocks, here the thrust carries Cambrian and Devonian in its immediate hanging wall. Furthermore, stratigraphic relationships in the hanging wall of the Lewis Thrust are significantly different in the Front Range than those displayed in the klippe on Crowsnest Mountain (Figure 2-5-3). In the High Rock Range just north of Crowsnest Pass the Lewis Thrust follows a stratigraphic horizon low in the Devonian Fairholme Group. The thrust cuts up section to the east, to near the top of the Palliser Formation, which it follows at the base of the Crowsnest Mountain klippe. The klippe, folded into a gentle syncline, is thrust onto Upper Cretaceous Belly River Group. The peak of Crowsnest Mountain is Livingstone Formation (Rundle Group).

The Lewis Thrust also cuts up section in a northerly direction. South of Crowsnest Pass, progressively older formations occur in the hanging wall of the Lewis Thrust, as we saw in Waterton Park. In Crowsnest Pass the Cambrian Gordon Formation lies in the immediate hanging wall. North of Crowsnest Pass, as noted above, Fairholme carbonates replace the Gordon and Elko formations above the fault, and west of the Allison Creek/South Racehorse Creek divide the Palliser Formation is in the immediate hanging wall.

There are exceptions to these general relationships across the fault. North and south of North Kootenay Pass the footwall of the Lewis Thrust is generally a bedding-glide zone in the Upper Cretaceous Belly River Formation. The Carbondale structure, however, is an anomaly in the footwall of the Lewis thrust fault (Kerber, 1991). The Carbondale structure comprises two overturned, east-verging thrust faulted synclines, and an intervening, thrust faulted anticline of Lower Cretaceous Kootenay, Blairmore, and Crowsnest strata lying below the Lewis Thrust in front of the North Kootenay Pass deflection. The Carbondale structure is a deformed tectonic wedge that results from the introduction of blind Paleozoic thrust sheet into the Columbian clastic wedge, delaminating the younger strata.

Anomalous Apparent Magnetic Poles From Iron Ridge: Early paleomagnetic results from Iron Ridge gave anomalous pole positions. These were interpreted as either evidence of a significant paleolatitudinal displacement or a biased sampling of the secular magnetic field variation. Although initially proposed, significant latitudinal displacement was rejected due to fundamental structural restrictions.

In the southern Canadian Cordillera the paleomagnetic memory of Paleozoic carbonate strata and Mesozoic strata at least as high as the Crowsnest Formation, in the Front Ranges and Inner Foothills, retain no record of their known deposition at low latitudes. Instead, by performing a number of fold tests, Enkin et al. (1997) found that each folded structure exhibits a similar, but asynchronous sequence of events including an eastwardly progressing, predeformational chemical remagnetisation during orogenesis (Figure 2-5-4). The remagnetisation of a "western Front Range" structure occurs during a period of normal polarity before 130 Ma. The paleomagnetic pole requires that the subsequent deformation of the western Front Range is Jurassic or younger. The remagnetisation of a "Front Range" structure in the Lewis thrust sheet occurs during a period of normal polarity after 130 Ma but before deformation which, from other evidence, occurred around 75 Ma. The predeformational remagnetisation of an "Inner Foothills" structure occurs during a reversed magnetic period that Enkin et al. (1997) interpreted to be after 75 Ma. An Early Cretaceous sill in the Lewis thrust sheet was remagnetised during a reverse polarity chron prior to the end of Lewis thrust deformation when about 70% of the present dip of the sill was acquired.

Remagnetisation consistently predates deformation, while the remagnetisation occurs later at more easterly localities (Figure 2-5-5). There are also similarities in character and style of the remagnetisation amongst localities. When coupled with the eastward progression of the deformation, our observations suggest that an important and pervasive, but hitherto unrecognized and unappreciated, orogenic chemical process affected Paleozoic carbonate strata in the van of the deforming Cordilleran tectonic wedge (Figure 2-5-6). Kisilevsky et al. (1997), working on the Belt Rocks of

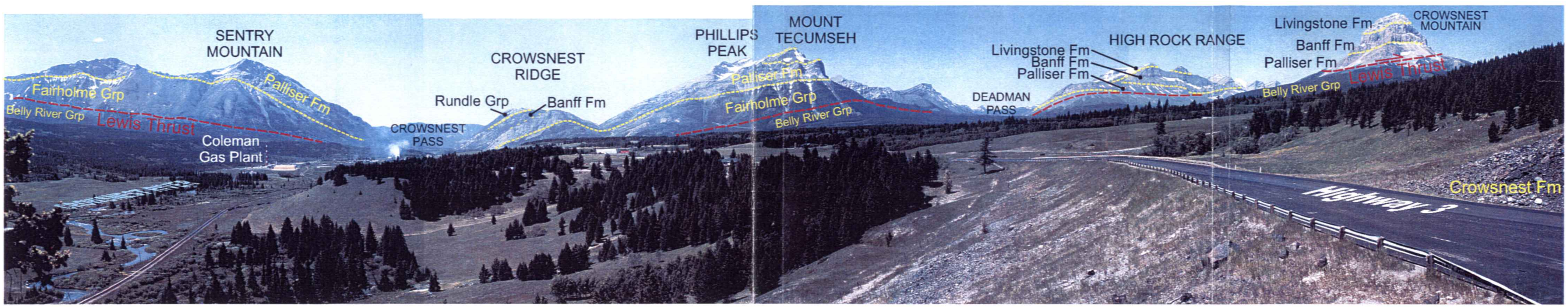


Figure 2-5-3. Panoramic, annotated view northwest and west from Stop 2-5, west of Coleman and east of Crowsnest Pass. The Lewis Thrust places Cambrian and Devonian rocks above Campanian Belly River Group strata. The Lewis Thrust cuts up-section in its hanging wall both to the west and to the north. Crowsnest Mountain is a klippe of the Lewis Thrust. Strata of the Albian Crowsnest Formation (volcanics) are seen adjacent to Highway 3, far right-hand side.

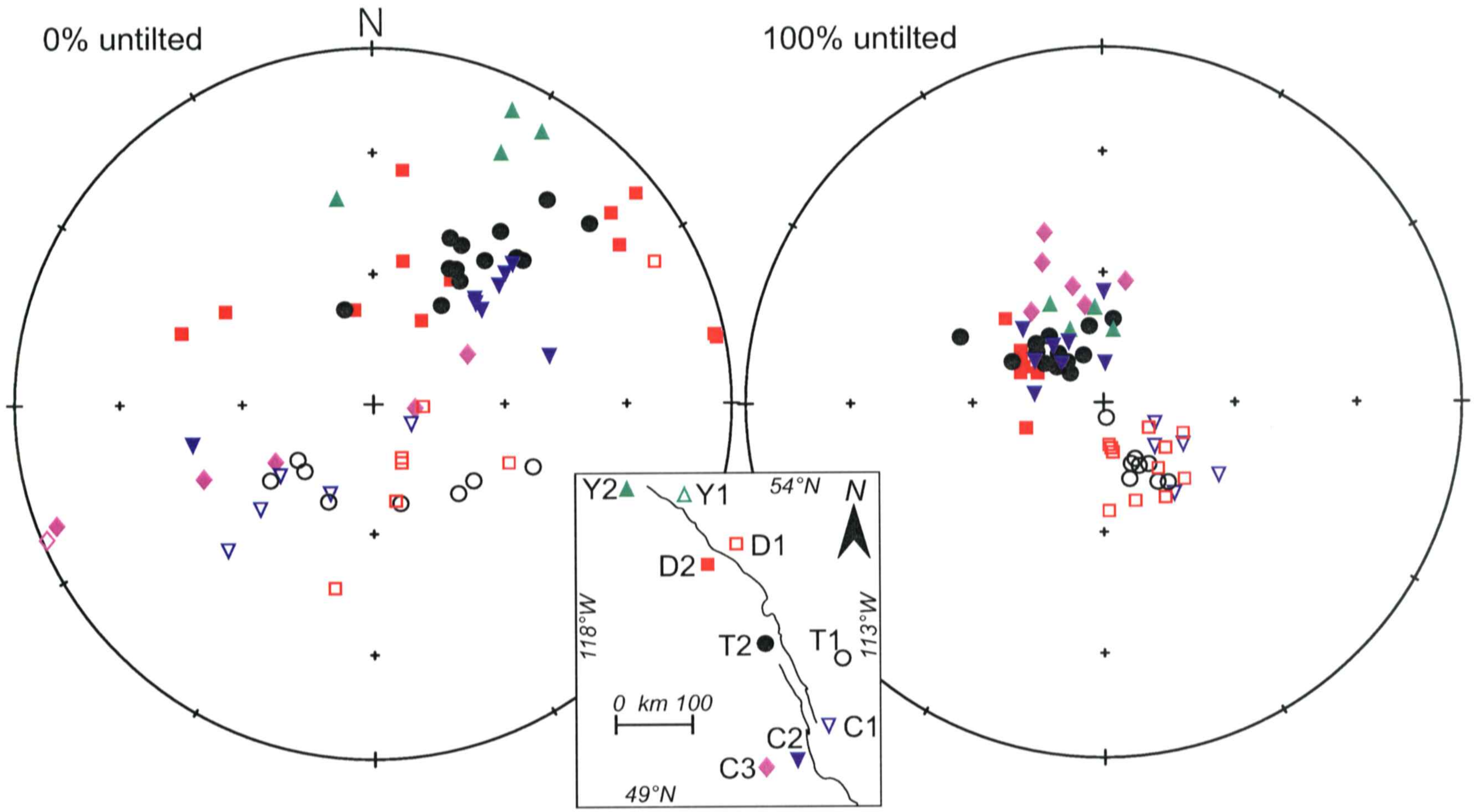


Figure 2-5-4. Poles to A Component of remagnetized carbonate strata in the southern Front Range and Foothills. Localities pooled here include Crowsnest Pass ("C" on reference map inset), the Trans Canada Highway ("T"), the David Thompson Highway ("D") and the Yellowhead Highway ("Y"). Note that the A Component clusters better when bedding dip is removed, indicating a locally predeformational remagnetization. Individual sites behave in a similar manner. Normal and reverse fields are indicated by projections into the upper and lower hemispheres of the sterodiagrams. Front Range sites are characterized by normal magnetizations, while Foothills sites are characterized by reverse magnetizations, indicating that the process responsible for the remagnetizations operates over a protracted interval, with indications that it affects more easterly locations at later times.

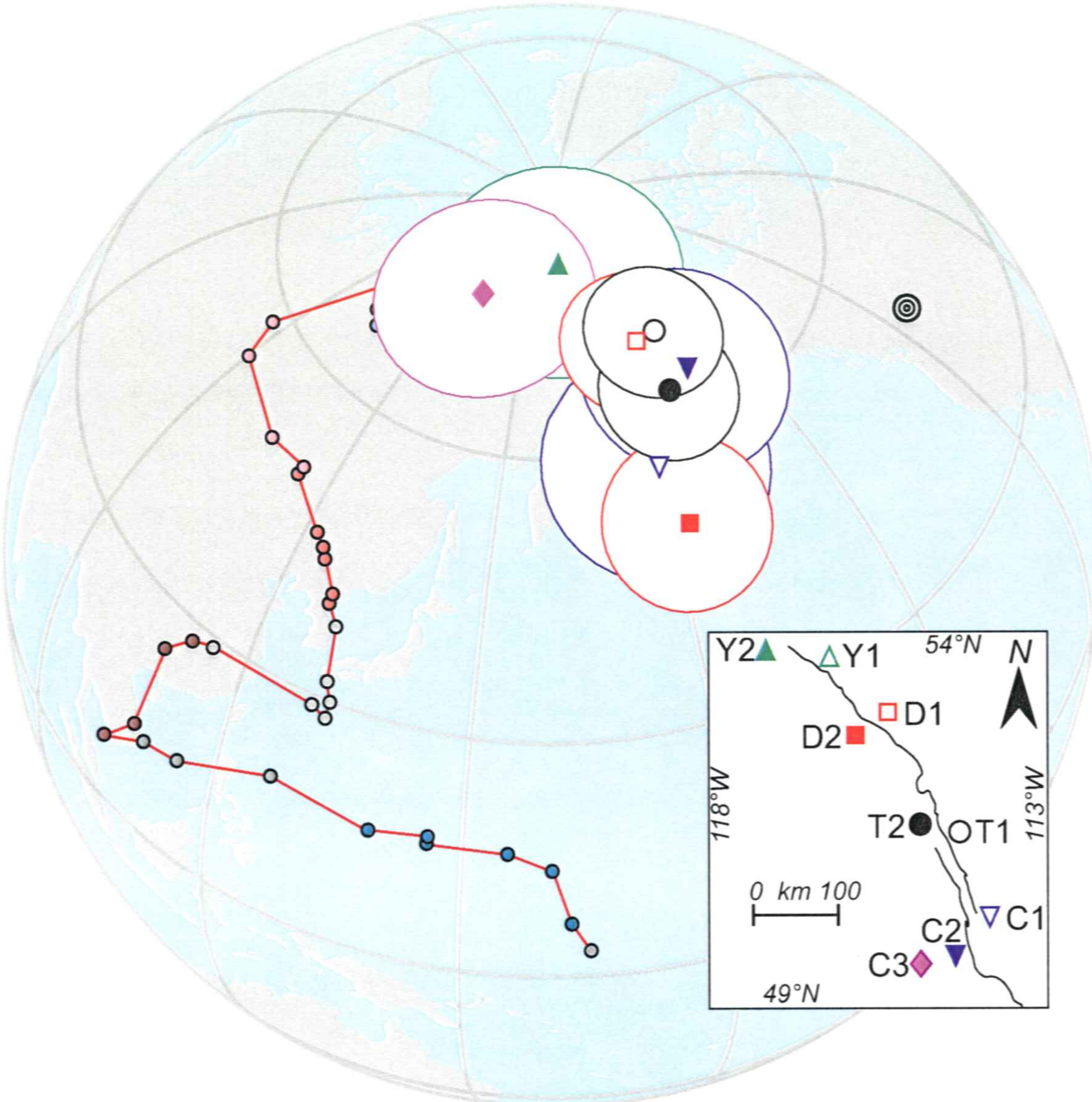


Figure 2-5-5. Pole positions for locality mean A component remagnetizations after 100% untilting of the bedding dip. Note the generally orogenic age, but locally predeformational (Figure 2-5-4) of the remagnetization and that sites lying further east can be inferred to have younger remagnetizations. The elucidation of details of the remagnetization are obscured by the geometry of the North American apparent polar wander path during the Cretaceous and early Tertiary.

the Lewis sheet, found no significant vertical axis rotation between the two segments of the Lewis sheet across the Crowsnest Re-entrant, as might be expected from the mesostructural evidence, and that the Cretaceous overprint, so pervasive in the Paleozoic carbonate succession, occurs only irregularly in the Purcell succession, where it occurs both as a primary and intermediate component. Much of the Belt is not remagnetised, but retains an inferred primary magnetization, like that observed elsewhere in the Purcell (Elston and Bressler, 1980).

Road Log:

2.60 km From Stop 5, continue west along Highway 3
4.05 km Cardium outcrop; view of Coleman Gas Plant
4.90 km Turnoff to Coleman Gas Plant
6.00 km Kerr cabins
7.10 km Railway overpass
7.40 km Crowsnest River bridge
8.10 km Alberta Tourism Information Centre
8.70 km Belly River Group outcrop
9.30 km Approximate trace of the Lewis Thrust

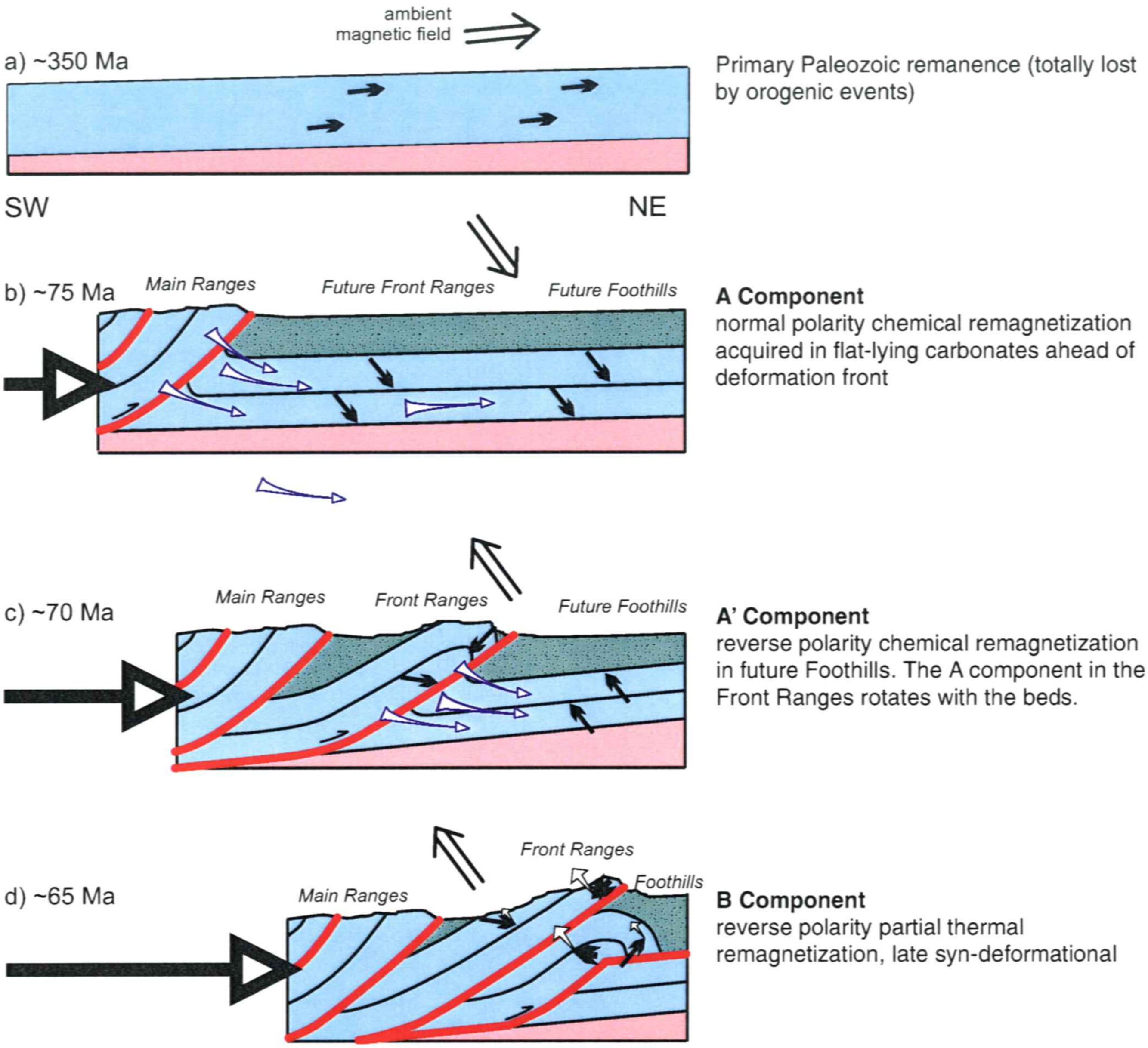


Figure 2-5-6. Diagrammatic illustration of the sequence of events affecting the magnetic history of carbonate strata in the Front Range and Foothills. Notice that the original shallowly inclined remnant that would be inferred from stratigraphic age is no longer observed and it must be inferred. The combination of changes in polarity with position and location suggest that the locally predeformational pervasive A component overprint is acquired orogenically. The less common B component overprint is a thermal viscous overprint restricted to select localities. Its presence may indicate major buried culminations underlying the Front Range at the latitude of the Trans Canada Highway. While the remagnetizations are chemical the process controlling them is uncertain.

9.50-9.70 km Cambrian and Upper Devonian section in large road cut

9.60 km **Stop 6a**; pull off paved shoulder – **exercise caution** along this busy road

Stop 6a: Cambrian-Upper Devonian unconformity and stratigraphy, immediate hanging wall of the Lewis Thrust Sheet, Highway 3.

Distance: 9.60 km from junction leading to lunch stop; 18.6 km from junction with Frank Slide access road

Access: Pull off highway, off the paved shoulder, near the middle of the outcrop; **exercise caution** along side this busy road

Theme: Lower Paleozoic stratigraphy.

Purpose: Outcrop examination of the Cambrian Elko Formation overlain by the Upper Devonian Fairholme Group.

Geology: Driving west, the first pre-Mississippian carbonate outcrops on the highway lie in the immediate hanging wall of the Lewis Thrust (Figure 2-6-1), thereby marking the eastern boundary of the Front Ranges. This large road cut, exposing section on both sides of the highway, exposes the Cambrian Elko Formation overlain unconformably by the Upper Devonian Fairholme Group. The unconformity is quite cryptic, but has been confirmed paleontologically. Before the most recent modifications to the highway, the Cambrian Gordon Formation was exposed beneath the Elko. There is a dike of Cretaceous trachyte intruded into the Fairholme Group in the western portion of the outcrop.

To the northwest, across Crowsnest Lake on Crowsnest Ridge, and farther north on Mount Tecumseh, Fammenian Palliser Formation, consisting of dark grey, fine crystalline limestone, can be seen overlying the Fairholme Group where it is almost doubled in thickness by a thrust. A thin shale, the Exshaw Fm. lies between the Palliser and Banff formations. It contains the Devonian-Carboniferous boundary and is well exposed by Crowsnest Lake (Stop 6b). The overlying Mississippian Banff Formation, consisting of shales and cherty limestones at its base and limestones and dolostones in its upper part, is overlain by clean, light-coloured carbonate grainstones of the Livingstone Formation. On Crowsnest Ridge, the total Mississippian succession has an apparent thickness of about 1400 m but, like the Palliser Formation, it is thickened by minor thrusts (true stratigraphic thickness ~1000 m). This west-dipping panel of Upper Paleozoic strata forms the bold peaks in both the High Rock and Flathead ranges, north and south of Crowsnest Pass, respectively.

Road Log:

9.60 km From Stop 6a, continue west on Highway 3

10.00-10.40 km Fairholme Group outcrops

10.60-11.00 km Palliser Formation outcrop – beginning of spectacular road cut

11.00 km Exshaw Formation outcrop

11.00-11.50 km Banff Formation outcrop

11.40 km **Stop 6b**; pull off highway into large paved truck pull out

Stop 6b: Palliser, Exshaw, and Banff formation outcrop, beside Crowsnest Lake, Highway 3.

Distance: 11.4 km from junction leading to lunch stop; 20.4 km from junction with Frank Slide access road

Access: Park in the large paved truck pull out near the west end of Crowsnest Lake, and walk across the highway to the outcrop. **CAUTION:** *You will be examining an outcrop from which numerous blocks and boulders fall (note the number in the ditch), but be careful venturing too near the road – many drivers will be watching the lake and the view, not watching out for distracted geologists! On the return walk, a good overview of the outcrop can be had from the other side of the highway, behind the relative safety of the guardrail.*

Theme: Mesostructures and Lower Paleozoic stratigraphy.

Purpose: Outcrop examination of spectacular mesostructures (duplexes and tectonic wedges) within the Banff Formation; Palliser, Exshaw, and Banff formation stratigraphy.

Geology: The extensive road cut exposes the lowermost Livingstone, Banff, Exshaw and uppermost Palliser formations. Here, in the hanging wall of the Lewis Thrust, but a significant distance from the thrust trace (Figure 2-6-1), the road cut provides an unparalleled opportunity to examine mesoscale contraction structures. Interestingly, although the section is intensely deformed, there is very little disruption of the general stratigraphic succession. Without the magnificent road cut, how might we have mapped the structure walking through the trees at the top of the ridge?

Numerous small faults in the well-bedded cherty limestones and shales of the Banff Formation illustrate, on an outcrop scale, the relationships that occur along many of the large faults in the region. Most of these faults are contraction faults which together form spectacular duplex structures (e.g., Figure 2-6-2) and tectonic wedges ("triangle zones"). An interesting comparison of scale can be made by recalling the discussion of the multiduplex structures of the Clarke Range and Waterton, and the size of these structures in the subsurface. Similar mesoscale structures are less easily identified in the Devonian succession at the eastern end of the outcrop, but they are there. Note that the Exshaw Formation is not structurally duplicated (as had been previously suggested by McClay and Insley, 1986).

The higher part of the succession occurs by the quarries up the road and around the end of the Lake. Several minor thrust faults thicken the Mount Head and Livingstone Formations. The contact with the Etherington Formation at the top of the Rundle Group is exposed along the highway on the Continental Divide above Summit Lake. The Paleozoic section starts with a condensed Permian section overlying the Pennsylvanian Tunnel Mountain quartz sandstones near the Alberta Natural Gas pipeline compressor station. To the west the structures become even more interesting, but that is for another trip.

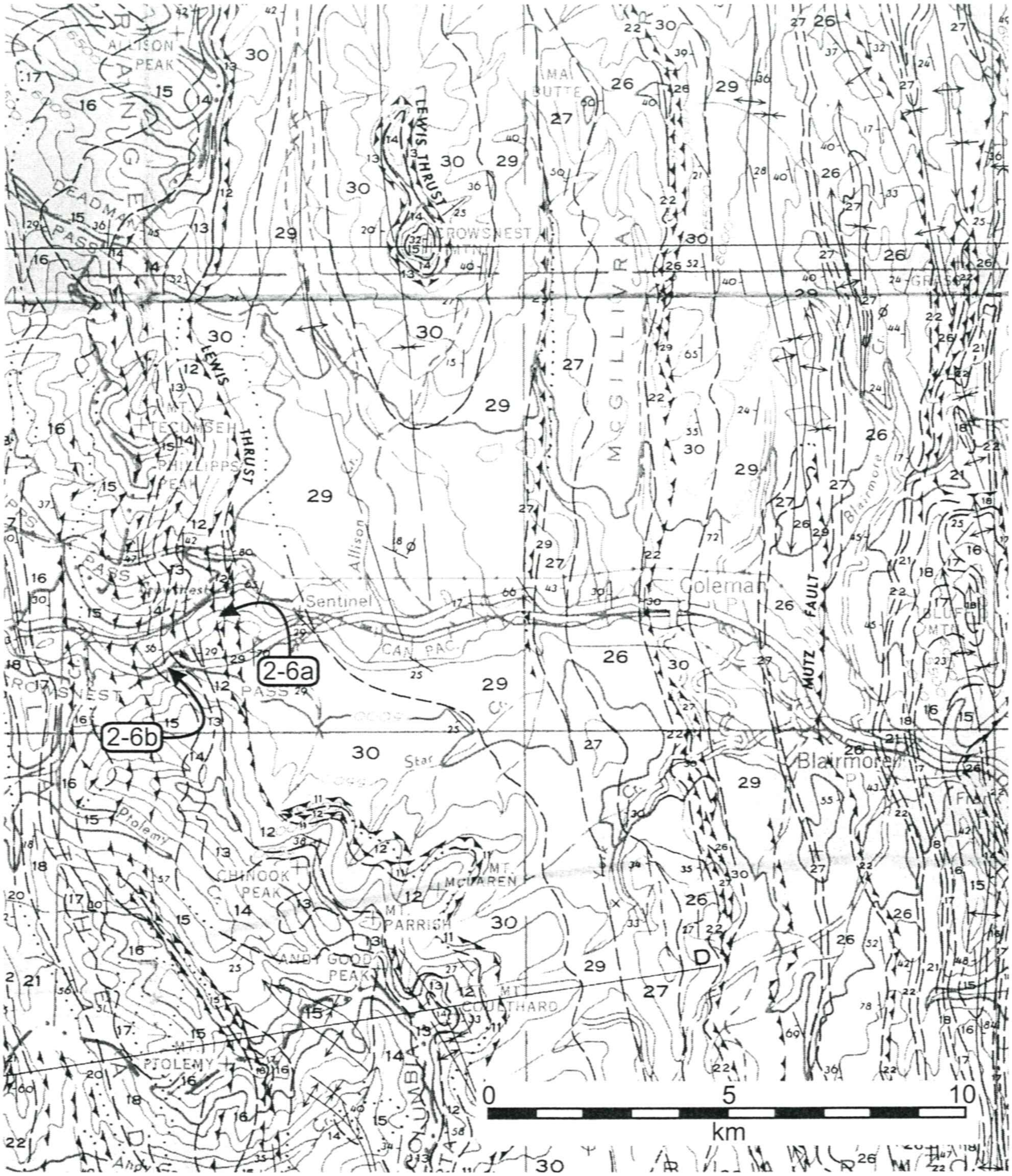


Figure 2-6-1. Detail of GSC Map 35-1961 (Price, 1962), Fernie (east half), centred approximately on 49°39'00"N, 114°32'00"W, showing locations of Stops 2-6a and 2-6b.

Thermal Evolution of the Lewis Thrust Sheet and Implications for Hydrocarbon Generation: There is currently no consensus regarding the timing and generation of hydrocarbons in the Foreland Belt. There are however, several indications of hydrocarbon source and timing of generation. In the Foreland Belt, oils generally lack biological markers. This makes it very difficult to correlate oil-oil and oil-source data with

Figure 2-6-2. Detail of large road-cut outcrop of deformed Banff Formation, Stop 2-6b. This view shows a spectacular duplex structure, the floor thrust of which is at the geologist's hand. Other thrusts are readily visible, especially to the upper right.

the large and growing data set for the Interior Platform. Limited isotopic data from oils suggests strongly that liquids are derived from Mesozoic sources such as the Colorado shale. This is consistent with the available molecular compositional data for oils. No such agreement exists for the origin of the gases. Models suggest that while liquids may be coming from Mesozoic sources there is nothing that precludes the involvement of Paleozoic sources, like the Exshaw and Banff mudstones seen at this location, from contributing to the generation of gases.

Thermal history analysis provides important insights into the mechanism of hydrocarbon generation in the Foreland Belt (Osadetz et al., 2000). Apatite fission-track data from the Lewis thrust sheet and environs exhibit systematic variations with present elevation. Present elevation serves as a proxy for deformed structural position (Figure 2-6-3). Apatite fission-track ages decrease from ~70 Ma, at the highest elevations in Lewis thrust sheet east of Flathead Fault (> +2000 m), to ~30 Ma below Lewis Thrust (~ -1000 m). In this profile, mean horizontal confined fission-track lengths (HCTL) are inferred to exhibit a "dog-leg", or piece-wise linear variation with elevation. Mean HCTL is >13 microns at the highest elevations. This decreases to ~12 microns at ~ +1400 m. At about +800 m mean HCTL is about 13 microns, indicating the top of the second segment of the profile. At lower elevations mean HCLT decreases progressively to ~11.5 microns at < -500 m. Lewis thrust sheet samples from the hanging wall of Flathead Fault have apatite fission-track data of comparable age and comparable, or longer, mean HCTL than that of the highest samples in

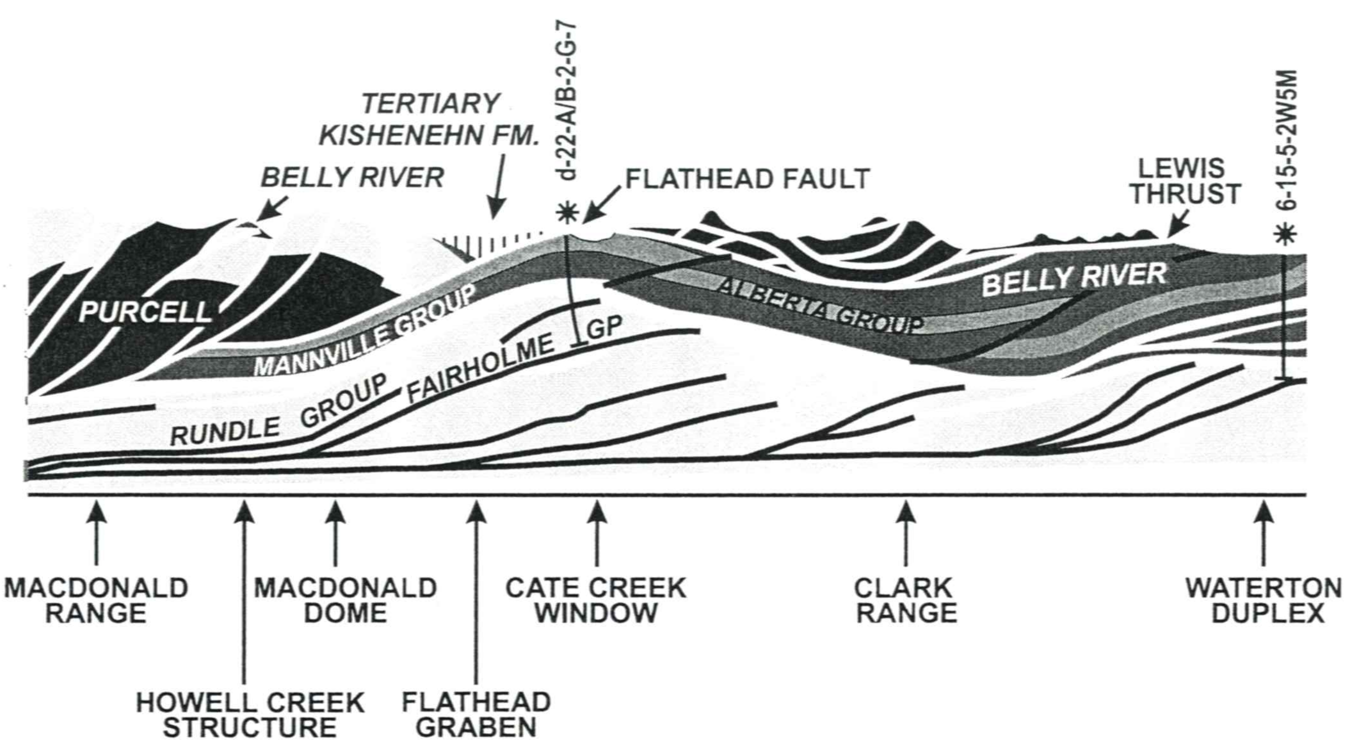


Figure 2-6-3. Present structure SW-NE structure section through Howell Creek, B.C. and Cate Creek, B.C., in the region between the Lewis and Mount Broadview thrust faults. Notice how the Middle Eocene and younger Flathead normal fault merges listrically with the Lewis Thrust Fault forming an overlying half graben filled with Tertiary Kishenehn Fm. Notice also the large fault bend fold, the Akimina Syncline, formed in the Lewis thrust sheet, between the underlying multiduplex structures at Waterton in the east and the immediate footwall of the Flathead Fault in the west. Fission track samples were taken from the topographic profile in the vicinity of this section.

the footwall of Flathead Fault. Rudaceous clasts of Lewis thrust sheet in Lower Oligocene Kishenehn Formation have apatite fission-track data like that in the highest portions of the profile east of Flathead Fault. Everywhere in Lewis thrust sheet zircon fission-track ages are older than both the youngest strata and the time of maximum Phanerozoic temperatures.

These and other data show that Lewis thrust sheet reached maximum Phanerozoic temperatures prior to motion on Lewis Thrust, in response to burial by a succession >7 km thick, imposed during the interval mid-Campanian to Maastrichtian (Figures 2-6-4, 2-6-5, and 2-6-6). This succession is no longer preserved. The Lewis thrust sheet geothermal gradient at peak coalification was significantly lower than that observed currently (17ºC/km; Figure 2-6-7). In late Campanian-Maastrichtian time (~75 Ma), Lewis thrust sheet exhibits a profound cooling and additional lowering of its geothermal gradient (Figure 2-6-7). This indicates motion on Lewis Thrust Fault. It is reasonable to assume that the peak coalification of and hydrocarbon generation from rocks below Lewis Thrust was achieved by tectonic burial below the cooling and eroding Lewis thrust sheet. This takes into account the short interval for burial and the high reflectance and low coalification gradient in rocks below Lewis Thrust. This model is fundamentally different from that proposed by others for the American Foreland Belt. Clearly there is a need for additional study.

In mid-Eocene time a second cooling affects the region east of Flathead Fault. This indicates displacement on Flathead Fault and links temporally the formation of Flathead Graben and the epeirogenic uplift of the craton with extension in the intermontane region.

Road Log:
From Stop 6b, return east along Highway 3 to Coleman

Return to Coleman for Overnight Accommodation and Dinner

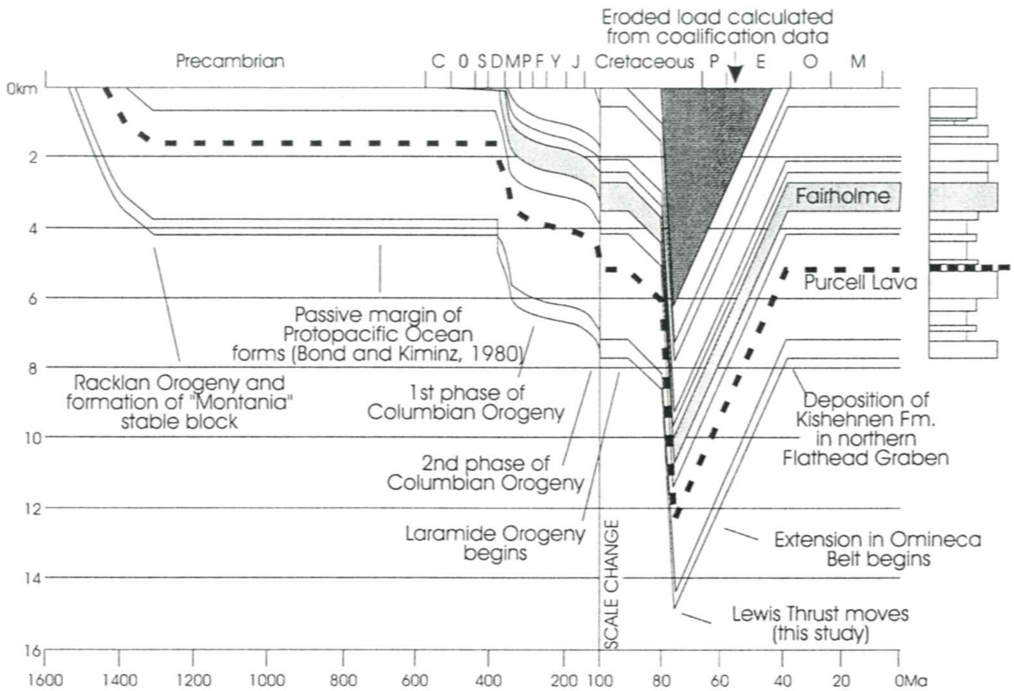


Figure 2-6-4. Burial history model for Lewis thrust sheet east of Flathead Fault in the vicinity of Figure 2-6-3. The preserved stratigraphic succession is shown at the same scale to the right of the diagram, with the Fairholme Group and Purcell Lava highlighted, as on the burial history diagram. The great thickness of Upper Cretaceous deposition on Lewis thrust sheet is required to achieve observed coal ranks in Kootenay Group prior to the motion on Lewis Thrust Fault. Erosional history of Lewis thrust plate is constrained by the preservation of Lower Cretaceous Blairmore Group below Tertiary Kishehnen Formation in Flathead Graben and the present topography. See Figure 2-6-5 for the technique used to infer the minimum thickness of Upper Cretaceous strata and Figure 2-6-6 for the implications of these inferences for the structure.

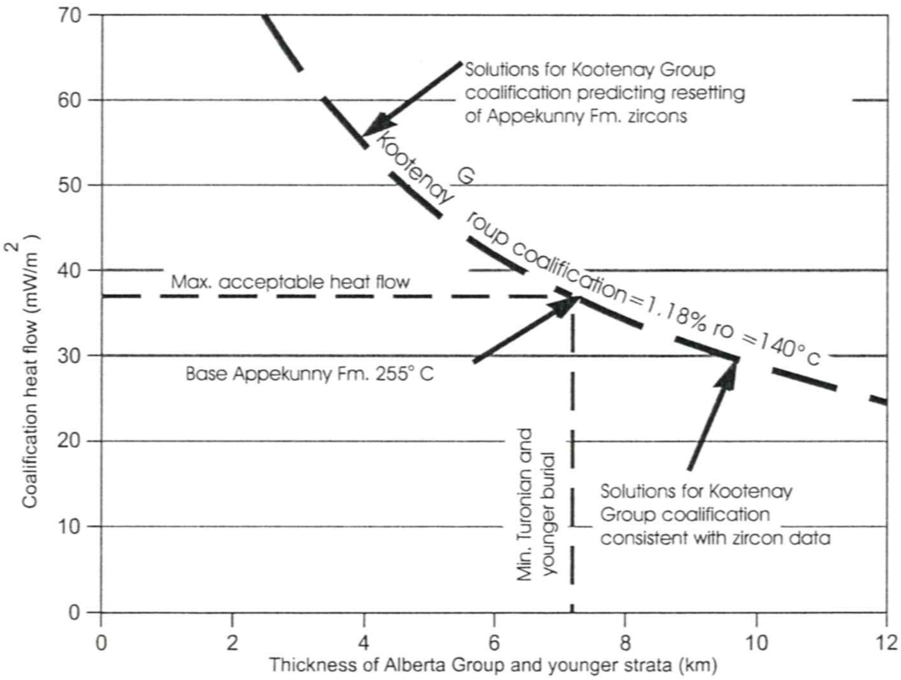


Figure 2-6-5. Cross plot of possible combinations of Alberta Group and younger succession thickness versus effective heat flow that produce a family of solutions consistent with observed coalification in Kootenay Group coals in Lewis thrust sheet. The minimum thickness and maximum heat flow thresholds indicate that subset of successful models that are consistent with temperatures in underlying Appekunny Formation being sufficiently low, <255°C, that fission tracks in detrital Appekunny zircon grains are not totally annealed accompanying peak coalification in Lewis thrust sheet.

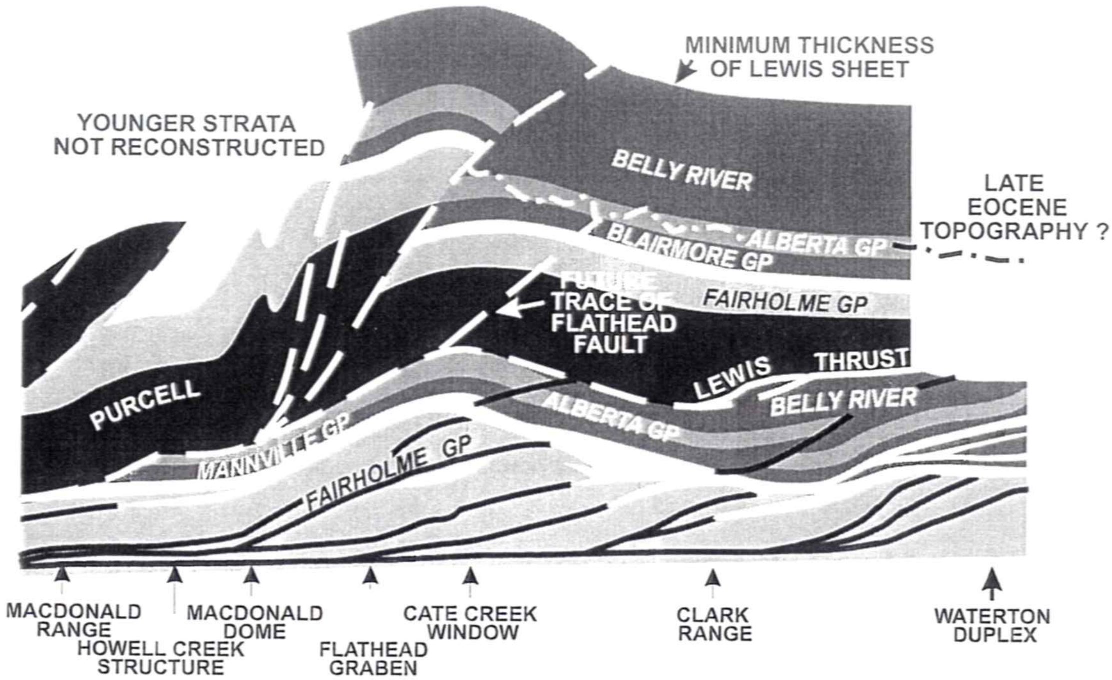


Figure 2-6-6. Paleostructure structure section for Figure 2-6-3. Displacement on the Flathead Fault has been removed and the continuity of the Lewis thrust sheet has been restored. Thickness of the inferred Upper Cretaceous succession is indicated (Figure 2-6-5), as is the inferred position of the erosion surface on Lewis thrust sheet immediately prior to motion on Flathead Fault.

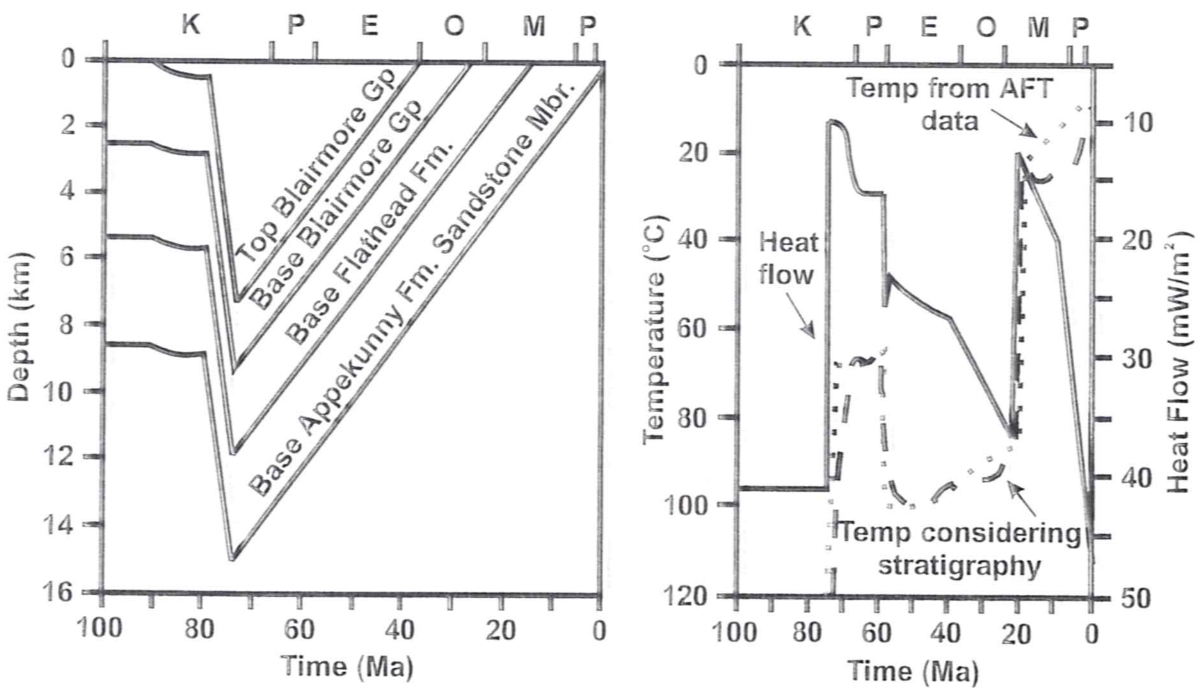
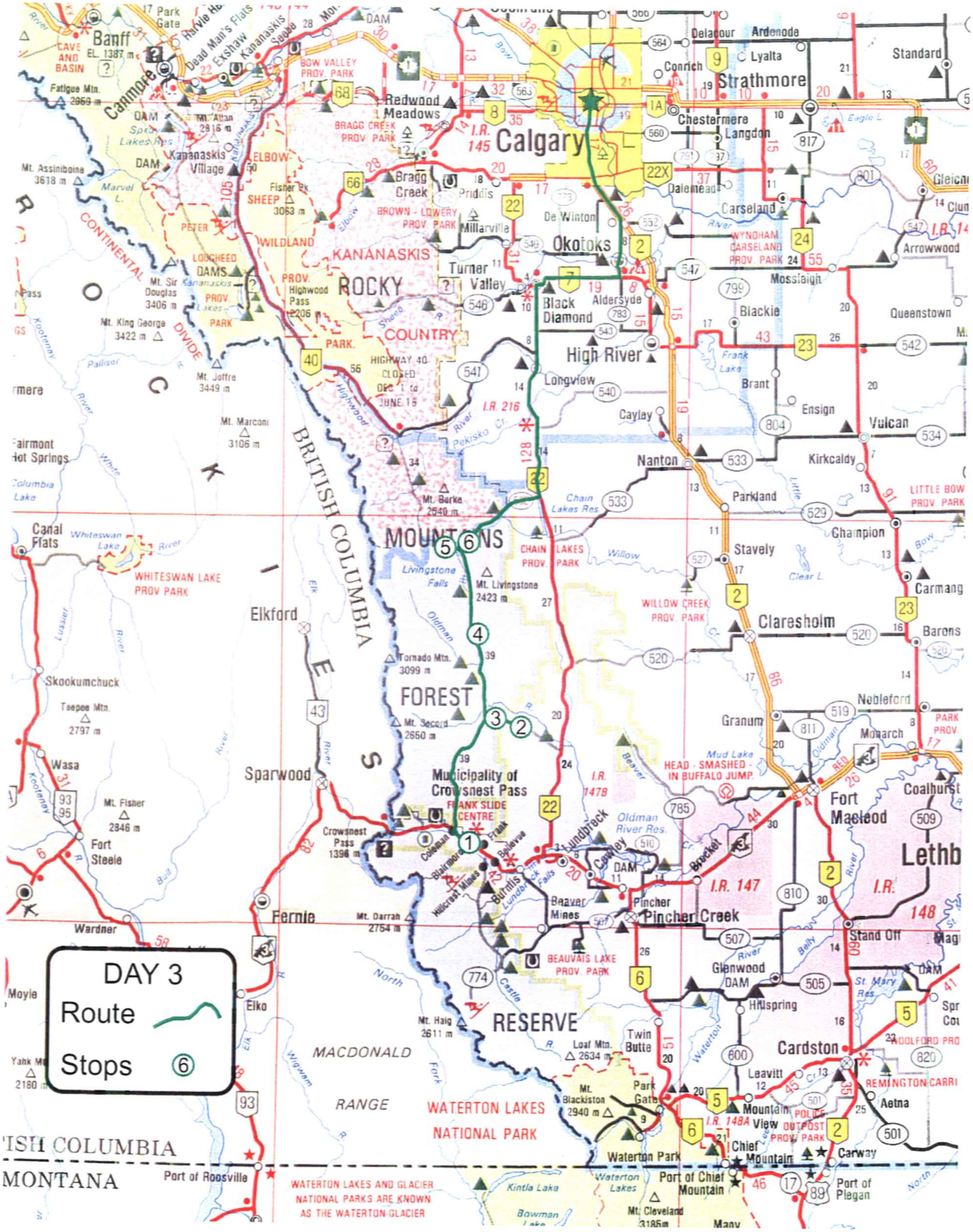


Figure 2-6-7. Portions of the burial history curve (left, after Figure 2-6-4) for Lewis thrust sheet lying east of Flathead Fault. Portions of a model thermal history (right) for the same region and time interval as constrained by, depositional history, coalification, and zircon and apatite fission track parameters and models. Termal history model is first derived without reference to stratigraphic constraint (dotted line) and subsequently with reference to stratigraphic constraint (dashed line). Heat flow implications (solid line) of the thermal model with reference to stratigraphic constraint are shown. Profound cooling of Lewis thrust sheet at about 75 Ma is inferred to indicate motion on Lewis Thrust Fault.



km 10 0 10 20 30 40 50 60 70 km
miles 10 0 10 20 30 40 50 miles

Figure 3-0-1. Road map of southern Alberta showing the route and stop locations for Day 3.

DAY THREE

The Inner Foothills

(refer to Figure 3-0-1)

Stop 1: Blairmore Turnoff Road Cuts, Highway 3
Distance: 0.00 km
Access: From Blairmore, drive to the Lower Carboniferous road cuts exposed north of Highway 3, at the junction of the highway and the access road to the east end of town; park off the paved shoulder
Theme: Mesostructural elements, and Carboniferous stratigraphy
Purpose: Outcrop examination of Carboniferous Rundle Group stratigraphy, with a focus on mesostructure, especially tectonic stylolites.

Geology: The purpose of visiting this outcrop is both to see the upper part of the Carboniferous succession that does not crop out at Crowsnest Lake (Stop 6b, yesterday) and to see a variety of mesostructures, particularly tectonic stylolites. The roadside outcrop of Rundle Group is in the upper portion of the Paleozoic succession carried by the Turtle Mountain thrust (Figure 3-1-1). Here, the complete Carboniferous succession, from bottom to top, is:

Banff Formation (predominantly on the east face of Turtle Mountain): Dark grey argillaceous and shaly limestone with abundant dark grey chert.

Rundle Group, consisting of:
Livingstone Formation, light grey coarse-grained echinoderm limestone and dolomitic to cherty limestone, approximately 240 m thick.
Mount Head Formation, which consists of several members:
Wileman Member, brown argillaceous dolostone, 20 m thick.
Baril Member, grey micritic limestone and dolostone, about 25 m thick.
Salter Member, brown-weathering silty dolostone and dolostone breccia, about 35 m thick.
Loomis Member, grey micritic limestone, about 20 m thick.
Marston Member, brown-weathering silty dolostone, about 45 m thick.
Carnarvon Member, dark micritic limestone, about 60 m thick.
Etherington Formation, cherty micritic sandy limestone, sandy dolostone, dolomitic and limey sandstones and green shale about 76 m thick, that was at one time overlain at this locality by Fernie Formation shales.

Structural Elements: Although the Foreland Belt has been locally well mapped and the structures well analyzed at map scale, significantly less emphasis has been placed on the use of meso- and microstructural elements. From the perspective of hydrocarbon prospectivity, the most important of these are fractures. Fractures can be planar or curviplanar with smooth, stylolitic or filled or coated surfaces (with vein minerals that are often marked with slickenside striae). Such fractures commonly bound individual rock fragments, which either lack or have comparatively little penetrative strain. These mesoscopic faults and fractures serve to accommodate the strain of larger structural elements. Such fractures are therefore discrete strain discontinuities during the deformation, and mesostructures can provide kinematic indicators of the progressive deformation A fracture filled or coated with vein minerals indicates dilation and constrains a local extension direction. Stylolitic fractures formed by pressure solution constrain a local compression direction. A slickensided fracture can be used to define three kinematic axes that include the slip line from the slickenside striae, a rotational axis lying in the plane of the fracture perpendicular to the slickenside striae and the normal to the fracture. The normal to the fracture and the slip direction defines the deformation plane.

Fractures can be categorized according to their angles of intersection with and orientations to bedding. Fractures can be open, or vein filled or coated. Stylolites may be localized on pre-existing fracture surfaces. Faults can be categorized similarly, using also the sense of displacement with reference to bedding. Extension faults elongate and thin beds, while contraction faults shortening and thicken beds.

Fractures commonly influence the occurrence of oil and gas through their effects on reservoir quality and migration pathway. Fractures are essential at Waterton, where they provide significant storage as well as communication between the Rundle Group and Wabamun Formation reservoirs. In the central Foothills fractures play an essential role in both storage capacity and permeability that allows production from otherwise unattractive reservoirs located in the fractures crests and forelimbs of asymmetric folds. Recently, wells have been completed in fractured bituminous mudrocks that are thermally mature source rocks.

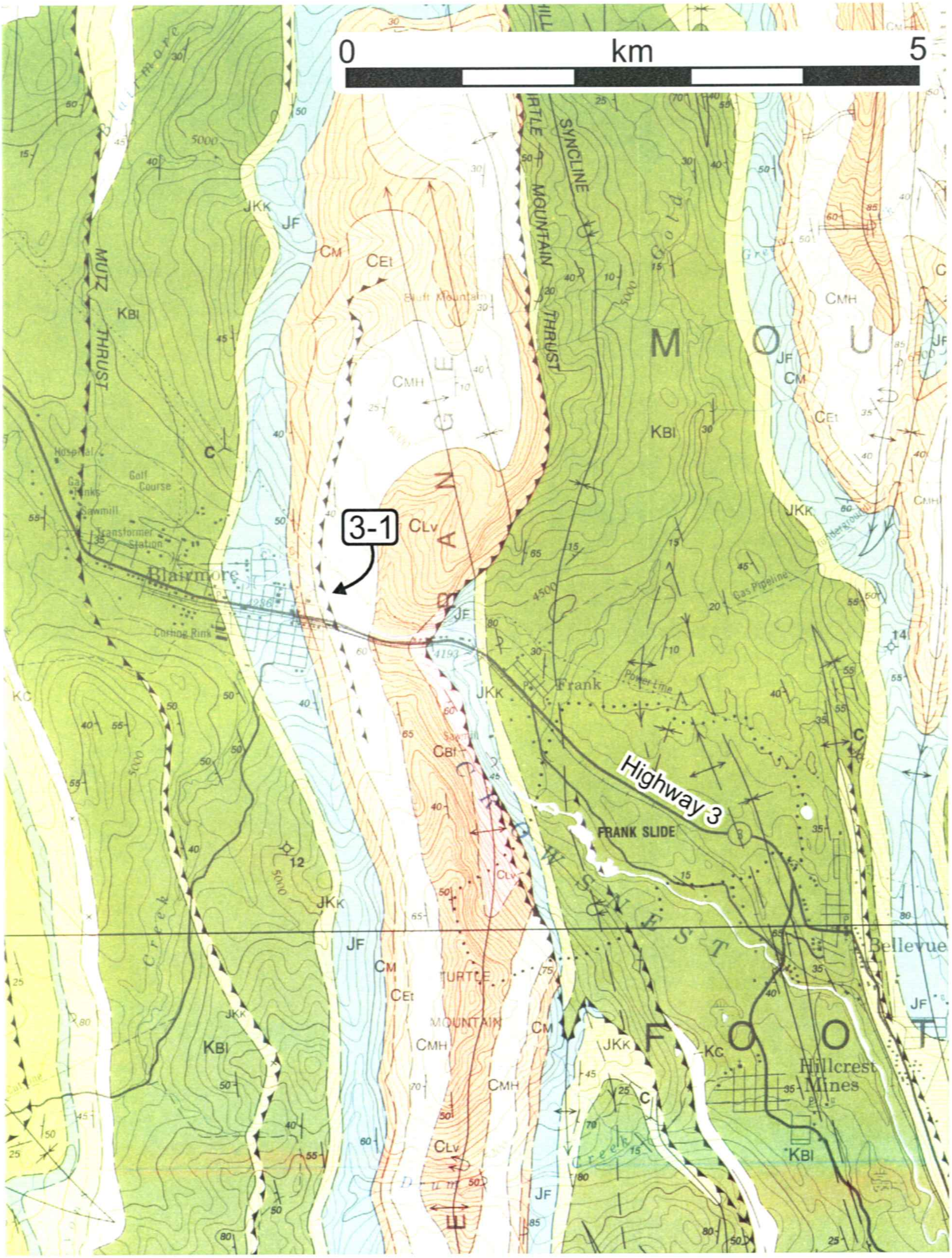


Figure 3-1-1. Detail of GSC Map 1829A (Norris, 1993) of Blairmore (west half), centred approximately on 49°36'00"N, 114°24'30"W, showing location of Stop 3-1. Note that the stop is at a series of road-cuts along the new highway, which by-passes Blairmore and is not shown on the map.

Fractures will play an essential role in the future exploitation of coal-bed methane potential.

Road Log:

0.00 km Stop 1, at east access to Blairmore
1.00 km Central access to Blairmore
2.80 km West access to Blairmore
5.60 km Junction with Forestry Trunk Road (Highway 940), **TURN NORTH (RIGHT)**

Reset odometer to ZERO

0.00 km Junction of Highway 3 and Forestry Trunk Road; follow main road to north (winding)
1.30 km Sign marking Kananaskis Road, Highway 940 (40)
7.10-7.40 km Wapiabi Formation outcrops
7.70 km Pipeline crossing
8.60 km Wapiabi Formation outcrop
9.00 km Wapiabi Formation outcrop
9.20 km Wapiabi Formation outcrop
9.40 km Wapiabi Formation outcrop
9.60 km Turnoff to North Coleman Gas Field: here, gas is trapped in several imbricates of Mississippian Rundle Group and Devonian Wabamun (Palliser) carbonates beneath the Livingstone thrust sheet. Maximum displacement on the Coleman Field thrust fault is ~10 km with vertical relief above the regional dip of ~1650 m; the field is ~10 km in strike length.
9.70 km Wapiabi Formation outcrop
10.40 km Wapiabi Formation outcrop
11.00 km Wapiabi Formation outcrop
11.50 km Wapiabi Formation outcrop (good quality)
12.20-12.50 km Wapiabi Formation outcrops (good quality)
14.40-14.80 km Wapiabi Formation outcrops (good quality)
15.00 km Wapiabi Formation outcrop
16.30-16.60 km Wapiabi Formation outcrop
17.20 km Wapiabi Formation outcrop
17.80 km Gully on east side of road with west dipping Wapiabi Formation
18.70 km Wapiabi Formation outcrop
18.90 km Wapiabi Formation outcrop
19.50 km Texas gate, outcrop to west
20.30-21.70 km Long scattered outcrop of Wapiabi Formation
22.00 km Wapiabi Formation outcrop
22.20 km Wapiabi Formation outcrop
22.30 km Turnoff to Morrison/Northstar well; stay right on Kananaskis Road
23.10 km Wapiabi Formation; steep west dip
23.70-23.90 km Wapiabi Formation outcrop
25.60 km Blairmore Group outcrop; deformed
26.10 km Blairmore Group outcrop
26.60 km Vicary Creek bridge; Blairmore Group outcrop
27.85 km Blairmore Group outcrop
30.10 km Texas gate
30.30 km Turnoff to Racehorse Creek Campground
30.40 km Blairmore Group outcrop
31.10 km Daisy Creek bridge; large Cadomin/basal Blairmore outcrop at 8:00
31.90 km Blairmore Group outcrop
32.80 km View north of anticline-syncline fold pair on northwest side of Racehorse Creek (by Canadian Centennial marker)
34.20 km Junction of Forestry Trunk Road with Highway 517; **TURN EAST (RIGHT)** toward The Gap
35.25 km Top of long series of exposures of the thick Carboniferous and thin Triassic section
35.55 km Lower Carboniferous upper Rundle Group outcrop
35.70 km Turnoff to primitive campground and parking area for Stop 3b – continue straight on
36.00 km Roadside Livingstone Formation outcrop (Stop 3b)
37.40 km Excellent views of Livingstone Range structure, both north and south (Stop 3a)
37.90 km Road turns to east, views out to Foothills structures in hanging wall of the Livingstone Thrust; Livingstone Formation outcrop
42.60 km Approximate trace of the Livingstone Thrust
45.00 km **Stop 2** – viewpoint to north and west

Stop 2: Footwall of Livingstone Thrust, Highway 517
Distance: 45.00 km from junction of Forestry Trunk Road with Highway 3, and 10.80 km from junction of Forestry Trunk Road with Highway 517
Access: Park at the side of the road, where the vista opens to the north and west
Theme: Foothills structure; informal boundary between Outer Foothills and Inner Foothills
Purpose: View the folded trace of the Livingstone Thrust, and Foothills structure in its hanging wall and footwall.

Geology: Facing north we have a panoramic view of the Outer Foothills, the folded trace of the Livingstone Thrust (Figure 3-2-1), and the Inner Foothills. To the east and northeast we see a series of closely spaced imbricate thrusts involving Alberta, Milk River, and Belly River group strata. Slightly west of due north from the viewpoint, the trace of the Livingstone Thrust lies on the west side of the Bob Creek drainage. The thrust is folded, in concert with the large folds traceable in Kootenay and Blairmore group strata in its hanging wall (Figure 3-2-2). From the viewpoint, and on our return drive back into The Gap, we can see that these large folds are well outlined by the resistant ledge of

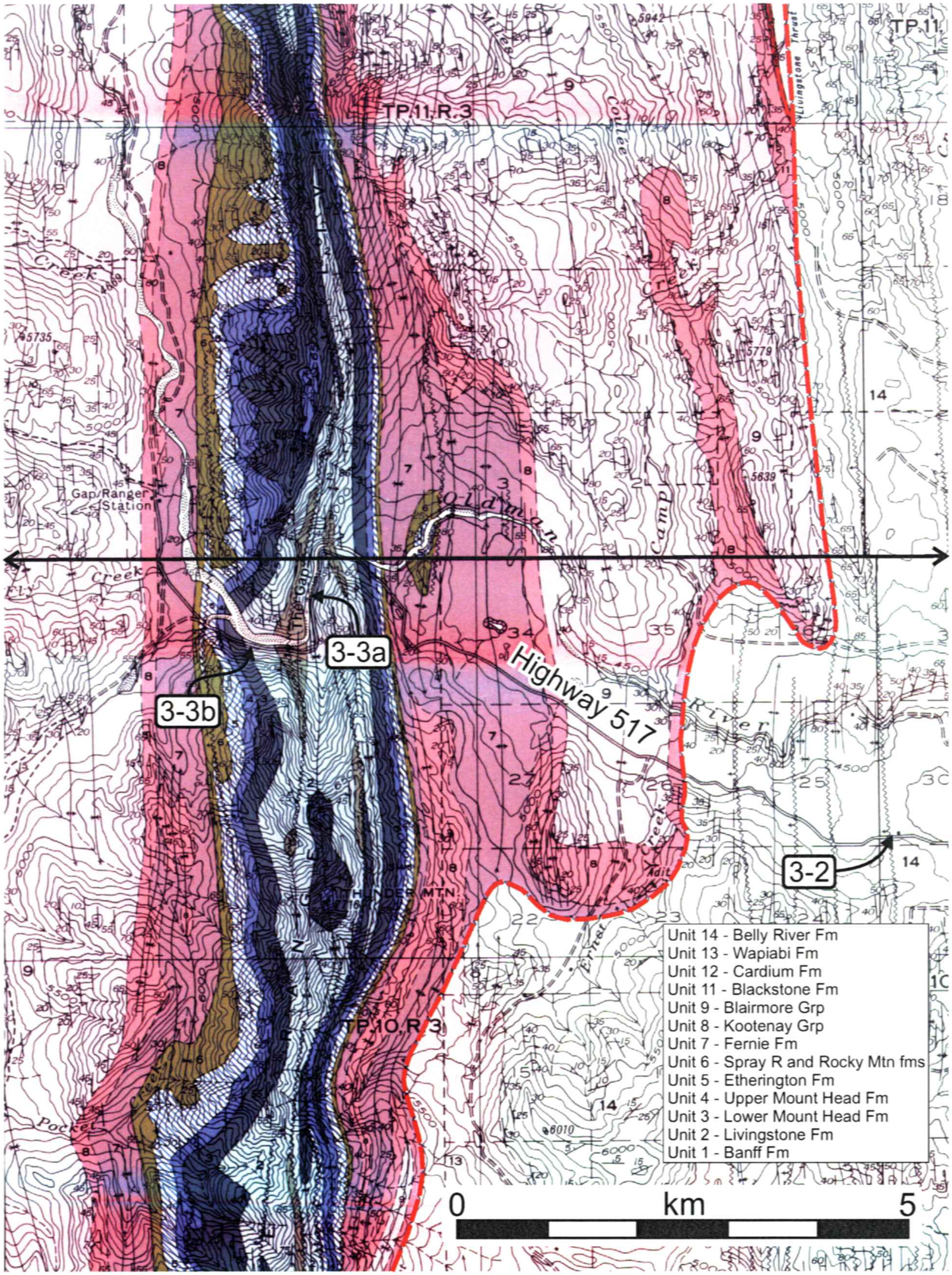
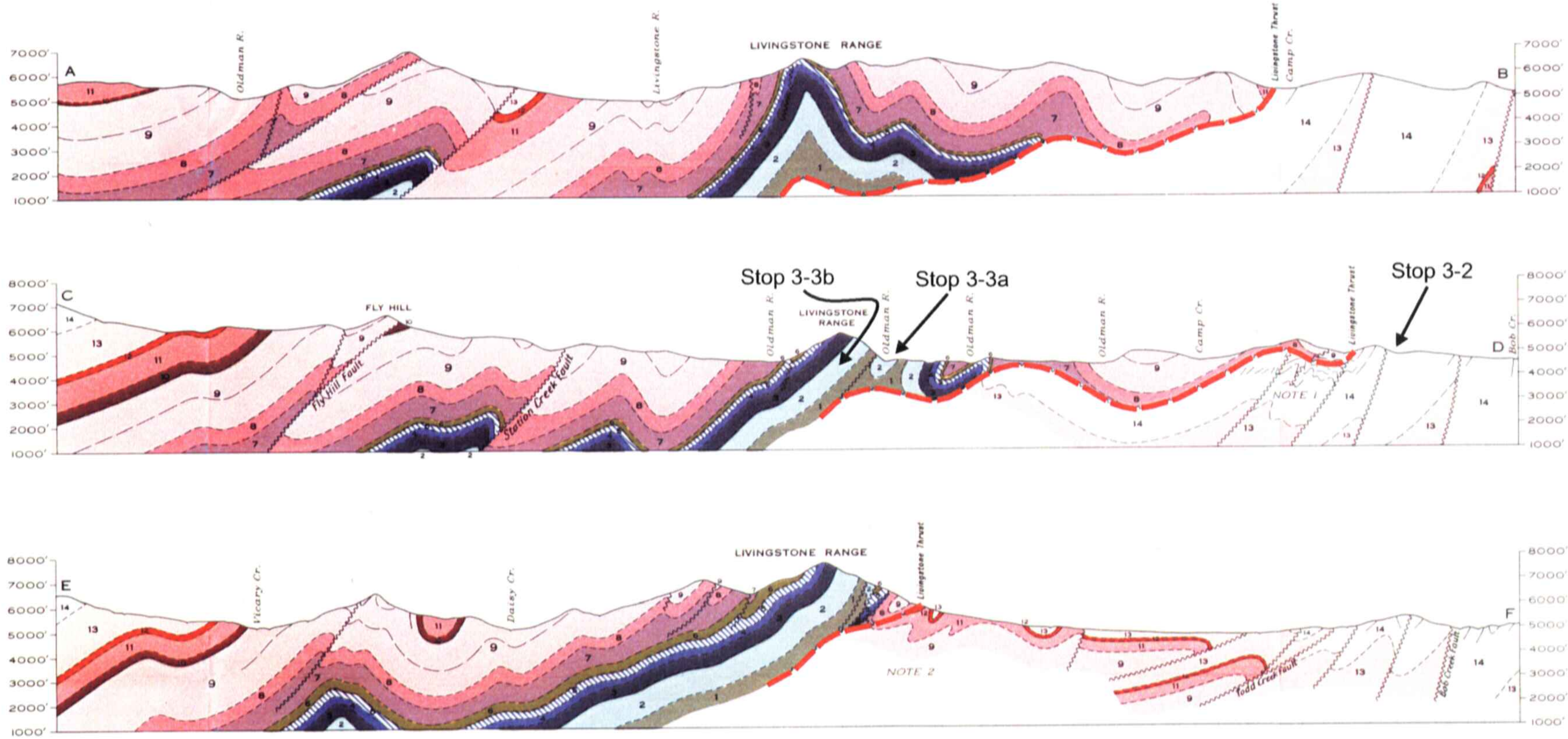


Figure 3-2-1. Detail of GSC Map 978A (Douglas, 1949), centred approximately on 49°52'30"N, 114°20'00"W, showing locations of Stop 3-2, Stop 3-3a, and Stop 3-3b. The folded Livingstone Thrust is highlighted in red.



Structure-sections along lines A-B, C-D, and E-F

Figure 3-2-2. Geological cross sections across Gap map sheet (GSC Map 978A, Douglas, 1949) showing north-south variation in exposure of the Livingstone Thrust and associated structures. The position of cross section C-D is indicated in Figure 3-2-1. Livingstone Thrust highlighted in red.

Cadomin Formation, at the base of the Blairmore Group. Some of these large anticlinal structures in the general area were of interest to early explorationists. However, because these structures are underlain by folded thrusts, generally repeating the Cretaceous section, the carbonate targets were beyond the reach of their relatively primitive cable tool rigs.

The Livingstone Range proper is underlain by Mississippian Rundle Group carbonates, complexly folded and faulted, as discussed at the next stop. The train of map-scale folds in the Livingstone Thrust hanging wall also includes Triassic and Jurassic units, immediately east of the high range (Figures 3-2-1 and 3-2-2). The Jurassic Fernie Formation, clearly folded and in places very strongly deformed, as mapped by Douglas (1950), is a regional detachment throughout the Rocky Mountains and Foothills. Commonly, the Cretaceous and Tertiary section detaches above the Fernie, effectively decoupling structure in the overlying foreland basin succession from the underlying platform succession. It seems probable that a major detachment lies in the Fernie here, along which relatively early shortening in the Cretaceous and Tertiary section was accommodated, prior to motion on the deeper thrusts involving the Paleozoic carbonates. These spatial and temporal relationships must be taken into consideration when balanced cross sections are constructed across these structures.

As seen in Figure 3-2-3, the ramp – flat – ramp geometry of the restored section is clearly evident

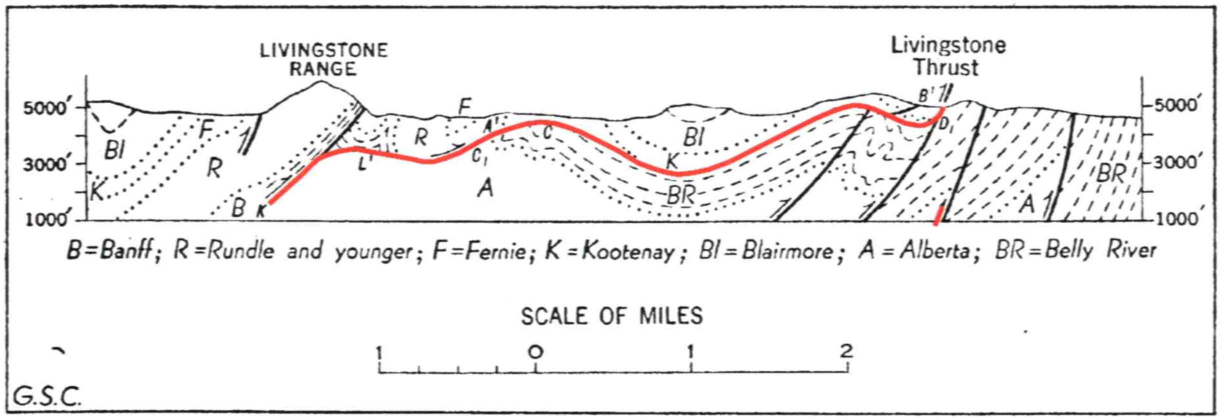


Figure 19. Structure-section through Livingstone thrust sheet, Gap map-area (cf. Structure-section C-D, Gap map).

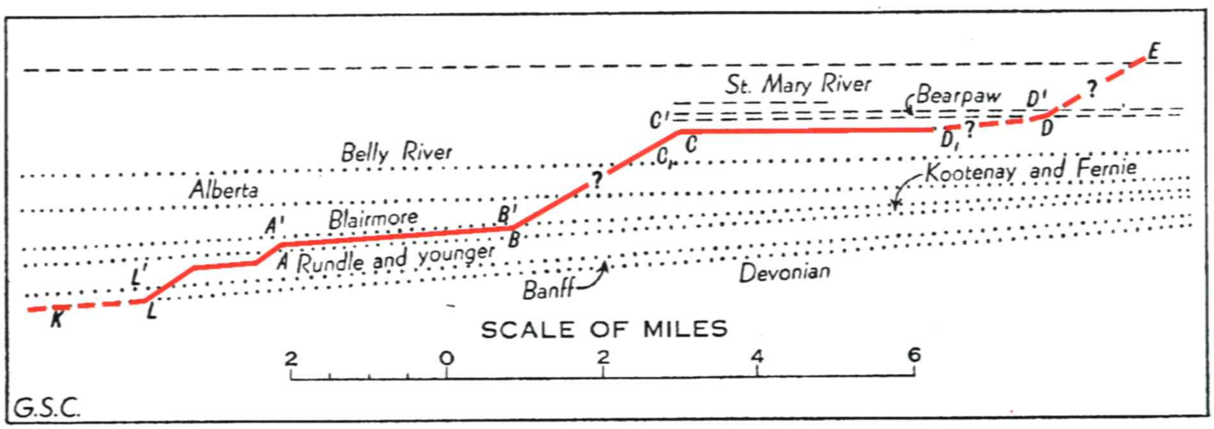


Figure 20. Path (K-E) followed by Livingstone thrust through Upper Palæozoic and Mesozoic strata, as inferred from Figure 19.

Figure 3-2-3. Figures 19 and 20 from Douglas (1950, GSC Memoir 255) illustrating the ramp-and-flat style geometry of the Livingstone Thrust. Above: deformed section; below: restored section.

(Douglas, 1950). In fact, Douglas (1950) was one of the first mappers to demonstrate these relationships clearly in the field. Following similar arguments, based in part on the principals of balanced cross sections, he is also credited by some with establishing that basement is not involved, i.e., the structure is thin-skinned.

Road Log:

Turn vehicle(s) around to return west along Highway 517

Reset odometer to ZERO

0.00 km From Stop 2 drive west back into The Gap
2.40 km Approximate trace of the Livingstone Thrust
7.10 km Road turns to east, views out to Foothills structures in hanging wall of the Livingstone Thrust; Livingstone Formation outcrop
7.60 km **Stop 3a**; viewpoint with outstanding views of Livingstone Range structure, both north and south (Stop 3a)

Stop 3a: Old Man River Gap (Eastern Side), Highway 517

Distance: 7.60 km from Stop 2 (traveling west); 3.20 km from the junction of the Forestry Trunk Road and Highway 517 (traveling east)

Access: Pull off on west side of the road, as far as possible, where the road is very wide; CAUTION: logging trucks, camper trailers and motorhomes, and other large vehicles use this access road

Theme: Hydrocarbon resources of the Foreland Belt (notes to read during the drive up), and characteristic structures of the Inner Foothills.

Purpose: View the folding of a thrust sheet that is partly the result of a superposition of hanging wall and footwall ramps. This structure is an exhumed model for a Foothills gas prospect.

Geology: The Livingstone Thrust is one of the major tectonic elements of the southern Alberta Foothills. It can be traced for more than 145 km from north of the Highwood River to near the northern end of the Waterton gas field, where it either merges upward with or simply passes displacement to the Turtle Mountain Thrust. To the north of the viewpoint, the Livingstone Thrust interacts with a number of thrusts, most notably the McConnell Thrust, which marks the Foothills/Front Ranges boundary at the latitude of Calgary and northward. The Livingstone and McConnell thrusts, defined originally as discrete, mappable features expressed in the surface bedrock geology, are probably linked at depth, representing splays from the same, major, subsurface thrust (Kubli et al., 1996). This is consistent with interpretations of industry seismic data which indicate that the footwall cutoff of the Mississippian section you see before you lies west of the Alberta/B.C. border, over 30 km away (P.A. MacKay, pers. comm., 1999). The interaction of the Livingstone and McConnell thrusts will be discussed again at the last stop of the day at Hailstone Butte.

Structure in The Gap (Figure 3-3-1) illustrates many of the major tenants of the "Foothills Style", particularly the influence of thrust ramps and flats. The structure in The Gap reflects the juxtaposition of a flat – ramp – flat through the hanging wall Banff-Rundle-basal Mesozoic succession onto a footwall of a ramp – flat sequence within the Cretaceous succession (Figure 3-2-3). The ramp in the Rundle Group has been thrust onto an inferred ramp through the Belly River and Alberta groups, resulting in the complex structural culmination in the Livingstone Range (Figure 3-3-2). As we have seen, east of the range the upper hanging wall flat near the base of the Mesozoic succession is juxtaposed on a substantial footwall flat in the Belly River group, very near the current erosional level in the valley (Figures 3-2-1 and 3-2-2). The structure plunges northward, however, preserving older Mesozoic strata on older Cretaceous strata north of Highway 517 through Maycroft map sheet (Figure 3-2-1).

At The Gap, in the long and moderately dipping western limb of the Livingstone Range Anticline, the Upper Paleozoic succession is very similar to that in the upper part of the Turtle Mountain sheet visited at the first stop today. A west-dipping thrust fault beneath the west-dipping Banff strata separates the two limbs of the anticline. This fault is a splay which branches from the Livingstone Thrust beneath the western limb (Figures 3-3-1 and 3-3-2). The adjacent syncline to the east can be viewed on the skyline south of the Gap, but is overridden by this fault to the north of the river. As viewed from the previous stop, east of the Livingstone Range the Livingstone Thrust is relatively flat, but outlines a few large open folds that plunge north. The Livingstone Range Anticline, and each of the anticlines to the east of it, coincides with the position of hanging wall ramps. That faults are folded in accord with their bounding strata is demonstrated by exploration wells that have targeted the up-dip edges of Mississippian carbonate fault slices. One of these slices, on the west side of the Livingstone Range, and driven across earlier today north of Blairmore, contains the Coleman gas field.

Road Log:

7.60 km From Stop 3a, continue south and west on Highway 517

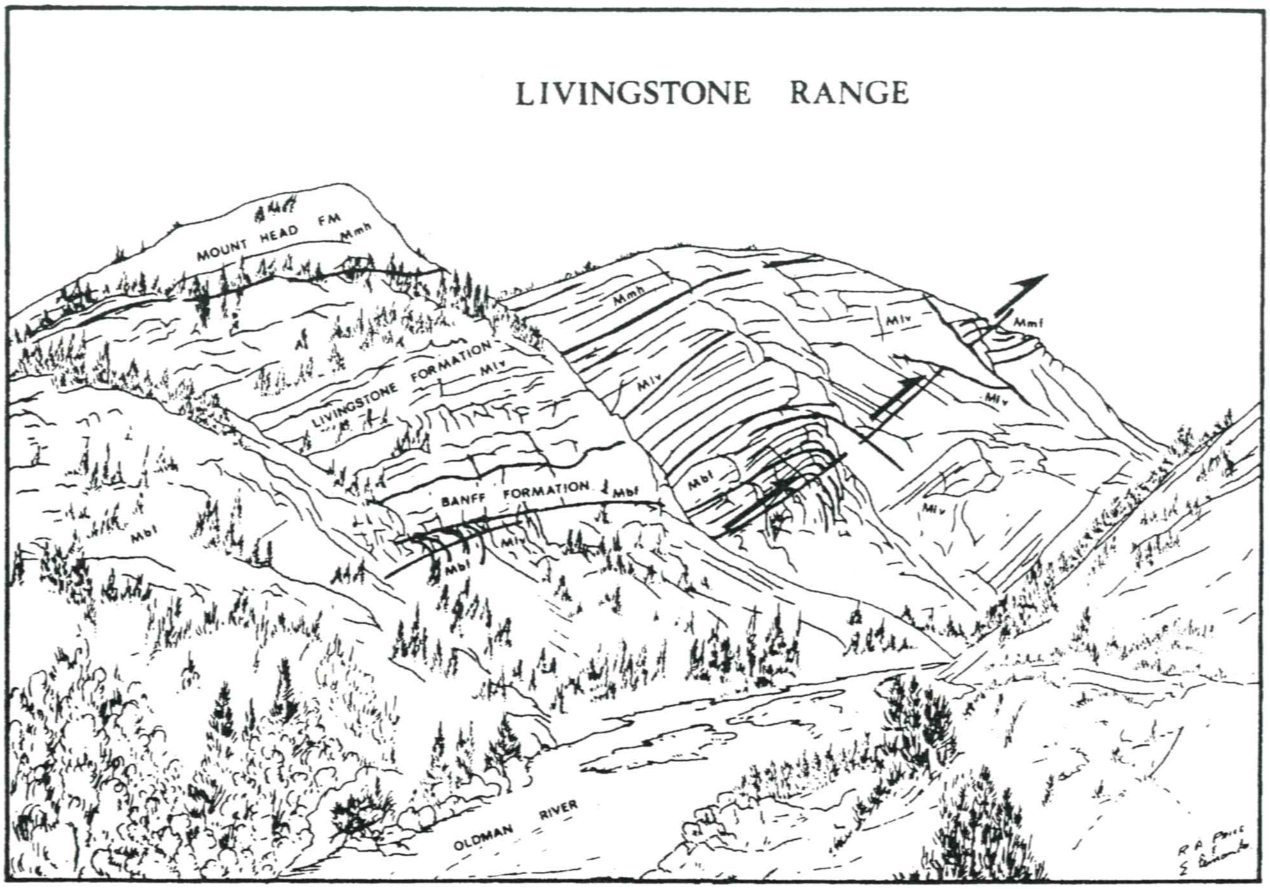


Figure 3-3-1. Sketch of the view north along the core of the Livingstone Range anticline at The Gap (R.A. Price with E. Fernando; from Price et al., 1972).

9.00 km Roadside Livingstone Formation outcrop (Stop 3b) – **continue on to primitive campground** and parking spot

9.30 km Turnoff to primitive campground and parking area for **Stop 3b** – turn right and park

Stop 3b: Oldman River Gap (West Side)

Distance: Primitive campground 9.30 km from Stop 2 (traveling west); 1.5 km from junction of Forestry Trunk Road and Highway 517 (traveling east)

Access: From the primitive campground, walk back (east) along the highway, exercising caution, to view porosity in Turner Valley-equivalent rocks

Theme: Porosity, diagenesis and thermochemical sulphate reduction (TRS) in Foothills reservoirs

Purpose: To view porosity in Livingstone (Turner Valley) Formation carbonates. Lunch stop.

Geology: Porosity development in the Upper Paleozoic Rundle Group reservoirs is a complex topic, and still poorly understood. Lithologies with the greatest original porosity, high-energy skeletal grainstones and packstones, with abundant crinoidal grains, are usually totally cemented by early marine cements. Originally tight argillaceous beds of dolomitic mudstones remained tight. Maximum reservoir development appears in lithologies like skeletal wackestones and have been subjected to selective and complex diagenesis including dolomitization, recrystallization, and porosity enhancement that lead to a complex combination of fossil moldic, interparticulate, and intercrystalline porosity. In terms of the Turner Valley Formation, these optimum porosity zones occur in the upper (Mt1) and basal (Mt3a) subdivisions. The major phase of dolomitization is considered to have occurred during deposition of the restricted-facies dolostones and anhydrite of the overlying Mount Head Formation. Solid hydrocarbon plugging, probably of thermochemical sulphate reduction (TSR) origin, is locally a problem in the reservoir. Fracture-related porosity and fracture enhancement of permeability are especially important at Waterton and Sukunka fields.

Although outcrops are usually a poor representation of subsurface porosity, we will examine porous zones in the Livingstone Formation that are probable stratigraphic equivalents to the porous zones in the subsurface Turner Valley Formation (Figure 3-3-3).

The underlying Palliser Formation (not viewed here) is a secondary reservoir target in the Foothills (Figure 3-3-4). The Crossfield Member of the Devonian Palliser (Wabamun) Formation is the principal reservoir unit within the Devonian section in the Foothills belt. The Crossfield Member is a transgressive wedge of dolomite that occurs within the restricted Wabamun Formation in central Alberta, where it forms an excellent stratigraphic trap. Where the "Crossfield Member" extends into the Fold and Thrust Belt and structural closure exists, gas may be trapped in commercial quantities. Fields at Waterton, Coleman, Moose Mountain and Burnt Timber are a few examples which produce from the Palliser/Wabamun Formation. Like the "type" Crossfield of the Plains, in the Foothills the Crossfield Member is a deeper water lithofacies sandwiched between more restricted facies above and below, although deposited in deeper water settings. An interesting aspect of Crossfield reservoir development is the enhancement of its quantity and quality by thermochemical sulphate reduction (TSR) which "makes" porosity.

***Refer to Appendix 2, "Resource Analysis of Natural Gas in the Foreland Belt", for a discussion of the resource analysis procedure.

Road Log:

9.30 km From turnoff to primitive campground, turn right (west) and return to junction with the Forestry Trunk Road

10.80 km Junction of Forestry Trunk Road with Highway 517; **TURN NORTH (RIGHT)**

Reset odometer to ZERO

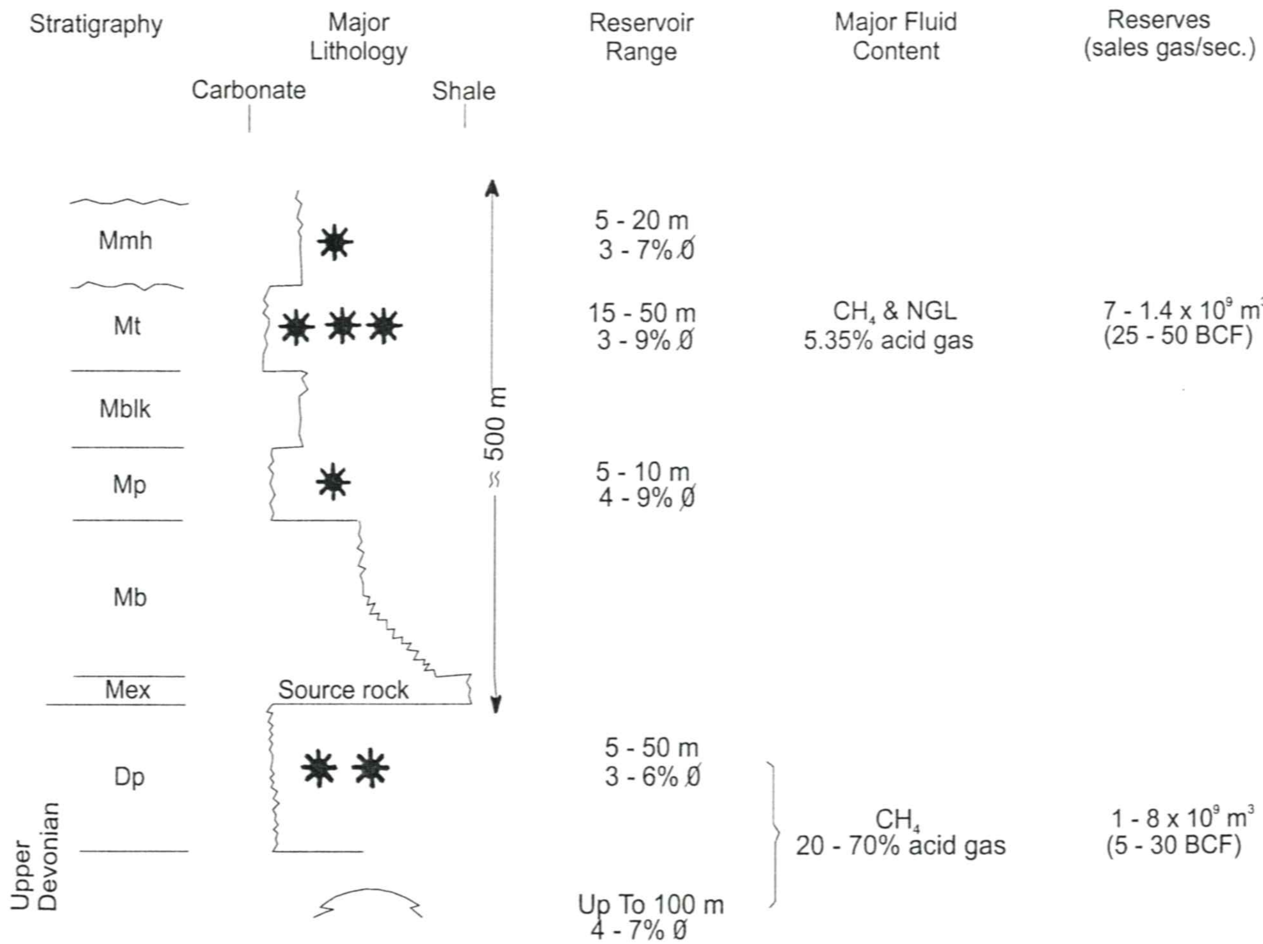


Figure 3-3-4. Summary of characteristics of Devono-Mississippian reservoir units, southern Alberta Foothills (after Fig. 10 in Tippett, C.R. et al., 1992, Southern Canadian Foothills - Hydrocarbon Habitat and Integrated Resource Planning, Guidebook #15, AAPG Annual Convention, Calgary).

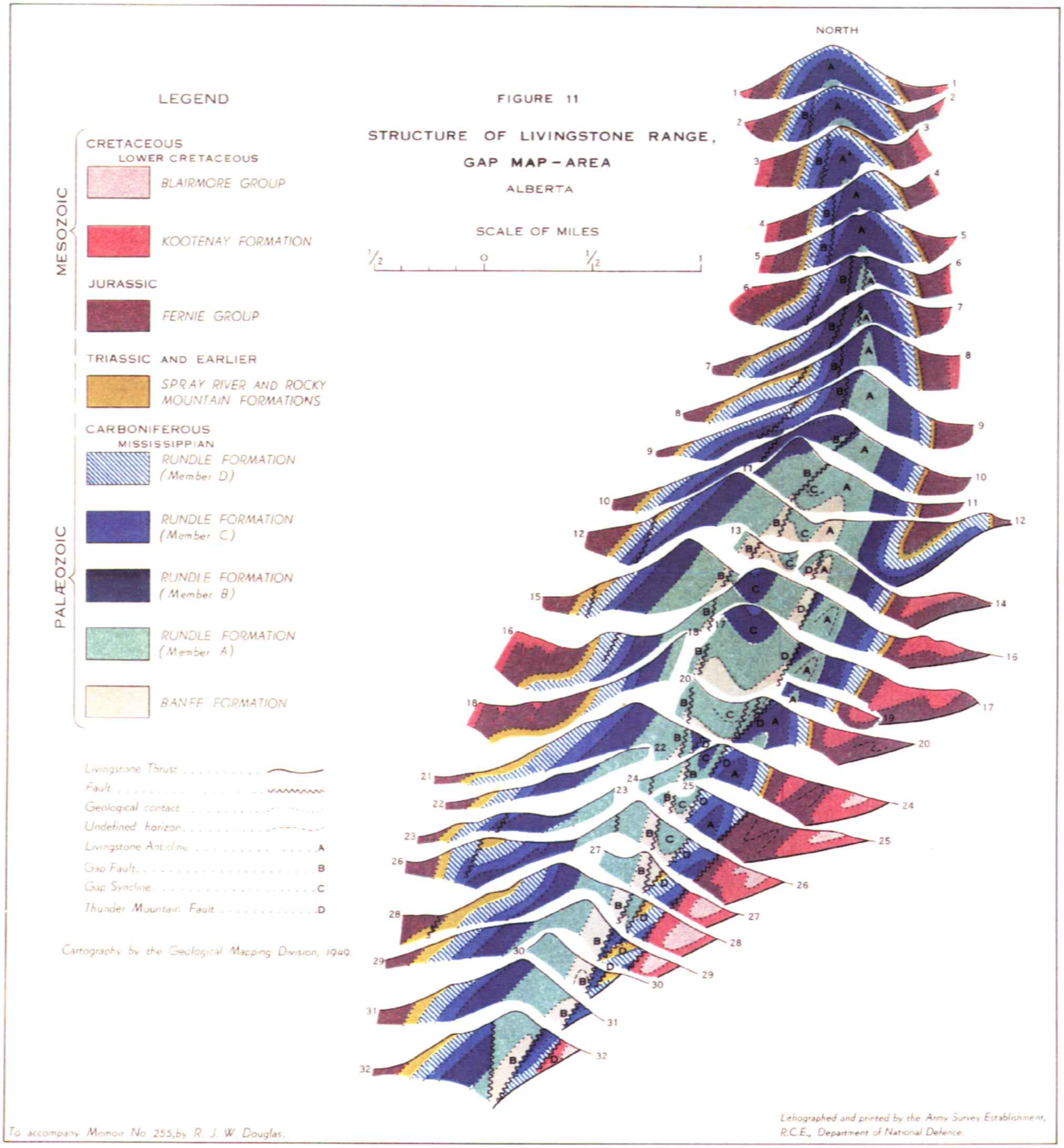


Figure 3-3-2. Closely spaced, serial cross sections through the Livingstone Range, Gap map area (Douglas, 1950), illustrating the nature of structural changes along strike. Section #12 corresponds to cross section C-D in Figure 3-2-2.

0.00 km Junction of Forestry Trunk Road and Highway 517

•*2.30 km Ranger station*

2.40 km Station Creek bridge

5.10 km Dutch Creek bridge; good views to east of Livingstone Range dip-slope

5.25 km Turnoff to Dutch Creek Campground

10.95 km Oldman River bridge; outcrop of uppermost Blairmore Group – note that the Crowsnest Volcanics are missing and the Alberta Group (Blackstone Formation) lies directly on the Mill Creek Formation

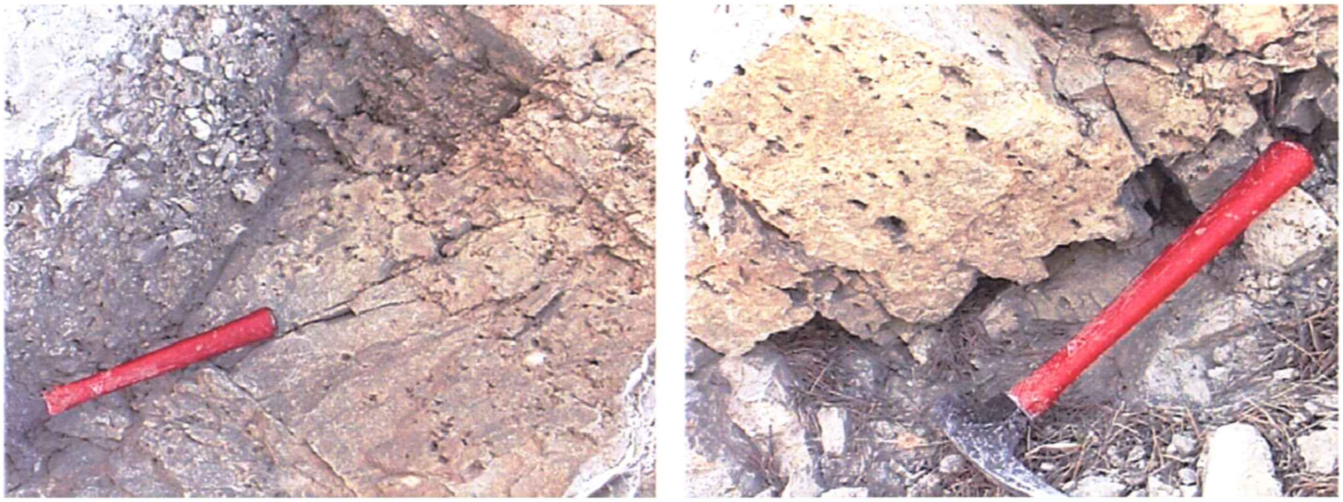


Figure 3-3-3. Porosity in the Livingstone Formation at the Oldman River Gap, Livingstone Range (probably enhanced by surface weathering).

11.10 km Turnoff to Oldman River Campground

19.90 km Pull-out for **Stop 4**; park at the side of the road, walk east toward Livingstone River

Stop 4: Bruin Creek section, Forestry Trunk Road

Distance: 19.90 km from junction of Forestry Trunk Road and Highway 517

Access: Park at the side of the road, walk east toward the Livingstone River; the outcrop is on the Livingstone River, just downstream (south) of the junction with Bruin Creek (Leckie, 1993)

Theme: Stratigraphic succession of the Foreland Basin

Purpose: To view Upper Blairmore section where the Crowsnest Volcanics are absent.

Geology: The Mill Creek Formation (upper Blairmore Group) and the Second White Speckled Shale of the Blackstone Formation (lower Alberta Group) are exposed along the Livingstone River, downstream of the confluence with Bruin Creek (Figure 3-4-1; Leckie, 1993; Leckie and Kristynik, 1995). The outcrop exposes over 100 m of the Mill Creek Formation at this locality (Figure 3-4-2), assigned to the Bruin Creek Member on the basis of facies associations. The unconformity at the base of the member, above the Beaver Mines Formation, is exposed. The basal quartz sandstone of the Bruin Creek Member is important petrographically because it differs from the overlying and underlying units. Other important aspects of the outcrop include the Bruin Creek paleosols and the McDougall-Segur conglomerate. The Blackstone Formation marine shales (Second White Specks) directly overlies the Blackstone, indicating erosional removal (or non-deposition?) of the Crowsnest Volcanics.

As defined by Leckie (1993), the Bruin Creek Member "is restricted to include interbedded cherty sandstone with abundant rock fragments, varicoloured mudstone, conglomerate and ash. It is in part laterally equivalent to the Crowsnest Formation and contains the McDougall-Segur conglomerate." It is late Middle Albian in age.

Road Log:

19.90 km From Stop 4 continue north along the Forestry Trunk Road

27.20 km Coal Creek crossing; limited view to west up Coal Creek drainage to the Lewis Thrust Sheet in the High Rock Range, along the continental divide.

35.90 km Kananaskis Country access-control gates

37.10 km Husky Oil Savanna Creek compressor

38.90 km Etherington Formation outcrop, good views to north into Savanna Creek structure (Livingstone thrust sheet)

39.00 km Texas gate

39.95 km First junction of Highway 40 (940) and Highway 532 – continue straight

40.10 km Second junction of Highway 40 (940) and Highway 532

Reset odometer to ZERO at second junction – continue straight on to northwest

0.00 km Second junction of Highway 40 (940) and Highway 532

0.25 km Pipeline crossing

0.55 km Creek crossing, Mount Head outcrop on east bank

1.30 km Views to south of surface dome across Savanna Creek structure, mostly Mount Head

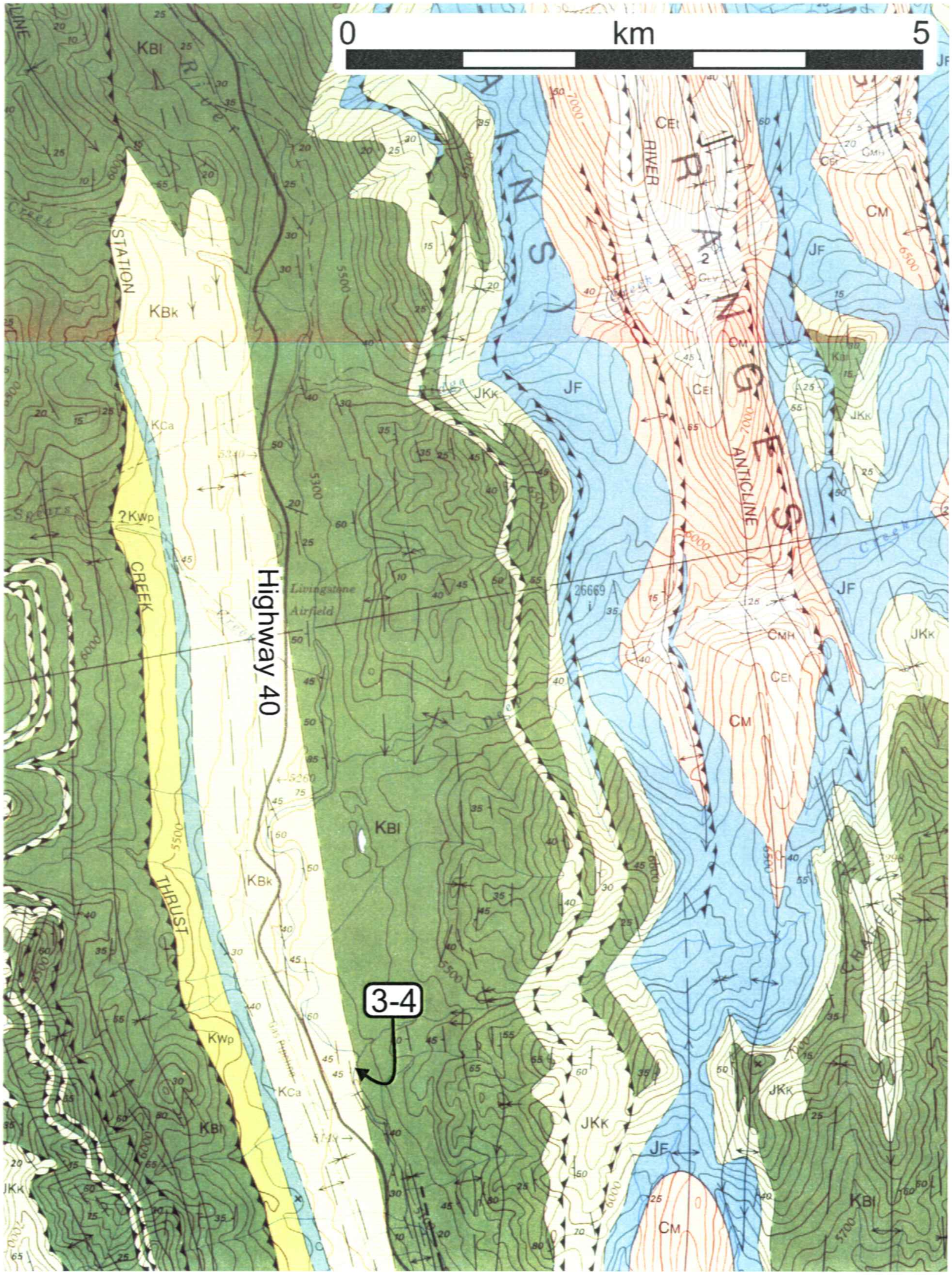


Figure 3-4-1. Detail of GSC Map 1837A (Norris, 1993), centred approximately on 50°03'00"N, 114°24'00"W, showing location of Stop 3-4.

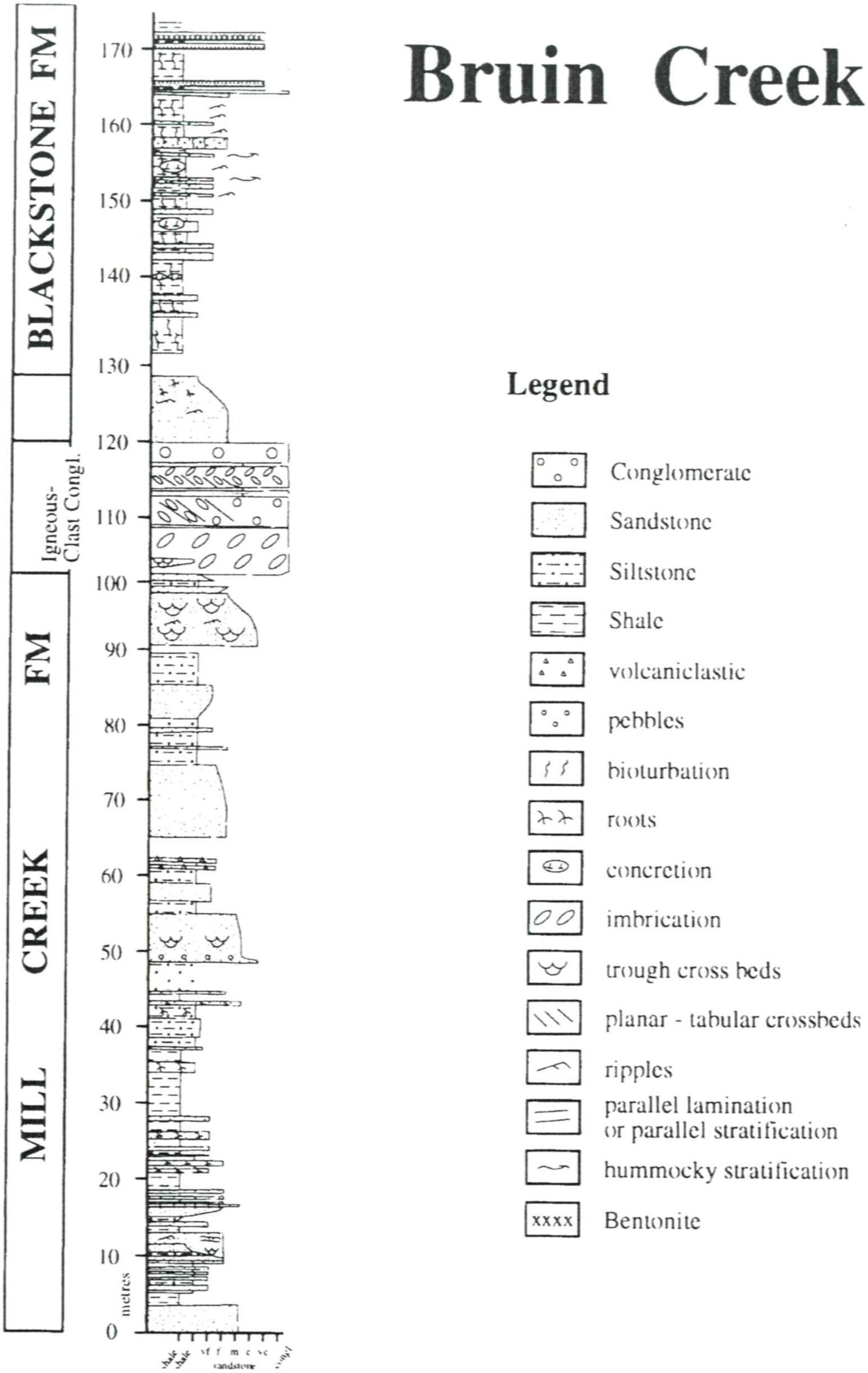


Figure 3-4-2. Measured stratigraphic section containing igneous clast conglomerate in the Mill Creek Formation, Stop 3-4, near confluence of Livingstone River and Bruin Creek (from Leckie and Krystinik, 1995).

2.85 km Views north up unnamed side creek to Plateau Mountain
2.90 km Wellhead south of road
3.20 km Views north up unnamed valley to Plateau Mountain
3.70 km Anglo Canadian Savanna Creek No. 1 5-20-14-4W5 wellsite (1939)
3.75 km Texas gate
4.10 km Husky wellsite, Savanna Creek 12-20-14-04W5, **Stop 5**

Stop 5: Savanna Creek structure
Distance: 4.10 km from junction of Highway 40 (940) and Highway 532
Access: Park just off the road, adjacent to the well site
Theme: Structural geology of the Inner Foothills.
Purpose: Discuss structural setting of the Savanna Creek field.

Geology: At this location adjacent to Dry Creek (Figure 3-5-1), we are approximately on the axis of the surface culmination within the Livingstone thrust sheet (Plateau Mountain Anticine) which is the exposed expression of the Savanna Creek structural culmination at depth. The highest point on the surface culmination lies along strike 2 km to the north, on Plateau Mountain (Figure 3-5-1). The Anglo Canadian Savanna Creek No. 1 well (5-20-14-4W5), drilled in 1939, was spudded south of Dry Creek a short distance to the southeast. It was positioned on the crest of the surface structure to test the Devonian strata naturally anticipated to underlie the Mississippian section exposed on the valley flanks around us. After penetrating surficial deposits, the well encountered Wapiabi Formation (upper Alberta Group) marine shales, eventually drilling through the Alberta Group and terminating at 1028 m depth in the Lower Cretaceous Blairmore Group. Clearly, the well had been spudded in a tectonic window, or fenster, through the Livingstone Thrust (Norris, 1993).

Kubli et al. (1996) describe subsequent interest in the play: "The No. 1 well was twinned in 1952 (12-20-14-4W5) *[just beside us]* and encountered small gas shows in the Mississippian section underlying the fault before another fault was intersected. This confirmed the folded fault hypothesis and resulted in increased interest in the play. The well was deepened in 1954 and penetrated an entire Mississippian section in the third thrust sheet. Based on gas potential in the Livingstone Formation, it was classified as a discovery. Several follow-up wells were drilled, including No. 3A (5-32-14-4W5) at an elevation of 2479 m on top of Plateau Mountain. This well was drilled to a depth of 4205 m and penetrated the Rundle Group in four imbricates of the Savanna Creek structure". (our italics)

To the north, on the top of Plateau Mountain (elevation >8200'), Upper Carboniferous (Pennsylvanian) Spray Lakes Group strata are exposed (Norris, 1993), overlying a Rundle Group section that includes the Etherington, Mt. Head, and Livingstone formations (see first stop today). Interestingly, the extremely flat top of Plateau Mountain was one of the few places in western Canada that escaped glaciation during the Pleistocene (a "nunatak"). A unique and sensitive alpine environment exists there, now with restricted access as part of the Plateau Mountain Ecological Reserve (created in 1991). An interesting geomorphological feature is "patterned ground", which is a polygonal pattern resulting from years of repeated freezing and thawing, that is usually associated with arctic or sub-arctic regions.

Subsurface Structure and Reservoir: Figure 3-5-2 is a constrained cross section across the Savanna Creek structure, from Kubli et al. (1996). The folding of the surface thrust sheet (the Livingstone Thrust) is clearly seen above an antiformal stack of Mississippian and Devonian imbricates. Gas production is primarily from the lower Mount Head (Baril and Wileman members) Formation and the uppermost Livingstone Formation. The bulk of these reservoirs consists of mudstones and wackestones, interbedded with tight, early syntaxially cemented grainstones, that have been preferentially dolomitized. The highest porosity at Savanna Creek reaches 15%, developed as microporosity in a dolomitized mudstone in 9-5-15-4W5 (Kubli et al., 1996). Fractures, better developed in the more brittle dolomites, are crucial components of the bulk reservoir.

As recorded by Kubli et al. in 1996: "Of the initial reserves of 233 Bcf raw recoverable gas in the Savanna Creek field, 146 Bcf have been produced to date. Average production rates declined rapidly when the field was first put on stream. Up to 1993, production rates from the Savanna Creek structure averaged 12-14 MMcd/day, supplied by 6 of the 12 well drilled in the field. Average pay is 54.4 m (178.5 ft) with 4% porosity, 15% water saturation and 13% H_2S."

Road Log:

Return eastward on Highway 40 (940) to the junction with Highway 532

Reset odometer to ZERO – proceed east on Highway 532

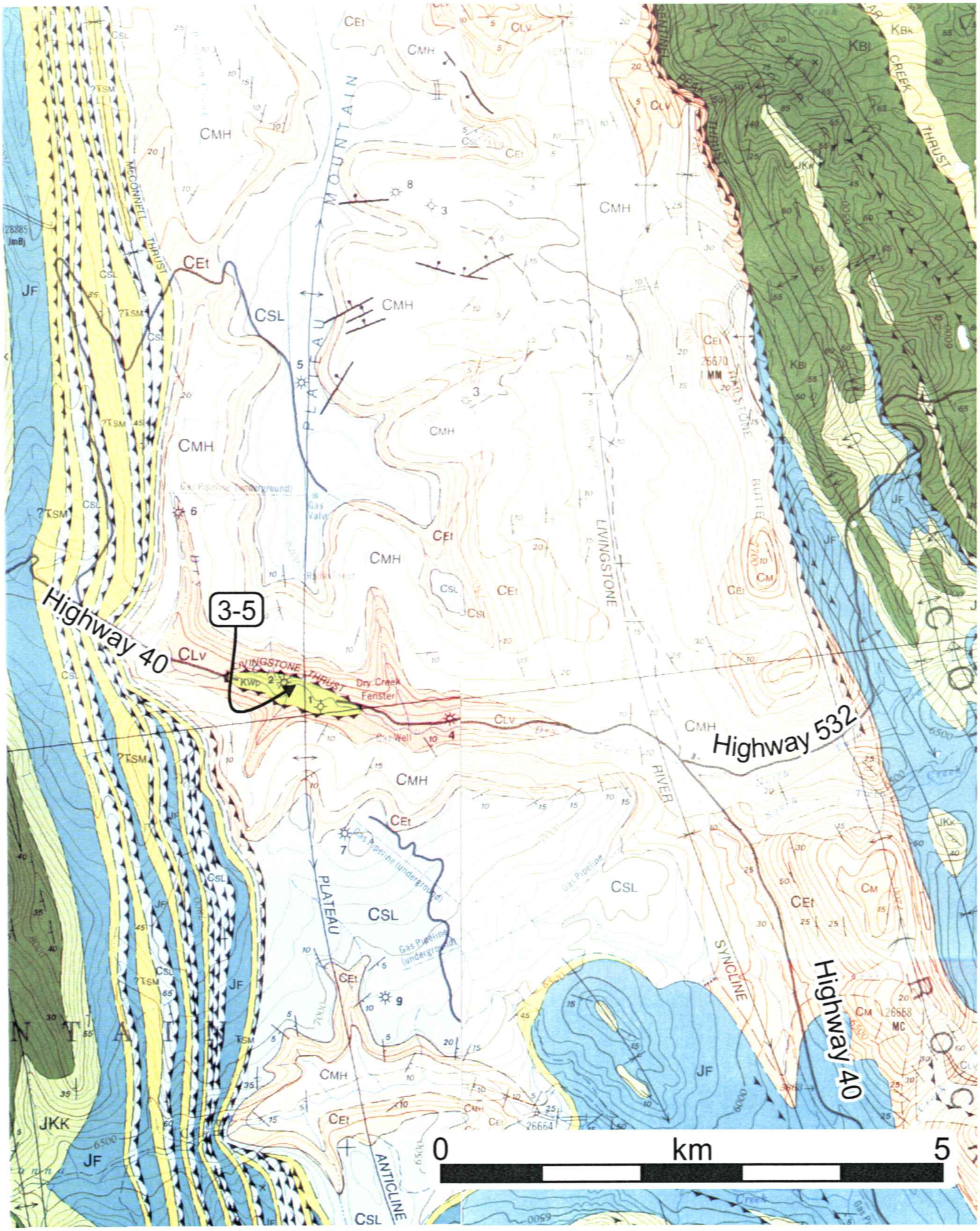


Figure 3-5-1. Detail of GSC Maps 1831A and 1837A (Norris, 1993), centred approximately on 50°11'30"N, 114°29'30"W, showing location of Stop 3-5, within the Dry Creek Fenster of the Livingstone Thrust.

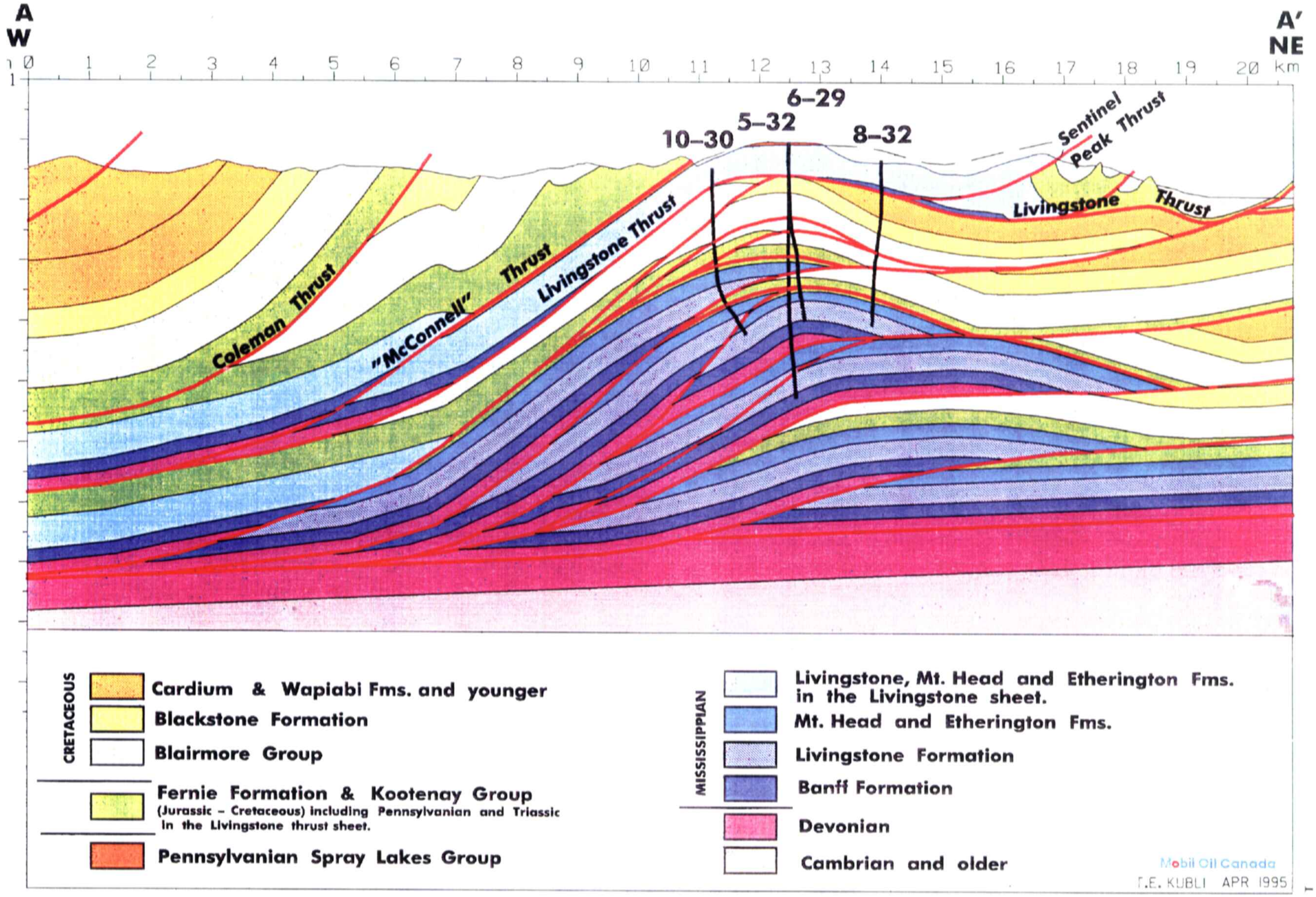


Figure 3-5-2. Geological cross section across the Plateau Anticline and the Savanna Creek structure, constained by well and seismic data (from Kubli et al., 1995, CSPG Field Trip Guidebook, 45 p).

0.00 km Junction of Highway 40 and Highway 532
0.15 km Junction with short-cut turnoff to Highway 40, Husky Savanna Creek installation
0.40 km Texas gate
2.15 km Approximate position of mapped Jurassic-Carboniferous contact; view south to Etherington Formation exposure
2.40-2.60 km Fernie Formation outcrops
2.85 km Fernie Formation; excellent views to north and west – Mississippian section carried by Sentinel Peak Thrust, with folded and faulted Blairmore Group in its footwall, all carried by the Livingstone Thrust
3.45 km Kootenay Group outcrop
3.90 km Kootenay Group outcrop
4.00 km Kootenay Group (?) outcrop
4.05 km Texas gate, and south end of small pond; spectacular views to northwest of Mississippian carbonates of Hailstone Butte carried by the Sentinel Peak Thrust
4.15 km Blairmore Group outcrop (Norris, 1993); turnout to small pond at crest of hill – **Stop 6**

Stop 6: Hailstone Butte overview
Distance: 4.15 km from junction of Highway 40 (940) and Highway 532
Access: Park on the south side of the road, next to the small pond. Walk up the low ridge to the southeast to a viewpoint.
Theme: Structural geology of the Inner Foothills and Front Ranges.
Purpose: Overview of the Outer Foothills, and discuss relationship between the Livingstone and McConnell thrusts.

Geology: The viewpoint provides us with a spectacular overview of the Outer Foothills. We are standing in the hanging wall of the Livingstone Thrust, but on Lower Cretaceous rocks in the shadow of the Mississippian section carried on the Sentinel Peak Thrust (to the west; Figure 3-6-1). The Sentinel Peak Thrust is a minor backlimb imbricate of the Livingstone Thrust, but its topographic expression is greater by virtue of the more resistant carbonates. To the east we have folded and faulted Jurassic and Lower Cretaceous clastics carried by the Livingstone Thrust over a series of tightly imbricated faults repeating Upper Cretaceous Alberta, Milk River, and Belly River group rocks. The upper detachment of the triangle zone is only 17 km to the east. The essentially undeformed Plains are visible in the far distance.

As we saw at Stop 2 earlier today, the Livingstone Thrust began to carry a significant section of Jurassic and Lower Cretaceous stratigraphy in its hanging wall, just south of the Oldman River, at which point its displacement is approximately 35 km. This stratigraphic relationship persists northward to this point. Approximately 21 km along strike to the north-northwest from the viewpoint the mapped trace of the Livingstone Thrust cuts laterally down-section in its footwall (Douglas, 1958), resulting in only modest stratigraphic separation across the thrust (thin slices of upper Kootenay Group onto Blairmore Group). This relationship, which appears only 2 km south of the Highwood River, then persists northward another 11 km to the mapped termination of the Livingstone Thrust just north of Flat Creek (Douglas, 1958).

The McConnell Thrust, which marks the Foothills/Front Ranges boundary at the latitude of Calgary (Bow River), places Upper Cambrian Eldon Formation on Upper Cretaceous Belly River Group (upper Brazeau Formation), with a displacement in excess of 35 km (similar to the Livingstone Thrust at The Gap). The McConnell Thrust loses stratigraphic separation and displacement southward, through a series of ramps. The mapped trace of the McConnell Thrust, folded at Mount Head a few kilometres north of the Highwood River and about 30 from our viewpoint, has only modest stratigraphic offset. (However, the trace of the "McConnell Thrust" has been mapped by Douglas (1958) and Norris (1993, 1994) as far south as the Crowsnest River.)

Notably, in the area around Mount Head, the Livingstone and McConnell thrusts are separated by and also intimately associated with a number of other thrusts, including the Cataract Creek, Mount Burke, Zephyr Creek, Sentinel Peak, Fir Creek, Greenfeed, and Bear Creek faults (phew!). Spratt et al. (1995) lucidly describe these map relationships, and suggest a reinterpretation of thrust nomenclature which clears up some of the confusion associated with the "displacement transfer" from the McConnell to the Livingstone thrust. At the latitude of the Highwood River, they term the Sentinel Peak Thrust the "Real McConnell Thrust", emphasizing its stratigraphic offset and its relative easterly location. Spratt et al. (1995) suggest that these faults form a duplex where the mapped trace of the McConnell Thrust forms the roof thrust, folded by the incorporation of horses into the duplex.

Therefore, the extensive and structurally complex zone of "displacement transfer" between the Livingstone Thrust and the McConnell Thrust extends from our viewpoint here (the Sentinel Peak Thrust is interpreted to terminate only 2 km to the south) to the vicinity of Flat Creek, north of the Highwood River – a total distance of approximately 32 km.

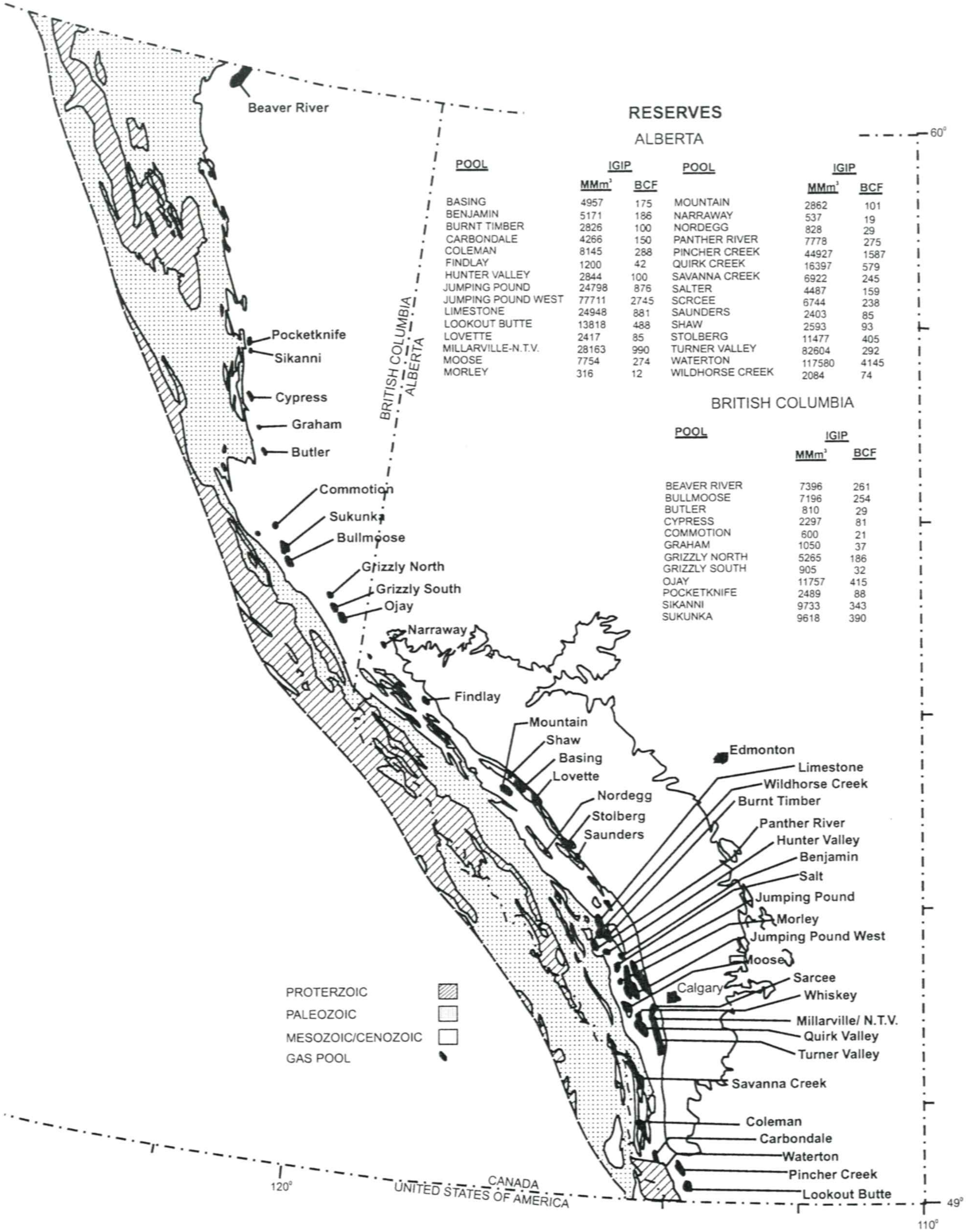
Figure 3-6-1. Detail of GSC Map 1837A (Norris, 1993), centred approximately on 50°12'00"N, 114°25'30"W, showing location of Stop 3-6.

At our location here at the Savanna Creek gas field (Figure 3-6-2) we are approximately 50 km south-southwest of the town of Turner Valley, where we began our trip. As seen in Figure 3-6-2, the gas fields we have passed over and discussed are the southernmost of a long series of Canadian Foothills gas fields stretching through Alberta and northeast British Columbia to the southern territories.

Road Log:

4.15 km From Stop 6, continue east (downhill) on Highway 532
4.30 km Kootenay Group outcrop
4.70-4.85 km Kootenay Group outcrop
4.85 km Cross axis of mapped overturned syncline, minor structures in the core of the fold
5.00 km Kootenay Group outcrop, in immediate hanging wall of the folded Bear Creek Thrust
5.10 km Good views south to anticline in Blairmore Group strata, footwall of Bear Creek Thrust
5.20-5.40 km Blairmore Group exposure (Beaver Mines); good views to east and north; in immediate footwall of the Bear Creek Thrust
5.55 km Blairmore Group outcrop
6.20 km View north to Bear Creek Thrust
6.20-6.40 km Blairmore Group outcrop, exposed on bend in switchbacks
6.65 km Blairmore Group outcrop
6.80 km Turnoff to parking lot for Bear Pond (K-Country)
7.80-8.00 km Beaver Mines Formation outcrop
7.90-8.40 km Views south of Blairmore Group strata carried in Livingstone Thrust Sheet
8.40 km Sharp bend in road, excellent views to east of Cadomin Formation thrust-repeated in the Livingstone Thrust Sheet
9.40 km Pipeline crossing
9.50 km Turnout to primitive campground
9.60 km Texas gate
9.90 km Approximate trace of the Livingstone Thrust
10.10 km Excellent exposures to north of Cadomin Formation, lots of rockfall next to road
11.40 km Turnout south to primitive campground
12.65 km Turnout to Indian Graves Recreation Area
12.70 km Johnson Creek crossing
12.90 km Outcrop of thick pale green and brown sandstone (Virgelle Formation?)
13.20 km Excellent view to north of Virgelle Formation sandstone
13.75 km Bridge over Willow Creek; excellent exposure of Virgelle just north of bridge
14.05 km Turnoff south to primitive campground
14.15 km Texas gate
14.40 km Stream crossing
14.90 km Approximate map boundary, Stimson Creek south to Langford Creek
15.80 km Belly River Group outcrop
16.20 km Stream crossing
16.80 km Belly River outcrop
17.70 km Texas gate; leaving Kananaskis Country
19.05 km Texas gate
19.85 km Belly River Group outcrop
22.90 km Texas gate
22.75 km Texas gate
22.80 km Stimson Creek crossing
23.30 km Excellent views to west of Hailstone Butte, carried on Sentinel Peak Thrust; Foothills underlain by imbricated Belly River, Milk River, and Alberta groups
23.60 km Interpreted position of Virgelle Sandstone
24.00 km Texas gate; views to south. Upper detachment (Big Coulee Fault) interpreted to lie just near eastern edge of the small irregular pond; St. Mary River ridge in hanging wall can be seen and followed all the way to the south into Langford Creek sheet.
24.20 km Cross under powerline
25.10 km Meinsinger Creek crossing (north outlet to Chain Lakes Reservoir)
25.90 km Intersection of Highway 532 and Highway 22 – TURN NORTH (LEFT) for return to Calgary

Return to Calgary, end of trip



RESERVES

ALBERTA

POOL	IGIP MMm^3	IGIP BCF	POOL	IGIP MMm^3	IGIP BCF
BASING	4957	175	MOUNTAIN	2862	101
BENJAMIN	5171	186	NARRAWAY	537	19
BURNT TIMBER	2826	100	NORDEGG	828	29
CARBONDALE	4266	150	PANTHER RIVER	7778	275
COLEMAN	8145	288	PINCHER CREEK	44927	1587
FINDLAY	1200	42	QUIRK CREEK	16397	579
HUNTER VALLEY	2844	100	SAVANNA CREEK	6922	245
JUMPING POUND	24798	876	SALTER	4487	159
JUMPING POUND WEST	77711	2745	SCRCEE	6744	238
LIMESTONE	24948	881	SAUNDERS	2403	85
LOOKOUT BUTTE	13818	488	SHAW	2593	93
LOVETTE	2417	85	STOLBERG	11477	405
MILLARVILLE-N.T.V.	28163	990	TURNER VALLEY	82604	292
MOOSE	7754	274	WATERTON	117580	4145
MORLEY	316	12	WILDHORSE CREEK	2084	74

BRITISH COLUMBIA

POOL	IGIP MMm^3	IGIP BCF
BEAVER RIVER	7396	261
BULLMOOSE	7196	254
BUTLER	810	29
CYPRESS	2297	81
COMMOTION	600	21
GRAHAM	1050	37
GRIZZLY NORTH	5265	186
GRIZZLY SOUTH	905	32
OJAY	11757	415
POCKETKNIFE	2489	88
SIKANNI	9733	343
SUKUNKA	9618	390

Figure 3-6-2. Locations of significant Foothills gas pools, Alberta and British Columbia. Reserves for individual pools derived from Energy Resources Conservation Board (1986) (from Fermor and Moffat, 1992).

APPENDIX 1

Historical Perspectives, Hydrocarbon Exploration in the Western Canada Sedimentary Basin

Seepages and Early Explorations

The earliest exploitation of hydrocarbons was the use of exudations from the tar sands and natural seepages from Precambrian rocks, in the Waterton area, by First Nations peoples for domestic and medicinal purposes. Similar use of natural seepages were made elsewhere and were noted by Hudson Bay Company and Northwest Company explorers and surveyors. Aside from a few exploratory and scientific expeditions that encountered and noted the occurrence of the Athabasca bituminous sands little comment was made on the occurrence of petroleum in Rupert's Land, the territory administered by the Hudson's Bay Company (encompassing all lands draining into Hudson Bay). The Company actively discouraged settlement and commerce other than furs. Identification of the great Athabasca oil sands (1778) and oil seepages along the Mackenzie River (1819), and Cameron Brook near Waterton Lake, Alberta (1874) were the initial indications of oil and gas potential in Western Canada.

With the transfer of Rupert's Land to the Dominion of Canada government, a more comprehensive exploitation of natural resources was envisaged and planned. Geological observers accompanied both the Palliser Expedition and the International Boundary Surveys. Dawson was attached to a Boundary Survey (1873-5) working westward from Lake of the Woods to the Rockies. During this time he engaged John George "Kootenai" Brown, a colourful character, to inquire of the Indians if any petroleum seepages occurred in the Waterton-Pincher Creek area. Brown's inquiries were successful and he was shown to the Cameron Brook seepages, which he later used to lubricate his own farm machinery, but there is no mention of the Cameron Brook petroleum seepages in Dawson's report and it is doubtful that Brown ever informed Dawson of their existence. Bauerman (1884) worked eastward from British Columbia from 1859-1861 and reached as far east as Little Chief Mountain Lake.

Both Selwyn and Bell conducted investigations in the old Northwest Territory in the mid-1870's. Both were frustrated by the deep glacial drift and the nearly horizontal strata over much of the Prairies. There were exceptions. In a number of places many hundreds of miles east of the Rockies, such as along the Clearwater River, near Avonlea Saskatchewan and even into Manitoba, significant surface structure could be mapped through the mask of glacial till. To the south in the United States, where the glacial deposits were absent, the immense structures of the Laramide Foreland extended well to the east. This led to the initial, albeit, for Foothills exploration, fundamentally incorrect assumption that a less deeply eroded equivalent to the American Rocky Mountain Foreland Province involving the Precambrian basement extended into Canada beneath the veneer of glacial till. As a result, the current distinctions between the Interior Platform and Cordilleran structural provinces were not recognized until the late 1920's to mid-1930's when a series of investigations by G.S. Hume suggested that structures geographically far removed from the Rocky Mountains might be due to either compactional drape or salt tectonics. (Hume was partly correct about the salt, but it was dissolution not diapirism that was the primary control on many Interior Platform structures). As recounted below, a coherent structural model was developed in the 1940s and 1950s that completely discounted basement involvement during Laramide orogenesis.

To overcome the problems presented by drift cover along the proposed transcontinental railway route the Geological Survey purchased a drilling rig with financial assistance from the railway survey who was keenly interested in the water and mineral resources in the vicinity of the proposed Canadian Pacific line. De Mille (1969) and Zaslow (1975; p. 116) recount the progress of these operations which, except for their historical importance, were of little result. The Geological Survey ceased operations in the Plains until the early 1880s when the selection of a southern route for the Prairie Section of the railway, against Palliser's recommendations, but motivated by a desire to counter American encroachment, called for an immediate survey of the resource potential of the region. The work led by Dawson spurred McConnell, Tyrrell and White to further field work in the southern Plains and produced several GSC reports that laid the groundwork for geological investigation of the Interior Platform geological province. Bell returned to the west during this period to investigate the bituminous sands along the Athabasca River.

During the last two decades of the 19th Century the extraordinary investigations of one of these men, R.G. McConnell, made known the general geology and petroleum potential of the western interior in an unparalleled fashion that surpassed even Dawson's efforts, and might best be compare with the work of J. W. Powell in the United States. McConnell served as Dawson's assistant in 1881. He wintered over in Calgary and in 1882 began independent investigations mapping the Foothills between the north fork of the Oldman River and the Elbow River. He identified the Turner Valley structure, future site of western Canada's first commercially successful oilfield. In 1883 he traversed along the Red Deer River. Consequently he worked in the area of the Cypress Hills and the Missouri Couteau and in 1886 made a geological section across the Rocky Mountains indicating the presence of a nearly complete succession of Paleozoic rocks, and mapping the trace of the great Front Ranges bounding thrust which bears his name. During 1887 McConnell accompanied Dawson and McEvoy into the Cassiar mountains and parted company with them at Lower Post on the Liard River to conduct independent investigations that saw him travel to Fort Simpson, up the Mackenzie River to Great Slave Lake and up the Slave River to the area of Fort Smith and back to winter at Fort Providence. In the subsequent year he traversed the Mackenzie, Porcupine and Yukon rivers and passed to the coast at Skagway via Selkirk and Whitehorse. He observed several seepages and showings of oil or bituminous shales and wrote:

> "The possible oil country along the Mackenzie valley is thus seen to be almost co-extensive with that of the valley itself. Its remoteness from the present centres of population and its situation north of the still unworked Athabasca and Peace River oil field will probably delay its development for some years to come, but this is only a question of time."

At the close of the 1880s and through the early 1890s he examined the Peace and Athabasca river country, commenting on the potential of the bituminous sands, and finding the oil and gas seepages at Tar Island on the Peace River, the first of several showings of petroleum to be found in the vicinity. He was the last of the great explorers and his investigations extended into the early days of the petroleum industry in the west.

Initial Discoveries

The construction of the prairie section of the Canadian Pacific Railway in 1882 provided the first line of economic communication across the Canadian prairie, opened the Northwest Territories to large scale settlement, and provided a demand for water and energy. The initial wells were drilled for water and coal to supply the railway. Wells drilled for water at Langevin Station (later Alderson) Alberta discovered natural gas in 1863. Another well drilled nearby at Cassils in 1884 had a small amount of gas (Hume, 1933, p. 344). A water well drilled in 1886 at Belle Plaine, Saskatchewan, had a show of gas. The first well drilled specifically for petroleum in Western Canada was spudded on Vermilion River, Manitoba with a second well drilled the following year (de Mille, 1969). In 1890 drilling at Medicine Hat, attributed variously to coal exploration or more probably to the exploitation of a seepage of gas into South Saskatchewan River, discovered gas (Dowling et al., 1919, p. 1). A subsequent well blew wild and with it the Medicine Hat gas field was discovered (3.4 T.C.F. proven recoverable; discovery of the Medicine Hat sand pool in 1904). The pool produces gas, of biogenic origin, from sandstones in the Upper Colorado and Lower Montana groups of Late Cretaceous age.

The Dominion of Canada Government, at the urging of Dawson and McConnell, set out to test the possibility of finding higher gravity oils down dip of the oil sands outcrops. A rig was bought and the first well was drilled in 1893-94 at Athabasca with no result. In 1897 the rig was moved up river to Pelican Rapids, where a well on a gentle anticline blew wild in 1898. From time to time lightning ignited the well. It was not capped until action by Dowling in 1918, by which time an estimated 60 to 65 BCF has been lost. Another government well was drilled downstream from Edmonton at Pakan without result. Government drilling along the Athabasca River continued and by 1920 five gas wells had been discovered. These wells were important for two reasons. First they were structurally located tests, drilled at a time when most exploration in the region was limited to the exploitation of surface showings. Second, the evaluation of the wells, and the subsequent suggestion by McLearn that exploration proceed down dip for an oil leg, showed an appreciation of the Anticlinal Paradigm (first promoted by the GSC's T. Sterry Hunt in 1863) that would have been useful if followed at Turner Valley.

Oil City (Waterton National Park)

In 1888 oil seepages were discovered in the Crowsnest Pass and at Turner Valley. The same year William Aldridge began exploiting a seepage on Cameron Brook. The next year A. P. Patrick, a Dominion Surveyor, filed a claim on the Cameron Brook seepages and two claims on Kishenehn Creek, British Columbia. All of this indicates that there was considerable local interest and probable knowledge of the seepages on the Flathead River side of the range prior to the discovery of the seepages at Kintla Lake in 1892. Selwyn's visit to the area in 1890 (Hume, 1964) observed a small oil boom in progress. The first well in the area was drilled in 1891, at Twin Butte near Pincher Creek. Not until 1901-02 was the first well drilled and completed as an oil well on the Cameron Brook locality. The boom was short lived and was largely over by 1907. Only approximately 8000 bbls. of oil were produced. The novelty of the wells, completed in Precambrian sediments, which produced oil from Upper Cretaceous source rocks through fractures, has captured the imagination of many. The most important contribution came from a well near Cameron Falls, now in Waterton National Park, that passed into the footwall of the Lewis Thrust Fault and Cretaceous strata (Hume, 1933, p. 79). This caused Daly to speculate as early as 1912 that entire sheet may be detached – a formidable hypothesis that would take some time to be demonstrated conclusively.

Establishing Municipal Gas Supplies

The discovery of gas at Medicine Hat was an important contribution to the growth of the town, and other municipalities in Alberta wished to obtain similar supplies of energy for domestic and industrial growth. Three wells were drilled in Edmonton by 1905 without success. Two wells were drilled in and around Calgary in 1906-07 and 1908. Consultation with the Geological Survey of Canada resulted in two recommended locations. The recommendations were made by Bell which he attributes to information obtained by consultation with D. D. Cairnes, not Dowling as suggested by De Mille (1969). His recommendations appears in the Survey's report of 1905 activities.

"Mr. D.D. Cairnes says the gas of Medicine Hat, Langevin and Cassils comes from rocks of the Belly River Cretaceous series, which are deeply buried at Calgary. At Cassils gas has been struck above the horizon of that of Medicine Hat and Langevin. Near Calgary the best chance for finding gas would be somewhere along an anticlinal which runs S. 73^{o} E. from a point two and a half miles due east of Cochrane Street. At the shallowest depth, however, on this anticlinal, any gas which might exist would probably lie 700 to 800 feet deeper than that at Cassils. The next gas horizon would be 600 feet below this last. There is also a third horizon corresponding to the Tar Sands below the last mentioned. If boring be undertaken on the above anticlinal near Calgary, it should be at the lowest surface level. The most promising locality would appear to be in the southwest corner of township 24, range 3 west of the 5th principal meridian, and section 2 or 10 may occupy the most likely position." (Bell, 1906, P. 8-9).

Discoveries at Calgary were small although they provided some industrial and domestic production. Wells drilled in southeastern Alberta in 1909 under the direction of Eugene Coste found production in the Lower Cretaceous Bow Island sandstone, discovered the Bow Island gas field, led to the construction of a pipeline from Bow Island to Calgary and the first general supply of gas to consumers in that city in 1912. Gas from this field was also used to supply Lethbridge (Beach and Irwin, 1940, p. 41). The discovery of gas at Viking in 1914 was supplied to Edmonton in 1923. A number of "farm gas" wells supplying single users were also produced.

Turner Valley

Oil seepages were first found in Turner Valley, on the Sheep River in 1888, and although several other gas or oil seepages were identified nothing further was done until William Herron collected some of the gas and had it analyzed. Taking advantage of the new 1910 regulations regarding oil and gas lands, he acquired a land position with the purchase of several farms and by filing claims over approximately 7000 acres of Crown Lands. He then set out to obtain financial support for the development of his interests. Taking two prominent Calgary businessmen on a fishing trip on the Sheep River Herron ignited one of the seepages and cooked the noon meal over the flame, a very practical demonstration and, up to then, an unrivaled act of effective promotion. The money was raised and a location selected on a small parasitic anticline within the structure, near the Sheep River seepages that burn today. At the beginning of 1913 the well was spudded. A small show of oil was obtained in October but it was not until May 14, 1914 that wet gas flowed to surface at approximately 4 MMCF a day from 2718 feet in the Lower Cretaceous Mannville Group.

Most historical accounts tend to attribute the location of the Dingman #1 well at the crest of the Turner Valley structure as being a fortuitous association of structure with the seepage on the Sheep River. However, the structure had been recognized by McConnell and as suggested by Dowling (1914; 1919), the association of the seepage and the apex of the anticline had been known for years. It has even been suggested that Herron himself mapped the structure, individually or in consultation with Dowling, although neither of these claims can be substantiated. With the completion of this well the Calgary area was gripped by a frenzy of speculation and poorly conceived well locations. The boom ended soon after, with much new wallpaper in Calgary. In 1924 the Royalite No. 4 well, failing to find production in the Blairmore Group, drilled ahead. No attempt to describe what happened next can improve on the recounting by Beach and Irwin (1940):

"Royalite 4 penetrated the Lower Cretaceous sands in which the other wells had obtained some production, without getting more than shows of oil. It went through dense black Fernie shales in which there was no porous reservoir rock, and found Paleozoic limestone beneath. The hopes of most men in the industry fell, for in other parts of the province the limestone had been sterile of oil, though sometimes yielding water. Drilling was continued, however, into the lime, even though hope was failing. About sixty feet below the top of this lime a little foul smelling gas was encountered, but it gave no sign of commercial values. At last, having penetrated 250 feet of lime without yield, 260, 280, it was decided to abandon the test. Then another 10 feet of hole was made and at 290 feet in the lime a burst of gas came.

Tools were pulled out and the valve closed on top of the well. A pressure gauge showed a rise of pressure of about 100 pounds a minute. After a few minutes the crew retired to a little distance and at the end of 15 minutes the casing started to rise and went to the crown of the derrick, later settling back as gas came up around" (Beach and Irwin, 1940, p. 22).

This well established the first production of gas and condensate from Paleozoic rocks in the Cordilleran Foreland Belt.

Norman Wells

Exploration of the northern portion of the basin also progressed in the early part of the century. By 1913 Bosworth had conducted an investigation of the Athabasca-Mackenzie river system and examined and claimed lands in the vicinity of the seepages at Windy Point and Fort Norman. Bosworth was appointed the chief geologist of Imperial Oil Company exploration subsidiary Northwest Company. Under his influence two rigs were sent north to drill the Windy Point and Fort Norman localities identified by Bosworth in 1914. The well at the Norman location was drilled, under the direction of Ted Link, to only 783 feet and on August 24th, 1920, oil flowed in a gusher that rose seventy-five feet above the derrick floor. The well was completed in Fort Creek (now Canol) Formation shales, producing from fractures. It was not until 1940 and the development drilling of the Canol project that the discovery well was deepened and the stratigraphic nature of the Kee Scarp reef trap for the main pool was recognized by Boggs (Hume and Link, 1945). One of the great, but patently incorrect myths of the industry is that the reef play had been recognized twenty-seven years before the discovery at Leduc (Sproule, 1968, p. 13; Hriskevich, 1970).

The Lean Years

Economic and political conditions conspired against the fledgling oil industry. The industry had initially been a local concern primarily addressing municipal demands for natural gas. The Dingman discovery was overshadowed by the Great War which siphoned off a significant number of young men and resources to bury them in the fields of northwestern Europe. A few major companies had entered the area during the war, Imperial and Shell most notably. With war's end several American companies entered the region. Some companies, such as Canadian Western Natural Gas, Light, Heat and Power Company Limited, Eugene Coste's corporate heir, remained while others, Calgary Petroleum Products, for one, were absorbed by major companies or their affiliates with the general expansion of the industry in the short economic boom following the Great War. This boom was followed by the Depression. It suppressed many economic activities, oil exploration among them. In addition, the early successes of the anticlinal tests could be neither duplicated nor expanded. Many firms were faced by tough times, and little encouragement. These companies folded their tents and left. By 1936 only Imperial and Canadian Western Natural Gas Co. Ltd. maintained permanent exploration offices in Calgary (Finch, 1985, p. 34) where, in 1927, there were enough geologists to organize the Alberta Society of Petroleum Geologists.

Fields at Wainwright (discovered in 1925, although a well had been drilled into the margin of the pool and produced since 1923) and Red Coulee (1929) were the most significant of these discoveries and shows. Exploration in the foothills was equally unsuccessful. Efforts had been directed towards the discovery of another Turner Valley Field, without success. Wells were usually drilled only through the first complete Mississippian or Devonian succession as the structural style was not yet understood. These were the darkest days of the anticlinal accumulation theory.

The Golden Age of Canadian Petroleum Geology

Years of Transition

Development proceeded down the dip on the west limb of the Turner Valley structure. In 1929 the Home No. 1 well yielded condensate production of 700 barrels a day, indicating that the amount of liquids increased progressively down the gas column. In 1930 the Model No. 1 well (8-22-20-3w5) was completed down dip on the western limb of the structure and is considered, by some, the first oil discovery (Gallup, 1975). The gravity of condensate and the gas to oil ratio dropped immediately after the well was completed. The well was not deepened until 1942, and then only by 376 feet, to be completed in the oil leg. Other wells on the west limb of the structure were making a discoloured liquid and slowly the possibility of a down dip oil leg was considered. It was not until 1936 when the Turner Valley Royalties well (13-28-18-2W5) was deepened that oil flowed to surface and discovery of the oil leg of the Turner Valley pool was recognized (Beach and Irwin, 1940, p. 25).

There were several reasons why the development of the field and the identification of the oil leg took so long. The economic effects of the depression of the 1930s, and the cycle of boom and bust that had followed the initial discoveries, had imposed restrictions on drilling activity. The Home No. 1 well and adjacent wells showed rapid decline that was attributed to a tight reservoir producing from fractures (Beach and Irwin, 1940). Perhaps most important was the accepted structural interpretation in the early 1930's. This stated that the structure was a decapitated anticline with the Turner Valley sole fault cutting up stratigraphic section down dip (Gallup, 1975). The salient details of the structural style were not understood until the early 1950's. Fortunately this did not prevent continued drilling. The discovery of oil at Turner Valley by Turner Valley Royalties No. 4 was the beginning of the end of the lean years. The well had to be completed with borrowed casing but when it came on stream its production established the Home Oil Company and motivated the entire industry which progressively increased its activity until the outbreak of the Second World War. At the time, Turner Valley was the largest oil field in the British Empire.

Other discoveries at Dina, Lloydminster, Del Bonita, Taber and Moose all preceded the Second World War. Perhaps the most interesting of these is Del Bonita, an anticlinal structure with surface expression, that produced oil from the Mississippian Rundle Group in 1936 (Slemko, 1960, p. 91). The structure is a Laramide anticline, one of the few well-documented Laramide structures to outcrop in the region commonly inferred to be the Interior Platform. The Del Bonita structure is a local culmination on a long antiformal hinge that had been drilled and showed oil at Spring Coulee in 1916 (Russell, 1932, p. 35-38). The Spring Coulee well had been drilled after the Turner Valley discovery during the exploitation of anticlinal prospects in the Foothills and western Plains.

Two tests were drilled on the Moose Mountain structure about 30 miles west of Calgary. One encountered an encouraging show in the Cambrian. The second well was completed and on production in 1937 producing oil from the Fairholme Group. It appears to be the first commercial production from the Devonian in Alberta, albeit a modest seven barrels a day (Beach and Irwin, 1940; Ower, 1975).

Exploration during the Second World War was the anvil on which the next phase of exploration was forged. Demands for petroleum for war industries and defense led to intensified demand for North American petroleum products. Two programs of exploration conducted by Imperial Oil Limited or its corporate children, the Canol and Norcanols projects, led to extensive but unproductive evaluation and drilling in the Territories and Saskatchewan. The disappointing Canol drilling results did develop the Norman Wells Field. The field developments led to the important recognition that a biological reef was the reservoir of the main pool and the that the trap was stratigraphic, even though Norman Wells Field lies within the Cordilleran structural province. Kerr (1986), without detail, suggests that problems associated with the interpretation of seismic data on the Norcanols program led to improved interpretation techniques by the War's end.

While Imperial was improving its seismic interpretation techniques, Shell and California Standard were successfully employing theirs. G.S. Hume of the GSC had been a tireless promoter of the Jumping Pound structure and he is attributed the role of convincing Brown, Moyer and Brown to have Heiland Exploration conduct experimental seismic surveys over the structure (Finch 1985, P. 49). These were used to attract Shell to examine the prospect. After one dry well and more seismic work Shell drilled and completed the Shell 4-24-J (Unit #1) well in 1944 and the first major field was found in the Foothills since the discovery of Turner Valley in 1914. Unfortunately there was no immediate market for the gas and the development of the field was delayed. In the same year, 1944, California Standard drilled and completed its Devonian pool at Princess using reflection seismic to outline the prospect (the field also has geomorphic expression). This was the first commercial discovery of oil in Devonian rocks on the Plains. Even the government was conducting seismic surveys. A seismic survey of the old Buffalo National Park (Camp Wainwright) area in 1943 led to the interpretation of the Wainwright antiform as a drape fold over paleotopography on the erosional surface of Paleozoic rocks (Hume, 1944). The years of effort, typified by the careers of Hume and Link, were about to pay off.

Leduc

By the mid-1940's hopes were fading that the Western Canada Sedimentary Basin would prove a significant conventional oil producing region. The vast bituminous sands stood as a sharp contrast to the apparently barren Plains. Perhaps it was this contrast that led to the wild and unconventional explanations for the origin of the bituminous sands, in spite of the Survey's recognition that they were an exhumed and degraded oilfield.

Tests in the Foothills had found one oil and gas field of economic significance. Drilling in the Plains had been less successful and the size and volume of untested structures was decreasing. At the same time Canadian demand for oil was increasing with very little domestic supply. Production at Turner Valley had fallen to 6.4 million barrels in 1946 from 10 million barrels in 1942. Other pools could produce only 0.8 million barrels in 1946. The price of American crude oils imported to western refineries was very high. Imperial's board was preparing to embark on a program of gasoline synthesis from natural gas using a Fischer-Tropsch process, but they were grudgingly willing to let Ted Link have one last shot at looking for oil. The board's actions were consistent with a recommendation from a senior technical committee in Toronto and to the responses of company geologists to a questionnaire formulated by Dr. Link. Both the senior technical group and the geological staff recommended evaluation of the Central Alberta Plains, down dip of the Athabasca oil sands.

A large crown reservation was assembled in 1946 and a preliminary seismic program was run along east-west lines that were shot at an interval of approximately one township width. One line located in the general pattern of the regional shooting pattern, but one mile south of the northern boundary of the township because of an imminent "road ban", had a single point anomaly at the level of the Lower Cretaceous. The reversal was followed up and a structure with approximately 75 feet of closure was defined in Township 50 Range 26W4. The crown reservation was increased in July of that year. It is in this additional acreage that the initial discovery well was located. The anomaly was not an impressive structure but its proximity to both Edmonton and a good supply of water, necessary for gasoline synthesis, made it a worthwhile test.

Layer's (1979) recount indicates that the well was located in central Alberta by a combination of factors. The planned gasoline synthesis plant for Edmonton and the combined recommendations of the technical staff and the senior technical committee in Toronto all favoured convergence on this region. The responsibility for the recognition, exploitation and definition of the structure to be drilled rested with the geophysical staff. The decision as to the target depth appears to be a compromise as opposed to a consensus. Most of the western technical staff favoured the Mesozoic section as a primary target for natural gas for the planned gasoline synthesis plant while the Toronto office (Dr. Link was then Chief Geologist and a member of the technical committee) considered a basement test following Dr. Link's suggested program of stratigraphic drilling. The well was planned to test the Paleozoic salt which was believed to be Silurian (in fact Middle Devonian) on the basis of incorrect correlations to the salts of the Michigan Basin following the Norcanols drilling in Saskatchewan. The planned stratigraphic test was to be a last effort for Imperial before the exploration for oil was abandoned and an emphasis on natural gas development for gasoline synthesis was begun. Imperial's plan was not, as commonly believed, to totally abandon the Western Canada Sedimentary Basin. The feeling of the Imperial Board was "that after $23 million (total exploration expenditures in western Canada) this is final" (Layer, 1979).

The planned stratigraphic test was never drilled. The well Leduc No. 1 (5-22-50-26W4) tested several encouraging shows of gas and some light oil in the Viking and Mannville sands of the Lower Cretaceous section. Shows of gas were encountered in the Wabamun Formation (Upper Devonian) and on penetrating the Nisku Formation tests of gas and crude oil were obtained, the formation was cored and tested. The final test flowed oil to surface and the efforts of the Imperial exploration staff were rewarded. A decision was made to complete the well in the Nisku.

Shortly after the encouraging tests in the Viking and Mannville sands a well was recommended to test the possibility of a down dip oil leg in these units and a location was picked south-southwest of the discovery well. Leduc No. 2 (1-16-50-26W4) was spudded the day before No. 1 was brought into production. Originally planned as a Cretaceous test, due to the result of No. 1 it was deepened and cored the entire Nisku Formation which, although oil stained, was tight. A decision had to be made whether the stratigraphic test planned for No. 1 was to be completed by No. 2 or if the hole should be abandoned and a new location picked to offset No. 1. The order came to drill ahead while awaiting a decision, a standard practice. S. Aubrey Kerr was the senior well site geologist:

> "When the Nisku was reached at No. 2 (after a great deal of coring and testing in the Cretaceous

and Wabamun), it was found to be virtually tight with only a few oil stains in the core and very minor porosity. While the company officials in Calgary were wondering what to do about the next location, the site geologist (S.A. Kerr) was instructed to resume drilling. Green shale was encountered. This was recalled as being similar to that at McColl Frontenac's Hobbema well drilled during the winter of 1946-47 where there were many hundred feet of green shale. After having drilled about 150 feet of green shale [I] noted a considerable speed-up in drilling. After having penetrated 6 feet of this soft drilling, orders were given to circulate for returns. These did not appear until 11 o'clock in the evening and when they did come up, they consisted of coarsely crystalline white dolomite with no trace of oil stain. [I] ordered a drill stem test, despite the indication that the zone appeared to be water-bearing. The well flowed the next morning (May 7,1947) in 7 minutes through 3-1/2" drill pipe using a full-hold packer. The well was full-hole all the way with only 150 feet of surface casing which after investigation was found to have been cemented in gravel. (Living dangerously!) Coring was immediately started (I believe using 5 ft. intervals) and continued with tests until the oil-water interface was encountered. It is interesting that No. 2 hit the Leduc (D3) just at the gas-oil interface" (S.A. Kerr in D.B. Layer, 1979)

If we analyze the discoveries of the Leduc-Woodbend Field it is clear that many aspects of the discovery were fortuitous. But some of this good fortune was luck that the Imperial staff made for itself. Large numbers of people and considerable experience were pooled to determine which area to explore. Geophysical leads were carefully followed up. During the drilling of both wells good well site practice assisted in the evaluation of the well. Yet the world did not immediately sit up and take notice. It was not until the blow-out and fire at Atlantic No. 3 development well that the rest of the nation noticed that something significant was underway in Alberta. It was, although unplanned, a demonstration of which William Herron (remember the shore lunch) would have been proud.

Much myth surrounds the two Imperial Leduc discoveries. Mr. Kerr (keynote speech to the C.S.P.G. conference on "Sequences, Stratigraphy, Sedimentology: Surface and Subsurface") has related an anecdote attributed to Dr. Stelck that "Jersey", the American mother company, had attempted to order the abandonment of the No. 1 well when it encountered evaporitic strata in the Wabamun Group, thinking that the Prairie Formation salts had been reached, but that Dr. Link had ignored the order. Whether this is true or whether it is this just the latest variation of the "we always knew there was oil there, if only they would let us drill ahead" stories may never be known.

Differentiation of the Cordillera From The Interior Platform

As a result of the seismic survey of the Wainwright area in 1943, Hume (1944) had recognized the role of paleotopography on the erosional surface of Paleozoic rooks in causing the structural closure in the Mesozoic rocks. The Leduc discoveries too were made using an anticlinal model of accumulation. The Leduc prospect had been mapped on a Lower Cretaceous seismic reflector and the distribution of rock bodies in the underlying Paleozoic succession had not been resolved. Drape of Cretaceous sediments over differentially compacted facies in the Woodbend Group led to the discovery. Who would have guessed that Upper Devonian facies distribution, subsequently buried by late Paleozoic sedimentation, uplifted and eroded in the Triassic and Jurassic, would have again been differentially compacted by Mesozoic burial? There may have been a dawning of the potential of reef facies as stratigraphic traps for oil and gas but they were found by drilling structures defined in higher horizons, most commonly the Cretaceous, because of fundamental technical limitations. Computational methods of the day could not be used to produce time-structure maps of events below the erosional surface of Paleozoic rocks because of irregularities at the erosional surface and their accompanying velocity variations (Reasoner and Hunt, 1952). The giant Redwater reef field lies below the subcrop of the Wabamun Group. With the identification of the compactional drape nature of structures that indicated the presence of Leduc reefs and the earlier analysis by Hume at Wainwright, a distinctive Interior Platform structural style was being distinguished. This had rarely been done. Most structures were attributed previously to a dissipation of Laramide deformation away from the mountain front.

Gas in the Cordillera

In the late 1940's and early 1950's increased demand for gas, primarily for export, with improvements in both understanding the structural style of the overthrust belt, and seismic techniques, led to improved geological models that could be used to interpret the results of seismic reflection and refraction surveys. Thus, the Foothills structural play was revived. The early Foothills exploration had failed on two accounts: technical and economic. Technical problems were attributable to poor understanding of the structural style, and the effect this had on the development of the Turner Valley Field has been discussed above. Turner Valley Field contains approximately 1 Billion bbls. of oil in place. The failure to identify the oil leg and develop it before significant gas production substantially reduced the ultimate recoverable reserve of the field (approximately 100 million bbls. ultimate recovery). It is the worst example of conservation technique and the best example of the importance of good geology, adequately available to all parties, industrial and regulatory. The failure at Turner Valley was a prime cause for the founding of the Alberta Petroleum and Natural Gas Conservation Board (Alberta Energy and Utilities Board).

Immediately following Turner Valley's discovery, exploration efforts had either failed to find the Mississippian carbonates, were abandoned in what appeared to be an endless series of Mesozoic imbrications, or, like the McColl Frontenac Moose Mountain No. 1 well, they had been abandoned because economic basement had thought to have been reached. These frustrations led one geologist to vow that the only thing he was certain of was that the basement complex was composed of Colorado shale. The successful application of refraction methods had been used to find the Jumping Pound Field (Keating, 1975). But the high costs of exploration, composition of the gas, and lack of demand prevented development. In 1947 Canadian Gulf Oil Company found the Pincher Creek gas and condensate field using careful geophysical work.

Despite these successes exploration was costly and difficult. Lack of a good structural model was a crucial factor hampering exploration. It was careful mapping and structural analysis by both Survey and industrial mapping parties that established the elements of the structural style that allowed the reevaluation of old prospects and the formulation of new ones. Based on fieldwork through the late 1940's R.J.W. Douglas outlined the fundamental elements of the structural style in his classical Geological Survey of Canada Memoir (1950) on the Callum Creek, Langford Creek and Gap Map areas. There continued to be some debate (Scott, 1953) about the details of the structural style, but the exploration in the Cordillera had turned the corner. With the new kinematic model of Cordilleran structure (the "Foothills Rules") it became possible to use map elements to predict additional occurrences of Mississippian and Devonian strata in the structure. J.C. Scott, using elements of the new style, inferred that the Savanna Creek structure could be underlain by other prospective thrust slices and in 1952 a test of the prospect recorded a strong gas show in the Mississippian before passing abruptly into Jurassic shales where the well was suspended. In 1954 the well was deepened into the underlying thrust plate and the field was officially discovered, motivated exclusively by geological analysis.

But the real secret weapon of the new kinematic model was the recognition that the deformation was "thin-skinned" and that it did not involve the crystalline basement, which dipped constantly and predictably westward. This was Shell's secret weapon, because it provided a way to avoid the "static" and surface problems that were plaguing the application of seismic techniques. The new structural style allowed the arrival of Paleozoic carbonate "events" to be timed relative to the arrival of the crystalline basement/near-basement reflector. This Paleozoic-basement "isochron" could then be plotted above the extrapolated basement surface to outline the structure and define prospects on the culminations of Paleozoic thrust sheets. The analysis of structural style in the Eastern Marginal Zone of the Cordillera is among the greatest scientific achievements of Canadian Petroleum Geology. By 1975 ultimate reserves of approximately 13 TCF of raw gas and 146.5 million bbls. of oil had been discovered (ibid.).

The Lessons Of History

This historical perspective is a fitting one for the Cordillera since most of the great foothills plays of today and tomorrow were established yesterday. This was clearly true of the rush to explore for Rundle Group pools in front of the McConnell Thrust between 1974 and 1978, when improved sulphur prices motivated a binge of exploration, in a play begun in 1924 when Royalite No. 4 found the first Turner Valley Formation production. Similarly, the 1962 discovery of the Baldonnel zone Falls gas field on the crest of the Pine River Anticline (c-18-G/93-0-09, Hughes, 1967) can be viewed as the initial central foothills Triassic discovery that established what became the hottest play of the early 1990s. The "new" oil potential at Moose Mountain follows on the result of Moose Dome Oils wells that found gas and condensate in Cambrian and Devonian rocks, one of which was completed as a surface plate Fairholme oil well that produced 8,944 barrels of 47^{o} API oil between 1941 and 1948 (Ower, 1975). We shall revisit the historical perspective during the field trip when we look at the inference of undiscovered resource potential.

While the kinematic models of the eastern marginal zone of the Cordilleran structural province have improved, the answers to many of the most important questions and themes remains no better answered today than they were a century ago. Consider the role and origin of fractures and the prediction of fracture porosity. Fractures were recognized as important from the onset of exploration at Oil City. They were again important when Norman Wells was first completed, not in the Kee Scarp Reef, but in the overlying fractured shale, and they are fundamental when we consider the reservoir at Waterton and in the Central Foothills.

One thing that appears certain is that exploration continues focused almost solely on the anticlinal paradigm. Continued anticlinal exploration will result in the discovery of new pools from a dwindling inventory of successively smaller structural targets with the inevitable result that the size of discoveries will progressively decline. This is not to say that there is a lack of attractive structural targets; the resource assessment shows there are clearly many interesting prospects yet to find throughout the Foreland Belt. Yet, there can be no denying that the exploitation of the anticlinal paradigm progressively depletes a finite set of prospects. The exploration history shows this is true. For example, one recent focus of exploration has been on Triassic plays in the Central Foothills around the Monkman and Sukunka fields. There are now about 95 pools discovered in the Triassic of the Central Foothills, but their cumulative reserve is roughly comparable to the reserves of the Rundle-Wabamun Sheet 3 pool at Wabamun pool at Waterton.

What then about stratigraphic plays within the Foothills? We know that they exist and a number of important fields and pools that are purely or partly controlled by stratigraphic entrapment have been discovered. These include Norman Wells (Hume and Link, 1945), Ricinus, (Walker, 1983; Plint et al., 1986) and Blueberry B.C. (Procter and Macauley, 1968). Surely this cycle of activity calls to mind Georges Santayana's aphorism, "Those who cannot remember the past are condemned to repeat it."

APPENDIX 2

Resource Analysis of Natural Gas in the Foreland Belt

Introduction: The natural gas resources of the Canadian portion of the Foreland Belt of the Cordilleran Orogen have been analysed using the PETRIMES resource appraisal system (Lee, 1993). This probabilistic resource appraisal system is a rigorous and object method for quantifying and characterizing undiscovered hydrocarbon resources. The great strengths of the PETRIMES analysis are its objective approach, on a play by play basis, and its ability to predict the characteristics, particularly size, of the undiscovered pools within a play. This allows a link between exploration and geology, since the parameters most important to economic success can be calculated in advance of drilling.

The Foothills Gas Resource-base: This analysis used the discovery history of seventeen mature plays with a discovered reserve of 675, 146 X 10^6 m^3 initial raw gas in place to predict that these same 17 mature plays contain an expected additional 799,356 X 10^6 m^3 initial raw gas in place in an additional 4,981 pools. The discovery sequence of mature plays was similarly analysed to estimate the volume of gas occurring in both immature and conceptual plays. The analysis suggested that a total of 50 foothills plays have a gas resource of 3,260,464 X 10^6 m^3 initial raw gas in place. In additional to the 17 mature plays, there are an expected 33 plays with a cumulative expected gas resource of 1,785,962 X 10^6 m^3 initial raw gas in place. These additional 33 plays can be divided into both immature and conceptual plays. The thirteen identified immature plays already have 233,609 X 10^6 m^3 initial raw gas in place discovered in 79 pools. Analysis of the subset of immature plays suggests that they can be expected to contain an additional 1,345,772 X 10^6 m^3 initial raw gas in place in 3,986 undiscovered pools. Therefore, the total identified gas reserve in the 30 identified mature and immature foothills plays is 908,755 X 10^6 m^3 initial raw gas in place in 681 pools. It is expected that an additional 1,911,519 X 10^6 m^3 initial raw gas in place is yet to be discovered in 8,888 pools in these 30 identified plays. The remaining 440,190 X 10^6 m^3 initial raw gas in place is expected to occur in 20 plays that have not yet been identified.

Play Definition: The PETRIMES probabilistic resource evaluation analyses the set of pools discovered within a play, or the set of plays discovered within a province, to quantify and characterize the undiscovered resource of both plays and provinces. An analysis that is based on plays is both natural and useful for the explorationist. The definition of plays and the assignment of pools to individual plays defines the discovery sequence within each play. This discovery sequence is potentially the only input to the PETRIMES system discovery process model. Therefore, how plays are defined can affect the outcome of the assessment and differences in play definitions could produce significantly different results.

Ideally, following the model of Dalhstrom, we could have grouped sets of structures of similar history and configuration. For example, the set of en echelon thrust plate culminations in Rundle Group reservoirs leading from Lookout Butte to north of Jumping Pound could form a play of related structures. Such a method of play definition would be prospect oriented, and probably more consistent with the models explorationists use in their daily work. However, as desirable as such a grouping of pools is, it is beyond both project resources and the information available to the GSC.

Therefore, we have used a simple geographic and stratigraphic subdivision of the foreland belt (Figure A2-1). In general, this subdivision follows the generally accepted major three-fold north-south subdivision of the belt into southern, central and northern Foothills. This major subdivision of the foreland belt follows major north-south variations in the composition of the stratigraphic succession, the tectonic history of the underlying basement and the style of the Cordilleran deformation, as influenced by the mechanical changes accompanying stratigraphic variations. The distribution of reserves and resources shows that there are significantly different geographic and stratal distributions of natural gases in the foreland belt from that of the Interior Platform. Within the foreland belt, there is a northward decrease in reserves and potential that follows a decrease in the amount of Laramide shortening, the stratal position of the highest reservoir strata below the major hydrocarbon seal and the stratigraphic position of the major seal. For example, in the southern and central regions the shales at the base of the foreland basin stratigraphic succession form the most significant seal. However, in the northern Foothills, the stratigraphic position of the most important seal changes from the base of the foreland succession to the Devonian Horn River shale. Thus, there is a need to further subdivide the belt to consider other important stratal and structural

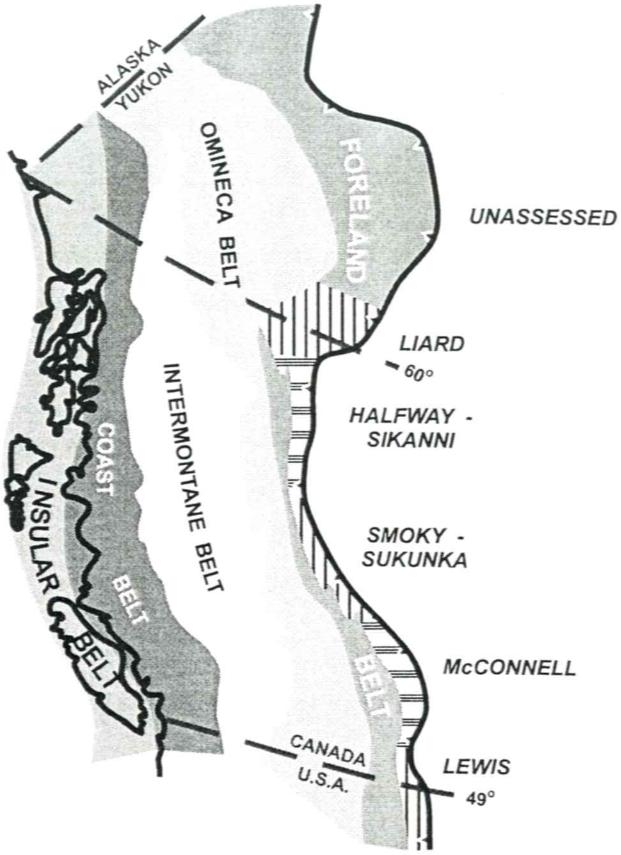


Figure A2-1. The geographic extent of gas play areas and their names in the eastern marginal zone of the western cordillera. Gas play areas are defined by characteristic stratigraphic succession that influences structural style and reservoir development.

variations not included in the tripartite geographic subdivision.

The central Foothills is equivalent to our Smoky-Sukunka geographic area. The southern Foothills has been further subdivided into three geographic regions. These follow structural and stratigraphic differences east of the McConnell and Lewis thrusts. The McConnell geographic region has an "Alberta Basin" stratigraphy, where the stratigraphic succession and structural style was influenced by the presence of the thicker Middle Cambrian succession and the presence of the Western Alberta Ridge. To the south, the Lewis geographic region has a "Montania" stratigraphic succession, and the structural style and history departs from that found farther north. In front of the Lewis Plate are structures, some of which may involve basement, and/or may have a younger component of movement associated with the western flank of the Sweetgrass Arch. These pools are grouped into our Del Bonita geographic region. The northern Foothills is similarly subdivided into two geographic areas: Halfway-Sikanni and Liard, again following differences in stratal succession, most notably the change in stratigraphic position of the base of the Devonian shale succession, geological history and structural style.

These geographic regions are again subdivided stratally, since the distribution of reserves strongly indicates that regional stratigraphic seals are important controls on the stratal distribution of resources, probably as restrictions on migration pathways. Furthermore, the structural style is strongly influenced by the stratal succession, not just north-south position along the foreland belt, following the major subdivisions of the geographic areas. Stratal position also controls the eastern limit of deformation and reservoir characteristics that further distinguish the stratally distinctive plays within each geographic region. Thus, individual play areas, while marked by the north-south limits of the geographic regions, also reflect major stratigraphic variations and the variations in structural style that follow stratigraphy. The eastern limit of each stratigraphically distinctive play lies at the limit of the deformation in that particular stratum. Because of the structural style the eastern limit of each play tends to lie progressively further east in progressively younger reservoirs. These plays, so defined, become the criteria by which pool lists were formulated to be used as input for the probabilistic analysis of natural gas resources in the foreland belt using discovery process analysis.

The analysis employs the PETRIMES resource evaluation system of the Geological Survey (Lee, 1993). PETRIMES estimates the undiscovered potential of either a hydrocarbon play or province while characterizing the size and number of undiscovered pools or plays, depending on whether the input data are the constituent pools of a play, or the constituent plays of a province, respectively. Whether pools or plays, the input data are a sample of the pool or play populations that is biased by the decisions of exploration geologists. In a free economy the underlying motive for exploration is profit, such that we may assume that exploration decisions seek to maximize profit. In an anticlinal hydrocarbon province this translates into the biased selection of prospects to be tested as a function of size. Hence, we can assume that the discovery sequence reflects the best efforts of explorers to find the greatest volume of hydrocarbons for the lowest cost. This bias is essential to the analysis, since it is only because of this bias that we can infer the number of pools within each play. Readers must understand clearly that this analysis is not based upon the mapping and identification of individual prospects, rather it is an inference and projection of the future of exploration, based upon the pattern of past success. A prospect-style analysis requires a detailed structural model of the foreland belt that is beyond current project resources but which, experience shows, would probably severely underestimate the total number of prospects. Where the GSC has made both prospect-oriented and discovery process analyses of petroleum resource, the results of the two techniques have been encouragingly similar in characterizing the distribution that describes pool sizes. However the number of pools estimated by prospect style analysis is usually much smaller than that which long exploration histories indicate. This analysis relies upon the exploration history to encapsulate the scientific and industrial knowledge of foreland belt exploration.

The Discovery Sequence In the Foothills: The time series shown in Figure A2-2 indicates the pool by pool growth of the cumulative initial raw gas reserve in the Foothills through time. Four discoveries are particularly notable: Turner Valley Blairmore, Turner Valley Rundle, Pincher Creek Rundle A, and Waterton Rundle/Wabamun A. The other significant reserve addition, shown by a jump in the curve subsequent to the discovery of the Waterton Rundle/Wabamun A pool, is the discovery of the Jumping Pound West Rundle Pool.

As mentioned in the historical review above (Appendix 1), the first discovery was that of the Turner Valley Blairmore pool by the Dingman No. 1 well in 1914. Three plays, as defined below, were discovered prior to Leduc (a type of cultural ground zero in the Canadian oilpatch). The other two significant discoveries were the Turner Valley Rundle pool, the first Paleozoic discovery in that segment of the foreland belt with an "Alberta Basin" succession, and the discovery of Rundle/Madison Group production below the surface anticline at Del Bonita, on the flank of the Sweetgrass Arch. The discovery at Pincher Creek in the Rundle Group is the first Paleozoic discovery in that part of the Basin with a "Montania" stratigraphic succession. That discovery was made later in the same year as the Leduc find in the Interior Platform. In total, 13 new "plays" were discovered between the discovery of Leduc and 1960, including the first discoveries in the northern and central Foothills. The interval 1953-57 was particularly successful in finding new plays in the southern portion of the northern Foothills. During the

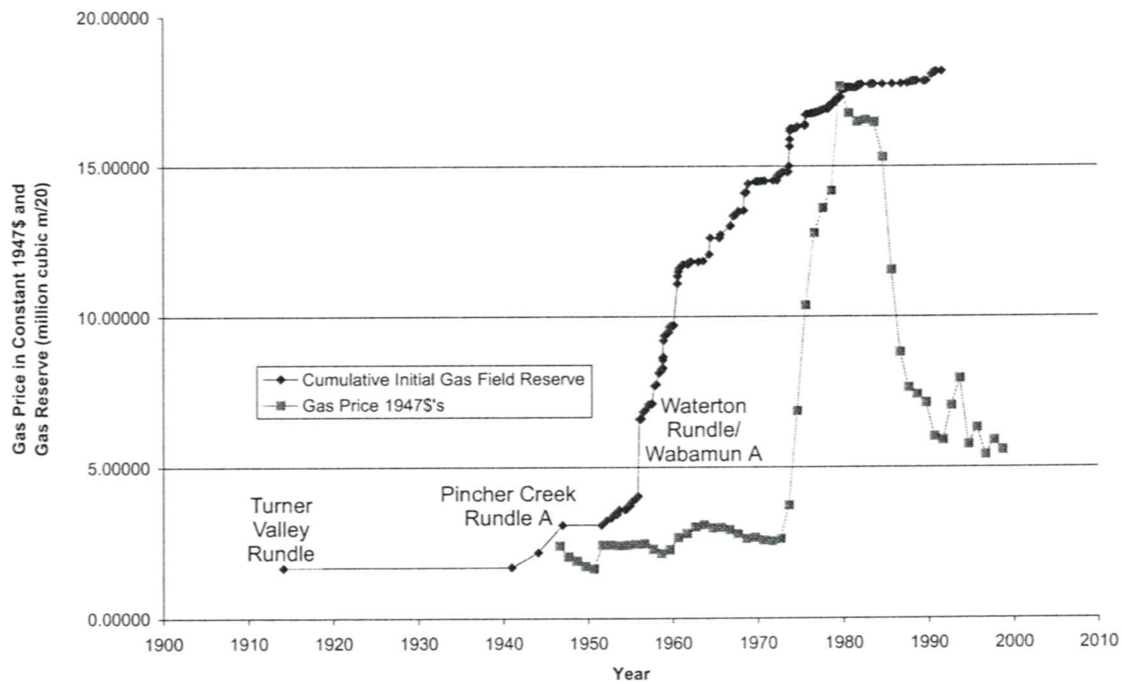


Figure A2-2. The cumulative growth of the initial raw in-place gas reserve in the Foothills (diamonds) as a function time, shown in units of (millions of cubic metres/20). The total initial in-place field reserve is credited back to the initial discovery in each field. Also shown, in units of constant 1947 dollars, is the annual average natural gas price (squares) calculated using Canadian Association of Petroleum Producers statistical data.

1960's six new plays were discovered in the first half of the decade. Most noticeable among these were the first discoveries in the Triassic of the central Foothills in the play that was to capture the attention of the industry in the early 1990's with further developments in the region around Sukunka and Monkman. No new plays were discovered during the last half of the 1960's and the first two years of the seventies. In 1970's seven new plays were added to the Foothills list between 1972 and 1977. The last play to be discovered, to date, was the Waterton Colorado Play, discovered in 1980.

Reserves: The total discovered initial in place raw natural gas reserve in the foreland belt is approximately 908,755 X 10^6m^3 in 681 pools in 30 identified plays (Table A2-1). This we have subdivided into 17 mature plays containing 602 pools containing 675,146 X 10^6m^3 of initial in place raw natural gas. The remaining 233,609 X 10^6m^3 of gas occurs in 79 pools of 13 immature plays. Mature plays are those with unfettered exploration histories and sufficient discoveries that they can be analysed using the discovery process model, whereas immature plays either have an insufficient number of pools to allow for the application of the discovery process model, or they have a restricted exploration history. An example of the latter type of immature play is the Waterton Rundle/ Wabamun Play, which extends into the United States, but which has not been freely pursued in that jurisdiction.

Table A2-1 Title (all values initial raw gas in place)

Play name	UAI	Discovered E6 m3	Expected E6 m3	Total Res. E6 m3	Discovered number	Total no. of pools	Undiscovered number	Largest Pool E6 m3
Identified Foothills Gas Plays								
SF2 Waterton Rundle/Wabamun	C4159205	220,687	530,910	751,597	28	200	172	1.39E+05
SF3 Limestone Fairholme	C4289205	4,586	73,870	78,456	9	142	133	5122
SF3 Burnt Timber Wabamun	C4279205	18,500	46,084	64,584	12	120	108	2317
NF2 Beaver River Devonian	C4729205	33,820	102,750	136,570	10	400	390	5121
SF1 Del Bonita Madison	C4129205	789	54,813	55,602	3	26	23	13982
SF3 Jumping Pound Rundle	C4269205	355,082	27,794	382,876	94	173	79	5180
CF Chinook Ridge P-Carb	C43C9205	1,449	92,634	94,083	3	44	41	21267
NF1 Jedney Permo-Carb.	C4669205	28,003	41,258	69,261	46	230	184	5075
NF2 Beaver River Carboniferous	C4719205	84	117,966	118,050	2	327	325	11733
CF Sukunka Triassic	C43E9206	84,124	183,960	268,084	42	300	258	11484
SF3 Nordegg Triassic	C4259205	3,003	84,443	87,446	8	300	292	1471
NF1 Jedney L. Triassic	C4679206	23,126	13,762	36,888	31	150	119	2088
NF1 Jedney Baldonnel	C4629205	34,287	162,370	196,657	29	410	381	6183
NF1Jedney Charlie Lk.	C4639205	2,375	19,539	21,914	13	550	537	265
CF Findley Nordegg	C4369205	952	59,552	60,504	3	207	204	1377
SF2 Waterton Mannville	C4149205	459	34,076	34,535	3	118	115	1216
SF3 Turner Valley Blairmore	C4249205	2,910	12,143	15,053	41	400	359	599
CF Grizzly Blairmore	C4359205	15,065	15,474	30,539	67	590	523	524
NF1 Jedney Blairmore	C4619205	6,212	13,583	19,795	19	400	381	4537
SF3 Ricinus Viking	C4239205	6,337	4,413	10,750	15	100	85	446
CF Jackpine Paddy/Cadotte	C4349205	2,278	9,878	12,156	10	200	190	545
CF Hinton Dunvegan	C4339205	1,979	34,242	36,221	9	1411	1,402	807
SF1 Del Bonita Colorado	C4119205	150	5,036	5,186	4	40	36	1212
SF2 Waterton Colorado	C4139205	199	27,405	27,604	2	212	210	4056
SF3 Lawrence 2WS	C4299205	257	32,664	32,921	1	253	252	4554
CF Edson 2WS	C43D9205	246	31,130	31,376	1	241	240	4412
SF3 Ricinus Cardium	C4229205	33,446	3,369	36,815	94	160	66	724
CF Ansell Cardium	C4329205	23,189	39,179	62,368	42	200	158	3272
SF3 Brazeau Belly River	C4219205	3,389	19,357	22,746	29	900	871	455
CF Red Rock Belly River	C4319205	1,772	17,865	19,637	11	765	754	591
		908,755	1,911,519	2,820,274	681	9,569	8,888	259,995
Total Foothills Devon/Carb		663,000	1,088,079	1,751,079	207	1,662	1,455	209,177
Total Foothills Trias/Juras		147,867	523,626	671,493	126	1,917	1,791	22,868
Total Foothills Lower Cretaceous		35,240	123,809	159,049	164	3,219	3,055	8,674
Total Foothills Upper Cretaceous		62,648	176,005	238,653	184	2,771	2,587	19,276

Table A2-1 cont. Title (all values initial raw gas in place)

Play name	UAI	Discovered E6 m3	Expected E6 m3	Total Res. E6 m3	Discovered number	Total no. of pools	Undiscovered number	Largest Pool E6 m3
IDENTIFIED GAS PLAYS								
Gas Plays in Devonian Strata (This study and Reinson et al., 1993)								
ND Keg shelf basin Rainbow	C41T9511	40704	11436	52,140	203	460	257	998
ND Keg shelf basin Zama	C41U9511	17544	11132	28,676	582	900	318	543
ND Keg shelf basin Shekilie	C41R9511	7084	13293	20,377	105	450	345	532
ND Keg isolated Yoyo	C4199510	102795	35146	137,941	31	300	269	2620
ND Keg platform July Lk.	C41A9511	2449	2055	4,504	14	80	66	232
ND Middle Dev. clastics	C41E9511	25665	18204	43,869	44	450	406	771
ND Slave barrier Clarke Lk.	C4159511	103317	21526	124,843	49	425	376	1154
ND Slave platform Adsett	C4169512	19467	59655	79,122	45	450	405	4537
ND Slave reef Cranberry	C41V9512	21100	67467	88,567	37	450	413	7755
CD Swan shelf margin Kaybob S.	C41F9601	254457	52541	306,998	15	450	435	4241
CD Swan isolated Swan Hills	C41D9601	125835	7758	133,593	16	60	44	1446
ND Leduc fringe Worsley	C41Z9511	7035	8445	15,480	17	200	183	1649
CD Leduc isolated Westerose	C4119512	297536	46099	343,635	48	210	162	4341
CD Leduc reef Nevis	C4129512	66954	8609	75,563	54	150	96	1102
CD Leduc/ Nisku Windfall	C41M9512	127776	54449	182,225	41	960	919	5245
CD Nisku shelf marg. Brazeau R.	C41Y9601	10970	7481	18,451	8	190	182	2553
CD Nisku isolated Brazeau R.	C41X9512	22691	8041	30,732	57	156	99	639
CD Nisku shelf drape Bashaw	C4139512	17745	4934	22,679	47	300	253	528
CD Nisku shelf drape Ricinus	C4179601	8754	5418	14,172	19	210	191	853
CD Blueridge strat. Karr	C4109512	6966	19190	26,156	21	460	439	2629
ND Jean Marie Helmet	C41C9510	11636	24035	35,671	18	300	282	3110
ND Wabamun Parkland	C41H9512	19281	40870	60,151	48	900	852	2021
CD Wabamun plat. Pine Ck.	C41G9601	20949	17832	38,781	20	450	430	2279
SD Wabamun platform Cross.	C41J9601	128162	2125	130,287	19	60	41	733
CD Up. Dev. subcrop Marten	C41Q9601	101734	16172	117,906	385	900	515	815
ND Sulphur platform Bistcho	C41B9512	1,913		1,913	51			
CD Leduc/Nisku Wild River	C41K9601	4,264		4,264	5			
SD Arcs structural Princess	C4189601	5,844		5,844	36			
Gas Plays in Permian & Carboniferous Strata (this study and Barclay et al., in review)								
PC Rundle Sweetgrass Structure	C4229207	6893	6495	13,388	44	600	556	306
PC Kiskatinaw Clastics	C4219207	29015	54322	83,337	115	1200	1,085	581
PC Bakken Strata/Sub. Loverna	C4239207	3290	12233	15,523	37	1100	1,063	341
PC Peace River Carb. Dunvegan	C4249208	48895	16640	65,535	90	220	130	2900
PC Belloy Peace R. Structure	C4409207	39943	72783	112,726	93	1000	907	1644
PC Miss Subcrop Edson/Harm.	C4259207	499115	52351	551,466	604	940	336	1893
Gas Plays in Triassic and Jurassic Strata								
TR Montney Distal Shelf Glacier	C4589507	713	12191	12,904	7			
TR Montney Subcrop N Ring	C45E9312	22993	15971	38,964	1			
TR Montney Subcrop	C4599207	25876	23258	49,134	73	500	427	1204
TR Halfway/Doig SZ Sinclar	C4579207	66600	27905	94,505	141	340	199	1949
TR Halfway/Doig SZ Peejay	C4549207	12731	10839	23,570	63	400	337	1577
TR Halfway/Doig Shelf Monias	C4559207	39710	88934	128,644	51	500	449	2635
TR Halfway/Doig Self Tommy L	C4569207	25915	23202	49,117	27	300	273	1444
TR Charlie Lk. Clastics Inga	C45A9207	6094	8866	14,960	25	200	175	207
TR Charlie Lk. Clastics Cecil	C45B9207	4529	5915	10,444	39	275	236	607
TR Charlie Lk. Carb. Boundary L	C45C9207	20123	9128	29,251	120	400	280	185
TR Baldonnel Subcrop Laprise	C4519207	52614	66610	119,224	31	500	469	3206
TR Baldonnel Structure	C4529207	10502	8336	18,838	42	480	438	342

Table A2-1 cont. Title (all values initial raw gas in place)

Play name	UAI	Discovered E6 m3	Expected E6 m3	Total Res. E6 m3	Discovered number	Total no. of pools	Undiscovered number	Largest Pool E6 m3
JU Nordegg Nrshore/Valley F	C5429210	42018	9205	51,223	144	250	106	900
JU Nordegg Platform	C5479306	7226	3878	11,104	15	150	135	1183
JU Sawtooth	C5449302	5614	7228	12,842	69	800	731	162
JU Rock Ck/ Up. Fernie	C5439210	39591	25419	65,010	147	350	203	1645
JU Nikanassin	C5459210	12913	22495	35,408	59	690	631	1004
JU Nordegg Shelf/Basinal	C5419212	228	3575	3,803	3			
JU Swift/Parkland	C5469302	533	5764	6,297	6			
Gas Plays in Lower Cretaceous Formations								
MA NW Spirit River	C4719202	102582	28888	131,470	275	400	125	1824
MA NW Bluesky	C4739202	105478	48585	154,063	304	500	196	4694
MA NW Gething & Dunlevy	C4749202	140681	22151	162,832	682	1000	318	635
MA NW Cadomin	C4759202	45691	100010	145,701	176	900	724	10856
MA Ath Gr. Rapids & Clearwater	C4869410	87535	55060	142,595	1275	2920	1,645	712
MA Ath Wabiskaw	C4839202	53957	21776	75,733	219	700	481	1346
MA Ath McMurray	C4849202	45450	13413	58,863	565	1100	535	408
MA LI Colony-Lloydminster	C4969409	212535	87008	299,543	3791	8860	5,069	255
MA LI Cummings	C4939202	5216	2160	7,376	198	540	342	245
MA LI Dina	C4949202	11102	13283	24,385	230	800	570	841
MA Cen Up. Mann. & Glauconite	C5069410	315572	91411	406,983	2335	4380	2,045	1127
MA Cen Ostracod	C5039202	38084	16677	54,761	297	500	203	1346
MA Cen Ellerslie & Basal Quartz	C5049202	257755	67399	325,154	2451	4400	1,949	1112
MA SAB Up Mann. & Glauconite	C5169410	38642	30312	68,954	280	1300	1,020	901
MA SAB Ostracod & Lwr Mann	C5179410	30508	12005	42,513	386	750	364	1046
MA ABSASK Detrital	C4859202	11432	33563	44,995	193	1200	1,007	966
CG Basal Colorado	C4749308	40206	15647	55,853	155	800	645	1210
CG Viking Regressive	C6129408	28033	13217	41,250	345	730	385	1069
CG Viking Channel	C6139408	19500	11235	30,735	71	300	229	821
CG Viking Transgressive	C6119408	343291	126840	470,131	2490	5320	2,830	1192
CG Paddy	C47E9311	26683	31022	57,705	98	450	352	1847
CG Cadotte	C47H9405	24872	43265	68,137	107	800	693	1729
CG Dunvegan Sandstone	C4729308	17935	5687	23,622	65	240	175	192
Upper Cretaceous Formations								
CG BFS	C4759308	1791	2964	4,755	46	300	254	254
CG 2WS Fractured	C4919405	1113	6261	7,374	12	300	288	291
CG 2WS Shallow Marine	C4929405	94421	16298	110,719	98	300	202	1429
CG Cardium Sandstone	C4719308	205861	26724	232,585	152	440	288	2034
UK Milk River/Medicine Hat	C4529310	455493	4863	460,356	25	600	575	200
CG Doe Creek/Poe Coupe	C4769308	8349	6578	14,927	50	300	250	166
UK Belly R. Dinosaur Pk.	C4819404	4686	25283	29,969	137	2000	1,863	196
UK Oldman Fm. Fluvial	C4829404	3179	15691	18,870	43	1000	957	323
UK Foremost Fm. Fluvial	C4839404	23252	18547	41,799	452	1280	828	882
UK Foremost Cycle 1	C5519406	116	3605	3,721	1			
UK Foremost Cycle 2	C5529406	19997	7404	27,401	104	280	176	1606
UK Foremost Cycle 3	C5539406	12295	6615	18,910	96	360	264	295
UK Foremost Cycle 4	C5549406	21513	17733	39,246	229	600	371	1128
UK Foremost Cycle 5	C5559406	6147	5088	11,235	141	320	179	365
UK Foremost Cycle 6	C5569406	4281	3406	7,687	90	380	290	189
UK Foremost Cycle 7	C5579406	3552	6666	10,218	46	280	234	787
UK Edmonton Gp. Fluvial	C5119405	532	5834	6,366	17	600	583	335
UK Edmonton Gp. Marine	C5129405	1237	9714	10,951	17	580	563	324

Table A2-1 cont. Title (all values initial raw gas in place)

Play name	UAI	Discovered E6 m3	Expected E6 m3	Total Res. E6 m3	Discovered number	Total no. of pools	Undiscovered number	Largest Pool E6 m3
Total Dev. Carb. and Perm. Plays		2,207,778	778,737	2,986,515	3,018	14,981	12,055	60,991
Total Ident. Trias/Juras Plays		396,523	378,719	775,242	1,063	6,135	5,089	18,250
Total Ident. Lower Cretaceous Plays		2,002,740	890,614	2,893,354	16,988	38,890	21,902	36,374
Total Ident. LF. Plays		867,815	189,274	1,057,089	1,756	9,920	8,165	10,804
Total Foothills Ident. Plays		908,755	1,911,519	2,820,274	681	9,569	8,888	259,995
Total Ident. Inter. Plat. Plays		5,474,856	2,237,344	7,712,200	22,825	69,926	47,211	126,419
Total Identified Plays		6,383,611	4,148,863	10,532,474	23,506	79,495	56,099	386,414
Unidentified Gas Plays								
Conceptual Devonian		5318	2079200	2,084,518				
Conceputal and Immature Perm Carb		2711	285909	288,620	10			
Conceptual Triassic			5615	5,615				
Conceptual Jurassic			9339	9,339				
Conceptual and Immature Mannville		2434	311356	313,790	4			
Conceptual Plays Foothills			440,190	440,190				
Total Unident. Plays		10,463	3,131,609	3,142,072	14			
Total All Plays		6,394,074	7,280,472	13,674,546	23,520	79,495	56,099	386,414

Throughout the foreland belt, there is a preponderance of reserves in the highest reservoir below the major regional seal, commonly at the base of the Foreland succession, but in the Liard geographic area marked by the Devonian Horn River shale. There is also a marked northward decrease in reserves along the foreland belt. In part this reflects the emphasis of exploration activities in southern regions with easier access and established transportation systems, however, it also probably mirrors a real trend of decreasing prospectivity northward that is discussed below.

Exploration Efficiency and Performance: The difference between mature and immature plays is verified by considering both exploration efficiency and performance. We have chosen to use the rate at which gas is found per exploratory metre drilled as an indication of exploration efficiency. The higher this rate, the "more bang for your exploration buck". This parameter also provides a rough indication of finding cost, without consideration of a geographical cost differential. Therefore we plot the amount of gas reserve established in a play as a function of the product of the number of exploration wells and the average depth to a pool in that play (Figure A2-3). Notice that those plays which we would consider the primary exploration target in each geographic area have values of this “more bang for your buck” parameter greater than 80. These plays also commonly occur in the highest porous strata below the regional seal at the base of the foreland basin stratigraphic succession, or the base of the Horn River shale in the Liard geographic area.

Most plays that would be considered secondary targets have values of this parameter less than 80 but greater than 1. In some cases these targets are deeper horizons, but in many other instances they are plays within the foreland basin succession, found incidental to the exploration and development of primary targets. Pools in this group usually include a stratigraphic restriction of the reservoir in the structure being tested, even if the mode of entrapment is completely structural. Those secondary exploration targets, with "more bang for your buck" parameter values between 10 and 1, are plays with a strong restriction of reservoir development to a portion of the structure. They predominantly occur in foreland succession rocks, although some deeper zones are also represented. Interesting members of this group are the Blairmore plays of the southern Foothills. This group of plays includes both mature and immature plays. The two immature Second White Speckled shale plays have values of this parameter less than one. Therefore this parameter also provides an indication of the importance of stratal controls on reservoir distribution within structures while emphasizing both the importance of the regional stratigraphic and the difference of the hydrocarbon systems in the miogeoclinal and foreland stratigraphic successions.

Notice that the efficiency of exploration is positively correlated with decreased exploration risk. The formulation of most prospects is structural, such that this correlation reflects the ordering of play potential and the recognition of this ordering by explorers. Among the most important considerations is the ability

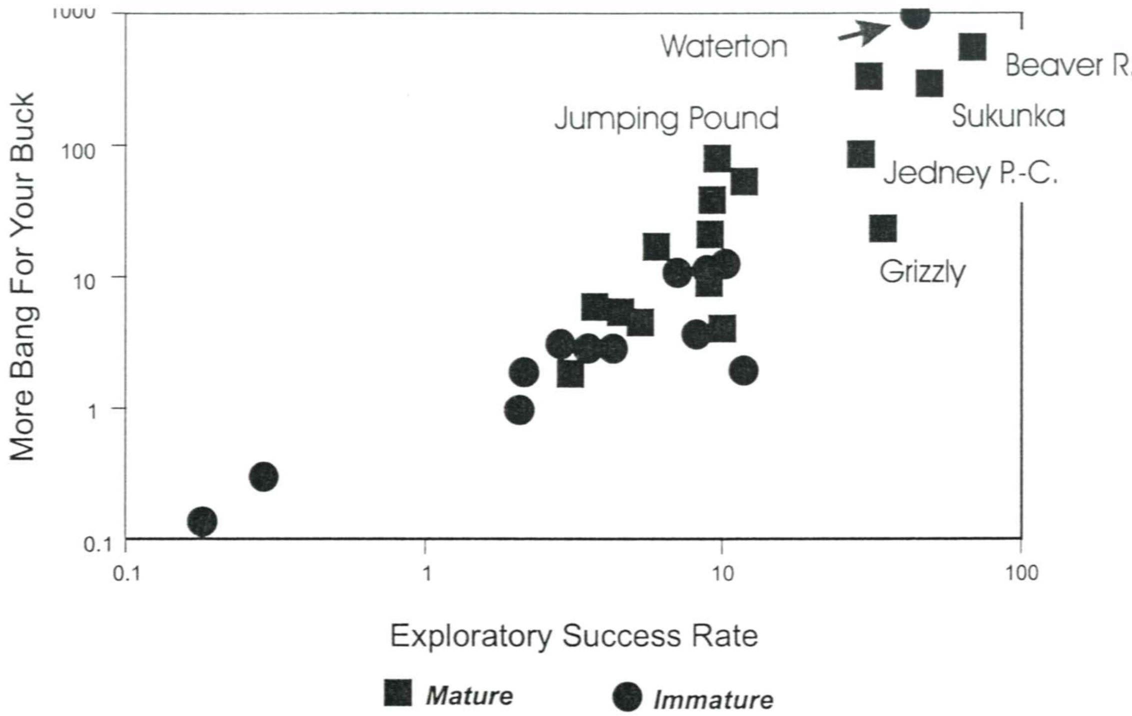


Figure A2-3. A cross plot of the rate of new pool and new field wildcat success rate in mature and immature Foothills gas plays plotted against an indicator of exploration facility, "More Bang For Your Buck". This indicator is the ratio of the initial raw gas in place reserve in millions of metres, to the product of the average pool depth and the total number of exploration new pool and new field wildcat wells drilled to establish that reserve. The figure indicates that highest rate of exploratory success is in those plays within which the rate of reserves addition is most facile.

of explorers to identify porosity under closure. Thus, those plays with fewer stratal restrictions on, or uncertainties in, porosity development and more reliable stratal and structural seals have been the most aggressively and successfully pursued. Historically there have been changes in both exploration risk and exploration efficiency. The best example of such represented by recent exploration in the Sukunka Triassic play which showed almost a doubling in the finding rate during the latest phase of exploration, both as a result of better prospect formulation and of improved drilling technique.

These two observations indicate that explorers have employed an extreme bias in their selection of prospects and that improvements in prospect formulation and testing can result in a significant change in the attractiveness of a play. This suggests that play concepts evolve with time and exploration experience. Thus we can conclude that explorers have made a strongly biased effort to select both plays and prospects from among a finite population of structures. This is an essential, but now well founded, assumption in our analysis. It allows us to infer the total number of pools within each play. Second we observe that play concepts evolve through time, even though their geographic boundaries remain constant. This suggests that the present characteristics of immature plays are not necessarily good indicators of the future characteristics of those plays. This is a necessary condition for our proposed analysis of immature plays as part of the total population of foreland plays, rather than through the use of their current characteristics and parameters.

A Historical Example of Discovery History Analysis: Having considered both the general characteristics of foreland belt gas reserves and after describing the assumptions used to define plays, we turn to the specifics of our analysis by considering one of the oldest and best described of Foothills plays: Jumping Pound Rundle. The historical analysis demonstrates that we can use a small subset of the exploration history to accurately predict subsequent discoveries; importantly, the same analysis gives estimates comparable to that obtained using the complete data set.

If we predicted, in 1966, that the Quirk Creek Field remained to be discovered, as it was the following year, this prediction may well not have been believed. If in 1974 we predicted that yet another pool comparable in size to Quirk Creek remained undiscovered, this prediction probably also would not have been believed, in part because the most intensive period of exploration in this play had passed. In the early 1970's, in four years, the number of new pools discovered were more than doubled the number found in the preceding fifty years. However, during that time no new pool more than a quarter the size of Quirk Creek was discovered. Well, that pool the size Quirk Creek was there, but Clearwater Rundle A would lie undiscovered until 1980.

The Turner Valley structure section illustrates the association of the Rundle pool with surface structure. The section shows the more than 1200 m of hydrocarbon column. To put this structure in physical perspective, imagine its base in the Bow River at Banff and looking to its top on the ridge of Mount Rundle. On a map view of a portion of this play, the area looks absolutely littered with gas fields. Looking at the map you would think it should be dead simple to find gas here, but nothing could be further from the truth. This has been, and still remains, an active exploration play for over seventy years. The seventh and eighth largest pools in the play were discovered 36 and 54 years after the initial discovery, respectively. These considerations make it easier to accept the model analysis that suggests the fourteenth largest pool in this play, something about half the size of Quirk Creek A, still remains undiscovered.

The discovery sequence of pool sizes in the Jumping Pound Rundle Play has a "wavy" pattern (Figure A2-4), but there is a clear and discernible general decrease in new discoveries through time (note that the logarithm of pool size is shown). Also discernible is the unevenness of the exploration history. The play begins more than seventy-five years ago in 1924 with the discovery of the Turner Valley Rundle pool by the Royalite number 4 well drilled in 12-7-20-2W5 to test a surface antiform in the Cardium Formation. This structure was similar to, but immediately east of the "Central High" antiform which the original Dingman No.1 well tested, after D. B. Dowling was consulted. (Note, however, that the AEUB credits the first discovery of a Blairmore pool to discovery to Okalta #1 at 1-1-20-3W5 that was drilled in 1926). In 1944, twenty years later, Shell added a second field to the play by discovering the Jumping Pound Field with a well located in 4-24-25-5W5. By the end of 1965 reserves had been booked for only 14 pools in a play that today has 94 pools. Between 1966 and 1974 reserves were booked for an additional eleven new pools, the most significant of which was Quirk Creek A, which was

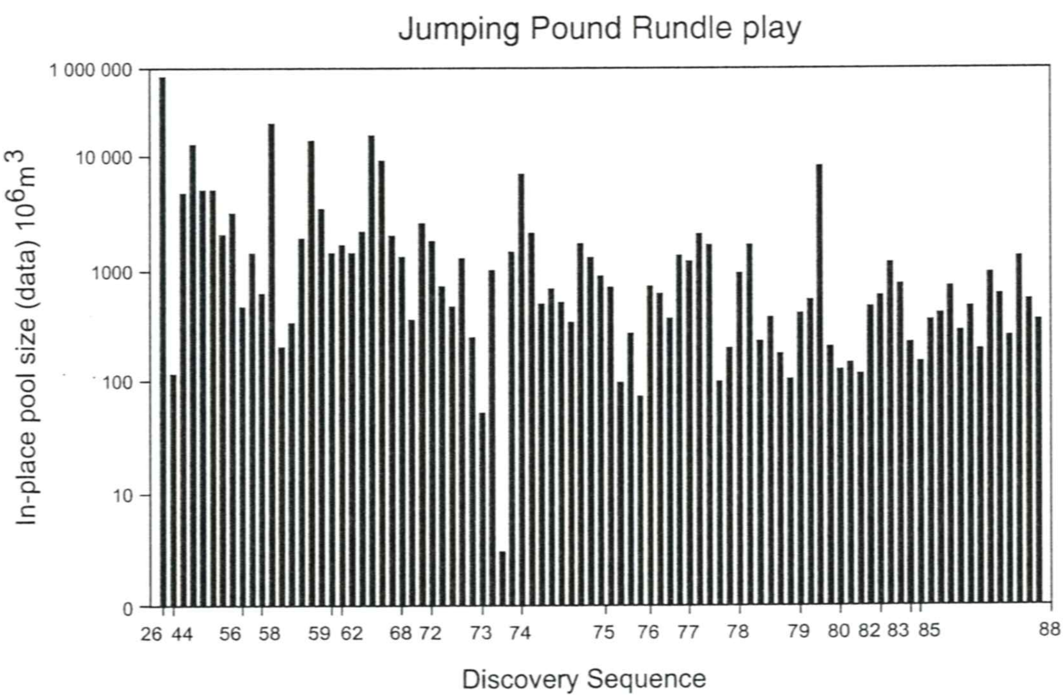


Figure A2-4. Discovery sequence of gas pools to 1990 in the Jumping Pound Rundle gas play. Pool size is scaled logarithmically. Notice the significant decrease in the size of pools with discovery order. The discovery sequence is annoted with the last two digits of the year in which discoveries were made.

discovered in 1972, but which is less than one-fifth the size of the largest Turner Valley pool.

The most active exploration of this play occurred fifty years after the initial discovery, between the years 1974 and 1978, when a short-lived rise in sulphur prices enhanced the economics of the play. During this four year period the number of newly discovered and booked pools more than doubled the number of pools found in the preceding fifty years, although no discoveries comparable to Quirk Creek were made. In the subsequent 12 years an additional 35 pools were discovered, the largest of which is the Clearwater A pool, of comparable size to Quirk Creek A, and discovered in 1980 (note the size versus rank distribution shown in Figure A2-5).

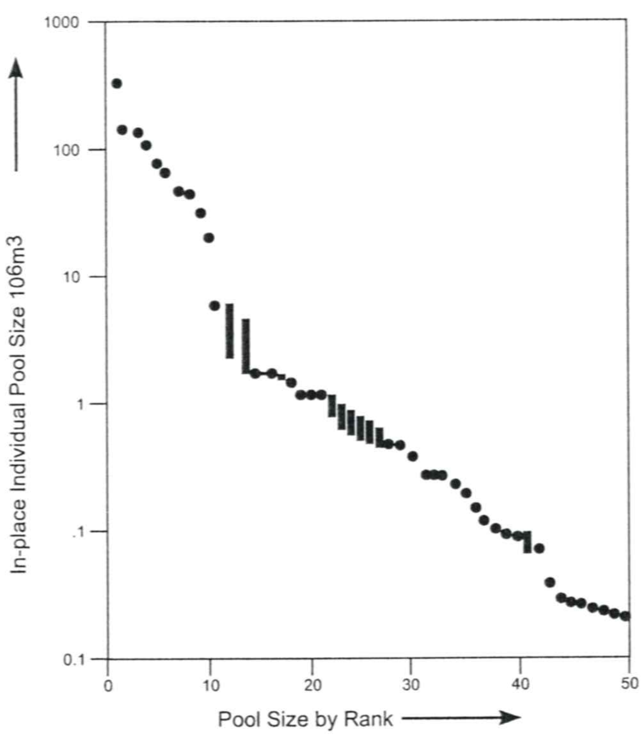


Figure A2-5. Predicted set of discovered (circles) and undiscovered (bars) pool sizes for the Jumping Pound Rundle gas play plotted with respect to pool size rank. This diagram is derived by predicting the size of pools as a function of play statistics, the total number of pools in the play and the rank of the pool. Discovered pools are then matched to predicted pool sizes. Undiscovered pool sizes are further constrained to lie between the sizes of discovered pools of higher and lower size rank. The undiscovered resource is described by the sum of the individual undiscovered pool size estimates. Pool size is scaled logarithmically.

Using the old AERCB data we performed a discovery process model using the pool size data available: (1) as of 1966, when 14 pools had booked reserves; (2) as of 1974, when 25 pools were booked; (3) as of 1978, using 59 pools; and (4) as of 1990, finally using the 94 pools that constitute our present assessment. As you can see (Figure A2-6), using only the first 14 pools gives an estimate of total potential that is almost 85% of the current estimate obtained using 94 pools. That variation is less than the total percentage variation in the booked value of reserves through time, which has shown a 31% fluctuation. This shows that our prognostication is at least as reliable as its input data, which is all that can be expected.

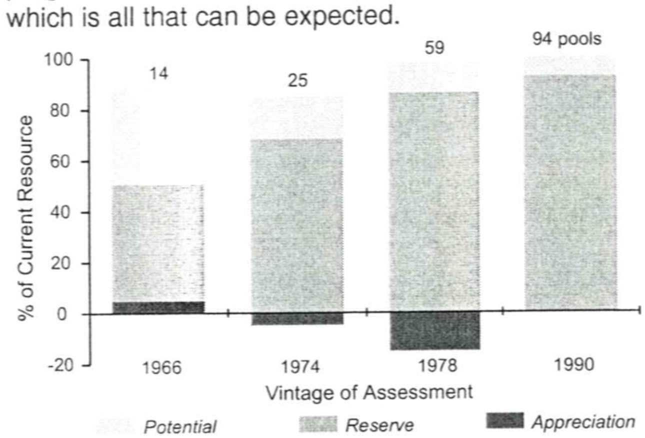


Figure A2-6. Predicted discovered reserve, undiscovered resource, and appreciation/depreciation of the reserve estimate as a percentage of the current (1990) total resource model for the Jumping Pound Rundle gas play. Estimates determined using discovery process modeling for four time intervals ending in 1966, 1974, 1978 and 1990, when 14, 25, 59, and 94 pools were discovered are shown. The reserve estimates at each of the dates analyzed are from EUB data for those years. Estimates of appreciation and depreciation indicate EUB revisions between indicated dates. Note that the discovery process method quickly estimates the majority of the resource after only about a dozen discoveries. The historical estimates of undiscovered potential are approximately as accurate as the description of the reserve, as indicated by the appreciation and depreciation of that reserve.

More important for explorationists is where that growth in the expected potential occurs. By the time only 10% of the currently estimated set of pools were discovered the estimate of the largest undiscovered pool size had dropped to about a fifth that of the largest pool, even though about half of the play potential remained undiscovered. Yet, as early as 1966 all the estimates suggested the presence of both the Quirk Creek and

Clearwater fields, even though the latter was not discovered until 1980. Currently we would suggest that the largest undiscovered pool is about half the size of Quirk Creek A, still an attractive target. Through time the total number of pools has increased significantly, almost 30%, from an expected value of 110, using the pre-1966 data, to 173, using the pre-1990 data. This increase is due to the addition of a large number of small pools, many of which will vanish once economic criteria are applied.

This analysis shows us that we can make predictions of resource potential and undiscovered pool size using a small subset of the discovery sequence. Our predictions are at least as reliable as our knowledge of the discovered reserve. Early in the game the analysis predicts the size of the largest undiscovered pools that have the greatest impact on exploration decision making. The growth of resources through subsequent exploration is due primarily to the addition of large numbers of small pools, which doubtless exist, but which may fail to contribute to the economically realizable resource.

Discovery Process Analysis of Mature Plays: A similar discovery process analysis was performed on all 17 mature plays using 1990 data (the best data available when the analysis was done in 1992). The total discovered raw initial gas in place is 675,146 X 10^6 m^3. The analysis suggests that the total undiscovered gas in these 17 plays (Figure A2-7) is 799,356 X 10^6 m^3. These will be discussed detail below, but we first consider the geographic distribution of this resource. Remember that neither the Lewis nor the Del Bonita geographic areas have mature plays. This is primarily because of the geopolitical constraints on the free exploration of the play that occurs at the 49th parallel. It also underlines the importance of understanding immature plays for this assessment. Notice also the apparent northward decline of total resource. It does follow a northward decline in reserves, but it is not due to exploration maturity. Rather we believe that this is a true reflection of the distribution of the resource, a point we will come back to once we add in the contribution from immature plays.

Play Potential and Largest Undiscovered Pool Size Among Mature Plays: Figure A2-7 shows the distribution of the undiscovered resource and largest undiscovered pool size among the mature plays. The most attractive play is the Sukunka Triassic play. It has both the largest undiscovered potential and the largest undiscovered pool. The largest undiscovered pool in the Sukunka play has an expected reserve of approximately 11,700 X 10^6 m^3 making it the second largest pool in that play and roughly comparable in size to the largest discovered pool the Sukunka, Pardonet-Baldonnel E pool, which itself probably has potential for appreciation. In all, there are six plays whose largest undiscovered pool has an expected size of more than 2,817 X 106 m3 (or 100 BCF). These include the Rundle Group in front of the McConnell thrust in the southern Foothills, the Ansell Cardium and unsubdivided Triassic of the central Foothills, the Triassic Baldonnel, Permo-carboniferous Debolt and Middle Devonian Manetoe of the northern Foothills.

We expect that in total there are almost 5600 undiscovered pools in the 17 mature plays with a total undiscovered gas resource of 799,356 X 10^6 m3. The greatest number of undiscovered pools in a single size class are the approximately 800 pools of approximately 1 BCF. Yet there are still nearly 700 undiscovered pools expected to be larger than 10 BCF and approximately 55 pools larger than 100 BCF. Ten large pools between approximately 200 BCF and 1/2 a TCF represent the most attractive targets in the mature plays.

Analysis of Immature and Conceptual Plays: Having considered and analysed the reserves and undiscovered resources in mature plays, it is possible now to extend the analysis to both immature and conceptual plays. This extension is critical to this assessment since there are 13 immature plays with a proven reserve of approximately 8 TCF.

Plays are immature for several reasons. In the case of the Waterton Rundle/Wabamun play, for example, the play is immature for geopolitical reasons. Much of the play is in the U.S. extension of the area, which has been removed from exploration for two reasons: (1) Land-ownership and land-use considerations and (2) unfavourable assessments of the play by the USGS. In spite of the empirical indications of a significant gas resource in Canada, the USGS continues to rate the region as unfavourable for exploration because of a perceived unfavourable temporal relationship between the predeformational timing of peak organic maturity and the syndeformational formation of traps. This might seem outwardly ridiculous, but similar arguments have been used in Canada to depreciate the potential of other overthrust and fold belts, such as the Georgia and Suquash basins in particular. Other reasons for a play being considered immature include both insufficient numbers of discoveries to allow the direct application of the discovery process analysis or unusual exploration histories, where numbers of pools should be sufficient to allow the application of the discovery process model, but the strange pattern of discovery history, sometimes indicated by a continuing increase in pool size through time, suggests either that

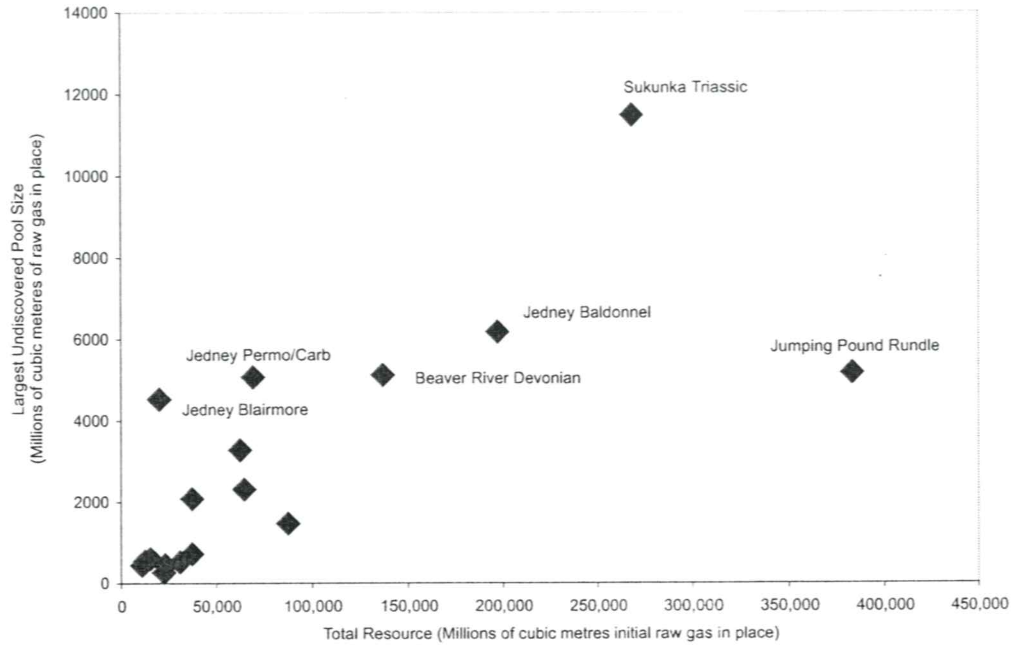


Figure A2-7. A cross plot of the total gas resource of mature plays in the Foothills and the largest undiscovered gas pool size predicted by the assessment of undiscovered resources.

the play is not sufficiently well understood to allow rational exploration, or that the play has been encountered by accident on the way to other primary targets, and is not itself the focus of a true exploration effort.

The approach used by the GSC for the analysis of immature plays is derived from that used for mature plays, but instead of using the discovery process to analyse the set of pools in a single play, we use the set of mature plays in the Foothills province to infer the complete set of foreland belt plays – mature, immature and conceptual. The total resource of mature plays, both discovered and expected undiscovered, are used and are arranged in order of their initial discovery, beginning with the 1913-14 discovery of Blairmore gas in the Turner Valley field (Figure A2-8). Through the second quarter of this century we see the discovery of the large plays in Paleozoic carbonates, although the exploitation of these waited until the end of the third quarter of the century, when sulphur prices were high. At that same time we see the discovery of several important new plays including Burnt Timber Wabamun, Beaver River Devonian and Sukunka Triassic, all the result of the surge of exploration into the foothills when improved sulphur prices motivated renewed exploration. The last mature play to be discovered was the Viking Ricinus play (1972).

This discovery sequence shows the most important characteristics of Foothills exploration history. They include a progressive expansion of interest northward through time that is overlain on the exploitation of both deeper and shallower horizons as exploration matures within a geographic region.

The calculations are straightforward. The discovery model predicts a population of 50 Foothills plays, and suggests the range of play sizes as a function of play rank. The matching of mature plays to the prediction further constrains the size of immature and conceptual plays. The important problem now becomes one of distinguishing the immature plays from the conceptual plays, first because the immature plays compete with mature plays for exploration dollars, but also because we must consider where to put the conceptual resource. The attempt to match immature plays to the predicted sizes of immature and conceptual plays that results from the discovery process analysis of mature plays employs three assumptions.

First, we assume that exploration of the foreland belt has been sufficiently efficient that most, certainly the most important, plays have already been identified and tested, even if they are not well exploited. The exploration history also supports such an assumption. Consider the hottest play of the late-1980's and early 1990's, the Sukunka Triassic play. It had been identified some twenty-years earlier. Remember also

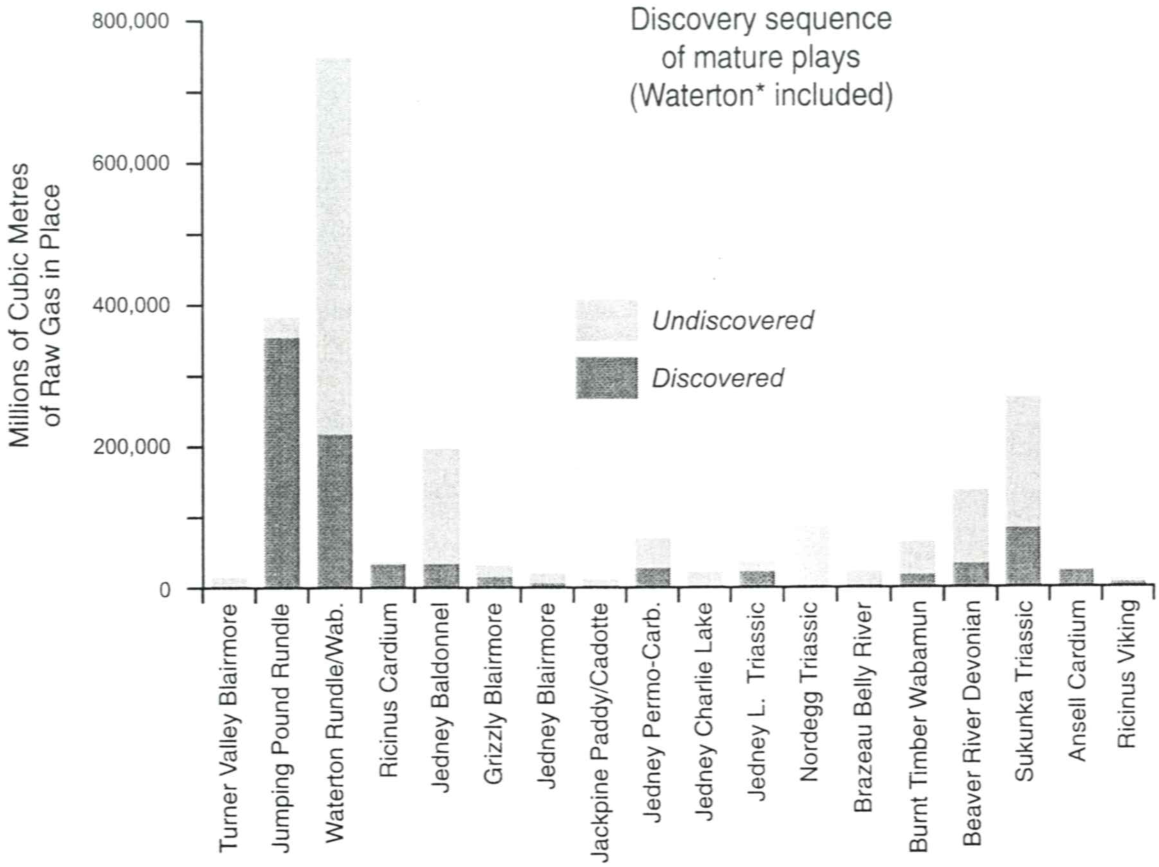


Figure A2-8. The discovery sequence of mature Foothills gas plays indicating the total play potential of discovered and undiscovered initial raw gas volume in millions of cubic metres of gas in place. The Waterton play which is considered immature because of the lack of exploration in the adjoining United States is included in this discovery sequence. The large undiscovered potential attributed to that play is due to the prediction of a large undiscovered pool and vast, relatively unexplored region in the adjacent United States. The predicted large undiscovered pool is best described as comparable to or larger than the Waterton Rundle-Wabamun Sheet III pool.

the historical analysis of the Jumping Pound Rundle play. It was first identified in the 1920's. But, by 1966 only 14 pools were discovered in that play. In contrast, more than 34 pools were discovered in the same play in between 1974 and 1978, when sulphur prices motivated an aggressive exploitation of that play. We can assume it is reasonable for history to continue following this pattern, such that the exciting plays of the early part of the next century have already been discovered.

Second, the geological setting, stratigraphic framework and stratal distribution of reserves also supports the contention that we have already identified the most important plays. There are a finite number of potential reservoir formations, all of which are know, either because they are exposed to the west in Front Range thrust sheets or because they are penetrated by either Foothills or Plains exploration wells. A quick glance at the stratigraphic succession suggests that there can be absolutely no more than approximately 60 potential plays, if the conventions of geographic and stratigraphic segregation we have used are applied to the complete succession. That this mental inventory suggests a number like the 50 plays inferred from the probabilistic analysis is encouraging, especially since reservoir potential of many of the stratal units in the mental inventory remains unproven.

When we examine the stratal distribution of proven reserves we see that there is a significant stratigraphic ordering to their distribution. The largest proven reserve and the greatest total potential among mature plays is usually located in the best potential reservoir immediately underlying the shaly Jurassic succession, that is both the most significant regional seal and a common locus of intensive penetrative deformation. This is commonly followed by deeper, usually Upper

Devonian reservoirs, for which a strong case can be made when higher gas volume factors, due to lower stratal position and relative greater depth, and stratal proximity to inferred potential sources is considered. Large reserves and potential in deeper Paleozoic and Triassic plays is followed by lesser potential in plays of the foreland basin succession. Among the foreland plays, it appears that proximity to Colorado Group source rocks is among the most important ordering factor, followed by lithology as it affects porosity as a secondary consideration. The result is a much different stratal distribution of the resource than that characteristic of the Plains, that will be discussed in greater detail later.

Finally, the mature plays show a very strong relationship between the proportion of the resource discovered and the proportion of pools that have been discovered. Immature plays can be added to this diagram using a weaker correlation that suggests the proportion of the resource discovered as a function of the reserve and the number of pools that have been found. This last technique confirms the relative rank-order of immature plays, one-to-another, suggested by the stratal ordering of resources, but it is too imprecise to allow a direct inference of potential. In this way the predictions of the discovery process analysis using mature plays can then be merged with the immature plays. It allows the resource potential of immature plays to be identified, not just as a function of their own characteristics, but also by considering their relative rank within the entire population of foreland plays.

Those predicted plays which are not matched to immature plays constitute the conceptual plays of the foreland belt. As a result of this analysis we suggest that only the 5th and 16th plays are undiscovered among the largest 25 plays, while most of those plays in the lower half of the population remain undiscovered. Exploration history would appear to bear this out. Little can be done regarding the assignment of a geographic and stratigraphic position of the undiscovered plays. The play everyone speculates upon the most is the 5th largest play with a potential somewhere between 200,000 and 130,000 million cubic metres of raw gas in place. Is this a Middle Cambrian play in the McConnell area? Might it be a Fairholme play in the Waterton area? or could it be sub-Carboniferous play in the Halfway-Sikanni area? The truth is we do not know, but there are both very strong suggestions that it exists and indications that it could be an attractive target for exploration.

Once the immature plays have been identified and attributed a resource potential they can be sorted into their respective regions to illustrate the geographic distribution of the resource. Just like the mature plays we see a very strong decline in the aggregate potential of the mature plays are we move progressively northward.

Play Potential and Largest Undiscovered Pool Size for Immature Plays: On a play by play basis we see that the undiscovered resource in each immature play reflects the matching process that was used to argue for the relative ranking of immature plays within different stratal levels of each single geographic area, and for the relative geographic distribution of resources among the various play areas. Except for the Waterton-Rundle Wabamun play, the potential in immature plays is generally better in the north than to the south (Figure A2-9). Again, the best potential appears in those reservoirs that are closest to regional seal, whether that would be the Fernie-Kootenay interval in the south, or the Horn River Formation in the Liard Basin. However, we must attempt to extract additional information form the set of immature plays if we want to compare the prospectivity of immature plays directly with that of the mature plays. In particular we must infer the size of undiscovered pools in the immature plays. The information required to compute individual pool sizes is the number pools expected in a play. This can be inferred if the average pool size is known, since the product of the number of pools and the mean pool size is the total resource. Average pool sizes can be constrained by analogy and comparison to other plays of structural style and stratigraphic setting. The estimates of individual pool sizes do, through this process, become subjective inference, but they are the best that can be managed. Such an analysis of the 13 immature plays suggests the logarithm of the largest expected pool size is roughly proportional to the logarithm of expected total gas resource. This relationship is also borne out by comparison to other settings.

As a result of such inferences, the analysis suggests that eight of the immature plays have the potential to have a largest undiscovered pool of approximately 100 BCF or greater (Figure A2-9). Using this analysis we see that the immature plays are as attractive exploration targets as the mature plays, both for their total potential and for their individual pool sizes. Notice that the attractiveness of other plays changes significantly when we consider the largest undiscovered pool, rather than the resource potential. Greatest interest probably lies in the prediction of individual pool sizes. Remember that the largest undiscovered pool amongst the mature plays was one of about half a TCF in the Sukunka Triassic play.

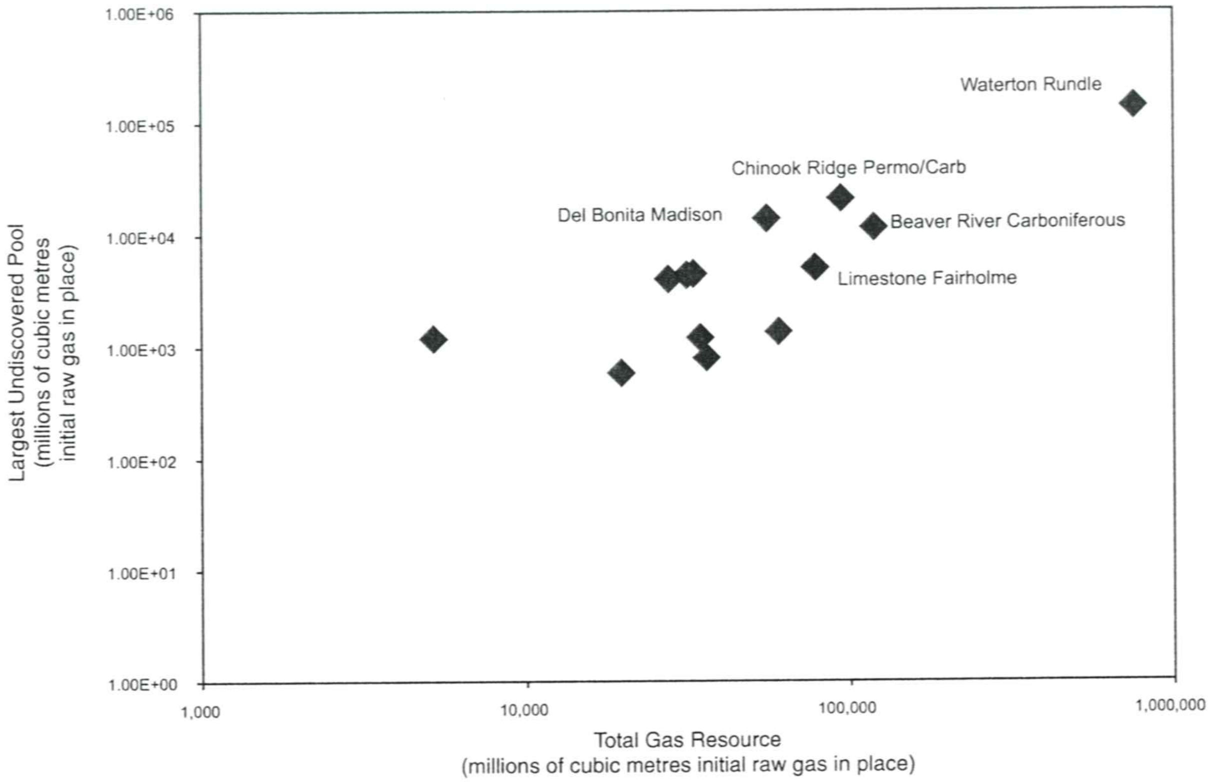


Figure A2-9. A cross plot of the total gas resource of immature plays in the Foothills and the largest undiscovered gas pool size predicted by the assessment of undiscovered resources.

The Waterton Rundle/Wabamun play is the most attractive target, since we infer that the largest single pool in the entire foreland belt remains undiscovered. The expected size of the largest undiscovered pool in the Waterton Play may be as large as indicated (Figure A2-9), however, one must remember that the predicted size of undiscovered pools is not a single value, but an infinite probability distribution. It may be that, if additional Waterton Sheet 3 reserves occur under the National Park, that the largest pool has been discovered. In that case the prediction would be for a pool comparable in magnitude to, but smaller than the augment size of the Sheet 3 pool. Alternatively, the largest pool may still be undiscovered, but here it would again be prudent to suggest that the undiscovered pool is comparable to that of Waterton Sheet 3. The precise location of this pool remains unknown, but it seems reasonable to expect that it will occur in some type of multiduplex like the Waterton Field. Fritts and Klipping and others have suggested the location of prospective structural culminations, while relatively recent tests in Montana have provided encouragement that some folding of Lewis Sheet south of Marias Pass may be bending over footwall multiduplex structures like the Waterton and Flathead (Livingstone) culminations. Regardless, the continued exploration of the Waterton Play remains the highest priority, although access to some of the most attractive targets may be hampered by non-scientific considerations, particularly in the United States.

The Chinook Ridge Permo-Carboniferous play is the next most attractive immature play, with an undiscovered pool of approximately 1 TCF. This play represents the structural analogue to the Rundle Group plays of the three southern Foothills regions. Unfortunately, changes in Rundle Group lithofacies result in the disappearance of the well developed Turner Valley Member porosity zones. Structures in this geographic region are abundant, but the trick will be to understand the distribution of porosity in the interval between the Devonian Perdrix and Lower Triassic shales. The Chinook Ridge play shows some parallels to the history of the Triassic Sukunka Play: early encouragement of gas presence, but a poor understanding of porosity distribution. Thus the focus of central Foothills exploration for Paleozoic reservoirs should be oriented toward understanding Rundle Group porosity in the central Foothills.

Other immature plays with attractive undiscovered pools include the Del Bonita Madison (essentially structure in front of Pincher Creek, but again a play that extends into the United States) and Beaver River

Carboniferous plays. other plays, some of which have very large aggregate potentials, like the Lawrence Second White Speckled shale play, are relative unattractive exploration targets when their individual pool sizes are compared with the four mentioned above.

General Characteristics of the Total Gas Resource: We infer a total resource of 3,260,464 X 10^6 m^3 of initial raw gas in place to occur in 50 plays, thirty of which are identified both geographically and stratigraphically, and which constitute the mature and immature plays of this analysis (Figure A2-10). There is a total of 908,755 X 10^6 m^3 of discovered initial raw gas in place. Approximately 74% of the discovered resource is in mature plays as we have defined them. If the reserves of the Waterton Rundle/Wabamun play are added to the mature plays the proportion rises to 98%. Thus the other 12 immature plays contain only 2% of the discovered reserve.

We also expect another 2,351,709 X $10^6 m^3$ of initial raw gas in place is undiscovered. The undiscovered resource is distributed such that 799,356 X $10^6 m^3$ of initial raw gas in place remains undiscovered in mature plays, 1,112,163 X $10^6 m^3$ of initial raw gas in place is in immature plays and 440,190 X $10^6 m^3$ of initial raw gas in place is in conceptual plays. 80% of the undiscovered resource occurs in the 30 mature and immature plays. 33% of the undiscovered resource is in 17 mature plays, but this proportion rises to 56% if the projected undiscovered resource of the Waterton Rundle/Wabamun play is added to the mature plays. Thus, only 24% of the undiscovered resource is attributed to the other 12 immature plays. 20% of the undiscovered resource is expected to occur in 20 additional conceptual plays, the geographic and stratigraphic locations of which are unknown.

When the total resource in mature and immature plays is assigned to geographic regions the northward decrease in potential that was apparent for mature plays persists. Consider the immature Mississippian plays in the two most widely separated regions, Beaver River Mississippian and Waterton Rundle/Wabamun. In many ways exploration in the Lewis region is much more difficult than that in the Liard Basin. The structures in the Waterton region have very little geomorphic expression, while the surface structures in the Laird Basin are readily mappable. There is a clear association between surface closure and closure on the reservoir in the Liard Basin, while closure areas on reservoir horizons in the Lewis region are often displaced from surface closures. This greater difficult is clearly reflected in the higher wildcat success rate and "bang for your buck" parameters of the Beaver River play that were discussed earlier.

The origin of this pattern probably represents a combination of several factors. The greater amount of supracrustal shortening in the south results in a more complex structure that has a greater number of prospects. Higher strain rates result in the more rapid development of structures. This means that foreland subsidence, sedimentation, and peak thermal maturity are followed more rapidly by deformation and trap formation in the south than in the north, or even that peak thermal maturity of some units is achieved syn- to

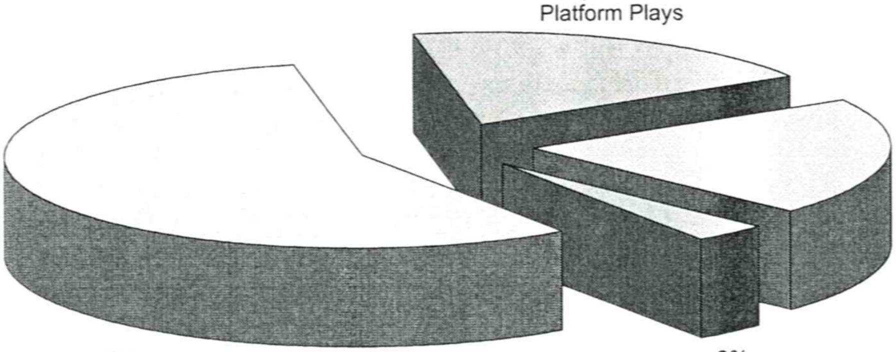


Figure A2-10. Pie diagram of the total gas resource in the Western Canada Sedimentary Basin as a function of structural province and level of identification. Conceptual plays have no discoveries, but are inferred from the play discovery sequence. The total resource estimated is 13,674,546 million cubic metres of raw gas in place.

post-deformationally in the south, whereas pre-deformational peak maturity is the rule in the north.

The greater abundance of porous units in Paleozoic strata in the south is also clearly important, as is the greater thickness and preservation of Mesozoic coarse clastic strata. The greater porosity of Paleozoic strata in the south reflects a fundamental tectonic control that is related to the pattern of Taphagnic (Silurian through Carboniferous) onlap, which could itself be related to both formation of the Paleozoic passive margin and Paleozoic Antler/Ellesmerian orogenesis. In the same region, the greater thickness and porosity of overlying Mesozoic strata reflects the greater shortening and tectonic loading of the southern Foothills during Laramide orogenesis. Thus, the fortuitous superposition of the deepest parts of the Laramide foredeep onto the persistent Devonian and Carboniferous carbonate platform of the Taphagnic onlap, in the region of the greatest Laramide supra-crustal thickening, provides possible factors controlling the north-south variation of resource potential.

If we move to the stratigraphic distribution of the resource we see it is predominantly concentrated in stratigraphically lower reservoirs that are commonly deeper in the structure (Figures A2-11 and A2-12). This makes intuitive sense, especially when considering the great importance of formation volume factor on gas volumes. What is more interesting is the proportioning of resources between Cretaceous reservoirs in the Foothills (Figure A2-11) and the Plains (Figure A2-12). This is best illustrated by the Blairmore and Mannville groups. In the Plains, Mannville Group reservoirs contain 28% of the discovered gas in place and other work by our group suggests that Mannville reservoirs will ultimately contain 25% of the total resource. These numbers consider only conventional gas. In stark contrast, the Blairmore Group in the Foothills contains only 3% of the discovered gas and our analysis suggests that Blairmore reservoirs are expected to contribute only 3% of the ultimate total resource. When the amount of Mannville resource is compared to that in the Blairmore we find that the ratio of discovered gas is 61:1 in favour of the Mannville. Although this ratio drops to about 22:1 when the total inferred resource is considered, it is still shows the disproportionate concentration of Mannville gas in the Plains when compared to Blairmore gas in the Foothills.

The probable explanation of this difference in stratigraphic and geographic distribution is two-fold. One contributing factor is inferred to be differences in hydrocarbon charge systems. The gas of Foothills plays appears to be predominantly thermogenic, although more work could be done to bear this out. If this inference is correct then it is possible that generation of large volumes of biogenic gases that are common in some Mannville pools did not occur in the foreland belt as compared to the Plains. Somewhat counter-acting this is the apparent generation of gases from coaly strata in the Foreland Belt that is inferred for

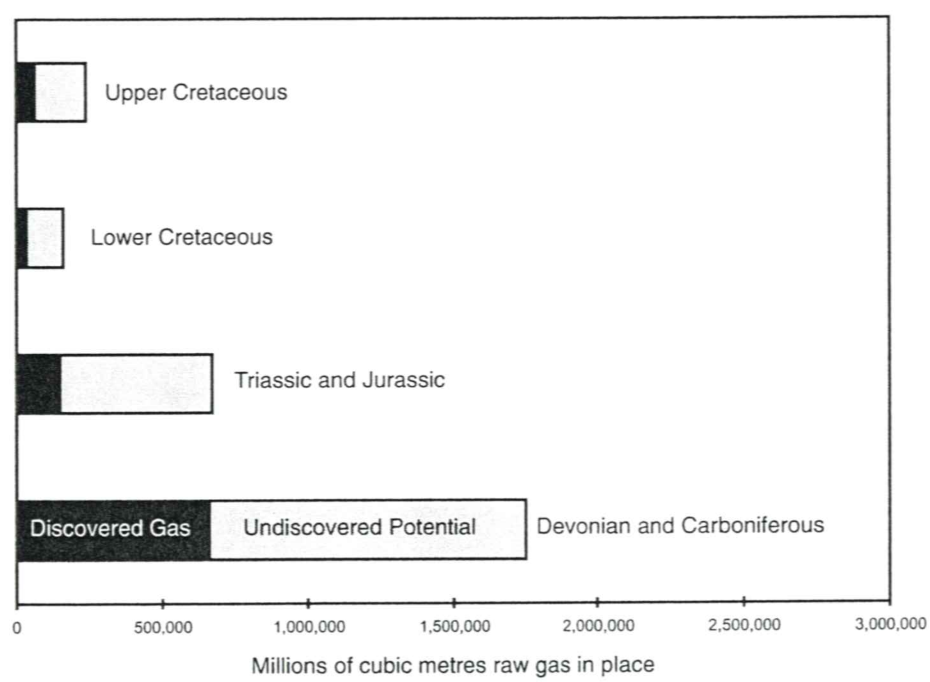


Figure A-11. Stratigraphic distribution foothills gas potential.

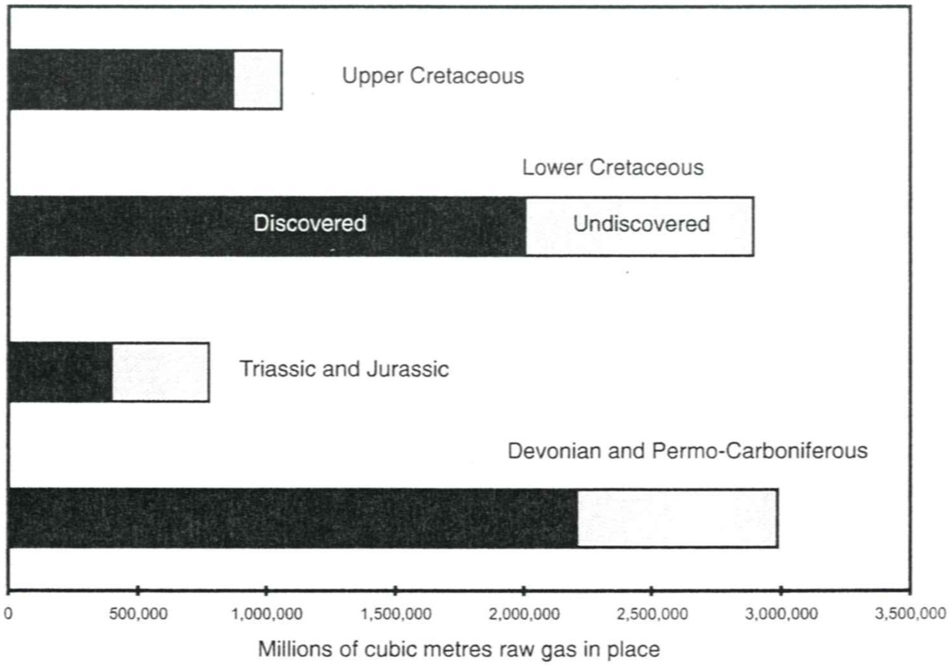


Figure A-12. Stratigraphic distribution of interior platform gas potential.

only the deepest portions of Mannville Group in the Plains. A second contributing factor is illustrated by the contrasts in the stratigraphic position of regional seals and their affect on migration pathways. In the Foothills the most important seals occur in the succession that spans the uppermost Carboniferous to the uppermost Jurassic and then again in the Colorado Group The exploration strategy bears this out and the distribution of Foreland Belt resources, both discovered and inferred, also follows this pattern. On the Plains, in contrast, the same succession is either thin or absent and basal Mannville aquifers are commonly in communication with Paleozoic aquifers that are the most productive reservoirs of the foreland belt. Although these speculations require much work before they can be verified, it is reasonable to speculate that differences there are real differences in the stratigraphic distribution of resources between the Foothills and Plains. These differences are controlled primarily by the composition of the stratigraphic succession, the strain rate during deformation, and the geological and thermal history as they affect hydrocarbon generation and secondary migration.

These indications of geographic and stratigraphic variations in resource potential are fundamentally important for the explorationist. To date, exploration of the Foothills has largely followed the anticlinal paradigm. The early exploitation of surface seepages following the anticlinal paradigm has resulted in a pragmatic and empirical approach to the exploration of this basin. What we lack is an integrated conceptual framework or model of foreland natural gas occurrence.

Where To Explore: The last discussion indicates the current ranking of effort to prove the potential inferred by this analysis and the identity of the most attractive exploration prospects, as a function of the largest undiscovered pool size within a play. Conceptual plays are not considered in this summary, primarily because they cannot be located, but also because of the inability to generate estimates of their individual-pool sizes.

The mature plays show a positive correlation between total play potential and the "more bang for your buck" parameter (Figure A2-13). With two exceptions the immature plays fall below this correlation line, indicative of a poorer exploration efficiency. Presumably this efficiency could be improved to be comparable to that of the mature plays if sufficient effort and appropriate technologies were applied to their exploration. For example, there is little reason to believe that the exploration of the Beaver River Carboniferous play could not become about as efficient as the exploration of the Jedney Baldonnel play, based on the variation of mature play potential and exploration efficiency. This expectation should be kept in mind when attempts are made to rank the relative prospectivity of individual plays.

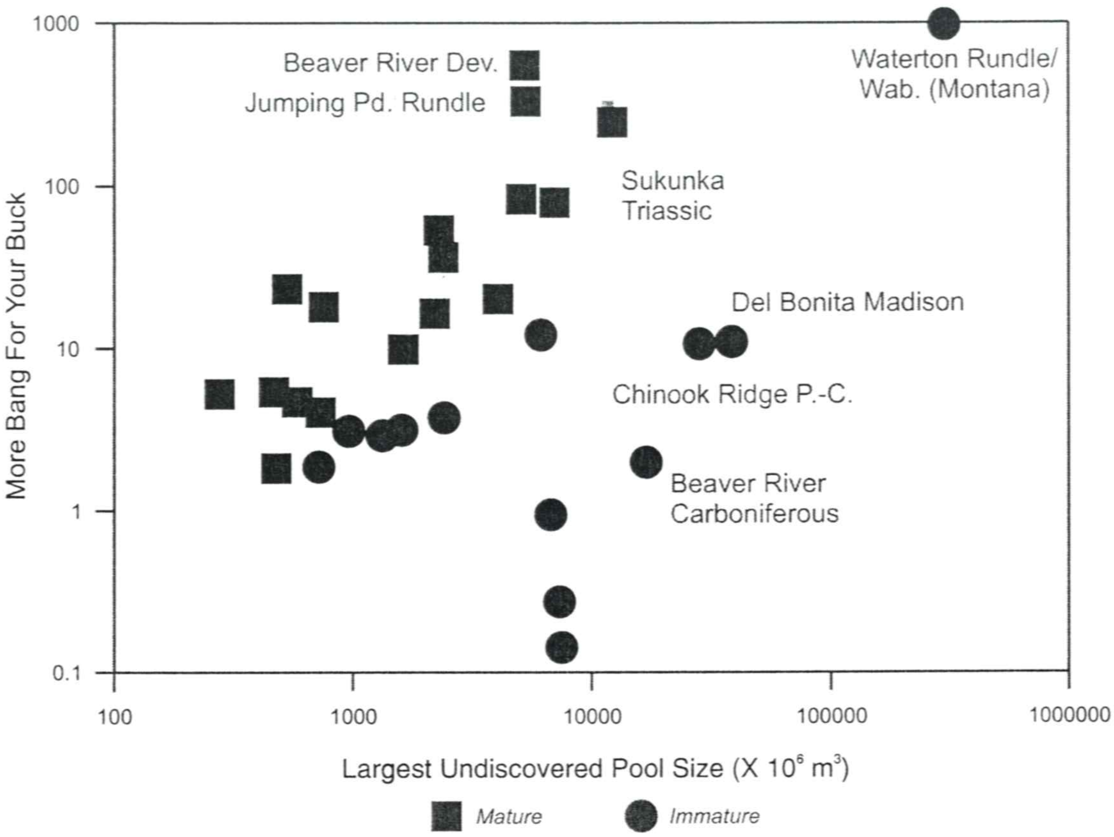


Figure A-13. A cross plot of the largest remaining undiscovered pool size in mature and immature Foothills gas plays plotted against an indicator of exploration facility, "More Bang For Your Buck". This indicator is the ratio of the initial raw gas in place reserve in millions of metres, to the product of the average pool depth and the total number of exploration new pool and new field wildcat wells drilled to establish that reserve.

When the "more bang for your buck" parameter is examined as a function of the largest undiscovered pool size the mature plays again exhibit a strong positive correlation that is not manifest for the immature plays. This diagram provides a clear indication of the expectation for the best undiscovered pool in each play as a function of the effort required to find it. The linearity of the mature plays on this diagram is a reasonable and intuitive expectation for an antiformal hydrocarbon province: big prospects are more easily identified and hold larger resources. Thus the diagram becomes an indicator of where to apply your effort and the size of the best possible reward as a function of that effort to explore. An interesting alternative is the construction of a similar diagram where the immature plays are plotted not using their current exploration efficiency, but by estimating the best exploration efficiency that could be expected if the play was actively pursued. The inferred efficiency would be calculated using the linear relationship that the efficiency of mature plays show as a function of their total potential.

The diagram is clear as to where the effort should be applied (Figure A2-13). The four biggest plays of the past will continue to be among the big plays of the future, but they will not be the only game in town. The development of the immature plays will become progressively more important, and because of their geographic position with respect to available land, it may be that the exciting new discoveries of the new century will be made in the immature plays.

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