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EVOLUTION OF THE LARAMIDE FOREDEEP AND THE ADJACENT THRUST BELT IN SOUTHERN ALBERTA

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with contribution by H.H. Hartmaier on:

EFFECTS OF THE GEOLOGICAL SETTING UPON THE DESIGN AND CONSTRUCTION OF THE OLDMAN RIVER DAM

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I. INTRODUCTION

This study of the Alberta Foreland Basin (Laramide Foredeep) and its overlapping position along the interface between the North American Craton and the Cordilleran Orogen is intended to illustrate a number of features of the Late Cretaceous and early Tertiary tectonic history of the Foreland Thrust and Fold Belt in southern Alberta. These features include: 1. The eastward progradation of the Laramide continental clastic wedges into the foredeep in the Late Cretaceous and early Tertiary; 2. The structure, facies and sedimentary environments of the Upper Cretaceous Belly River Formation; 3. The importance of palinspastic restoration in the paleogeographic reconstruction of the foredeep; 4. The facies and depositional environments of the autochthonous, Late Cretaceous to early Tertiary St. Mary River, Willow Creek and Porcupine Hills formations; and 5. The geometry of the Upper Cretaceous–Paleocene foredeep.

The Upper Cretaceous–Paleocene strata were deposited during the Laramide Orogeny i.e. during the final stages in the evolution of the Alberta Foreland Basin. They contain the record of convergence within the supracrustal wedge, the mechanical separation of the wedge from the underlying continental and oceanic lithosphere (Oldow et al., 1989), the horizontal shortening and vertical thickening of the wedge, isostatic adjustments in the crust leading to depression, compression and thermal alteration of the lower part of the deformed sequence in the hinterland (c.f. Shuswap Metamorphic Complex), isostatic uplift and erosion of the tectonically thickened wedge with concomitant downward buckling of the crust to form the Alberta Foreland Basin, and the eastward migration of the Laramide deformation front in the company of the foreland basin (Bally et al., 1966).

This guidebook is an updated and supplemented versin of a guidebook entitled "Anatomy of the Laramide Foredeep and the Structural Style of the Adjacent Foreland Thrust Belt in Southern Alberta (Jerzykiewicz and Norris, 1992). The guidebook does not pretend to be a comprehensive account of the Laramide Foredeep in southern Alberta. It is rather an attempt to stimulate discussion on a variety of topics and unsolved problems and to renew interest in this geologically interesting and economically important area. The field trip route with planned stops is shown in Figure 1.

The Alberta Foreland Basin is the southwestern part of the Western Canada Sedimentary Basin, a northeasterly-tapering wedge of sedimentary rocks extending from the Canadian Shield into the Cordilleran Foreland Thrust and Fold Belt. Active during late Mesozoic and early Cenozoic time, the Laramide Foredeep was part of a much larger foreland basin extending from Alaska to New Mexico that was complementary to an orogenic belt situated along the western continental margin of North America (Dickinson, 1976). The subsidence of the foredeep was controlled initially by tectonic loading of thrust sheets on the downdip extension of the foredeep ramps and subsequently for the

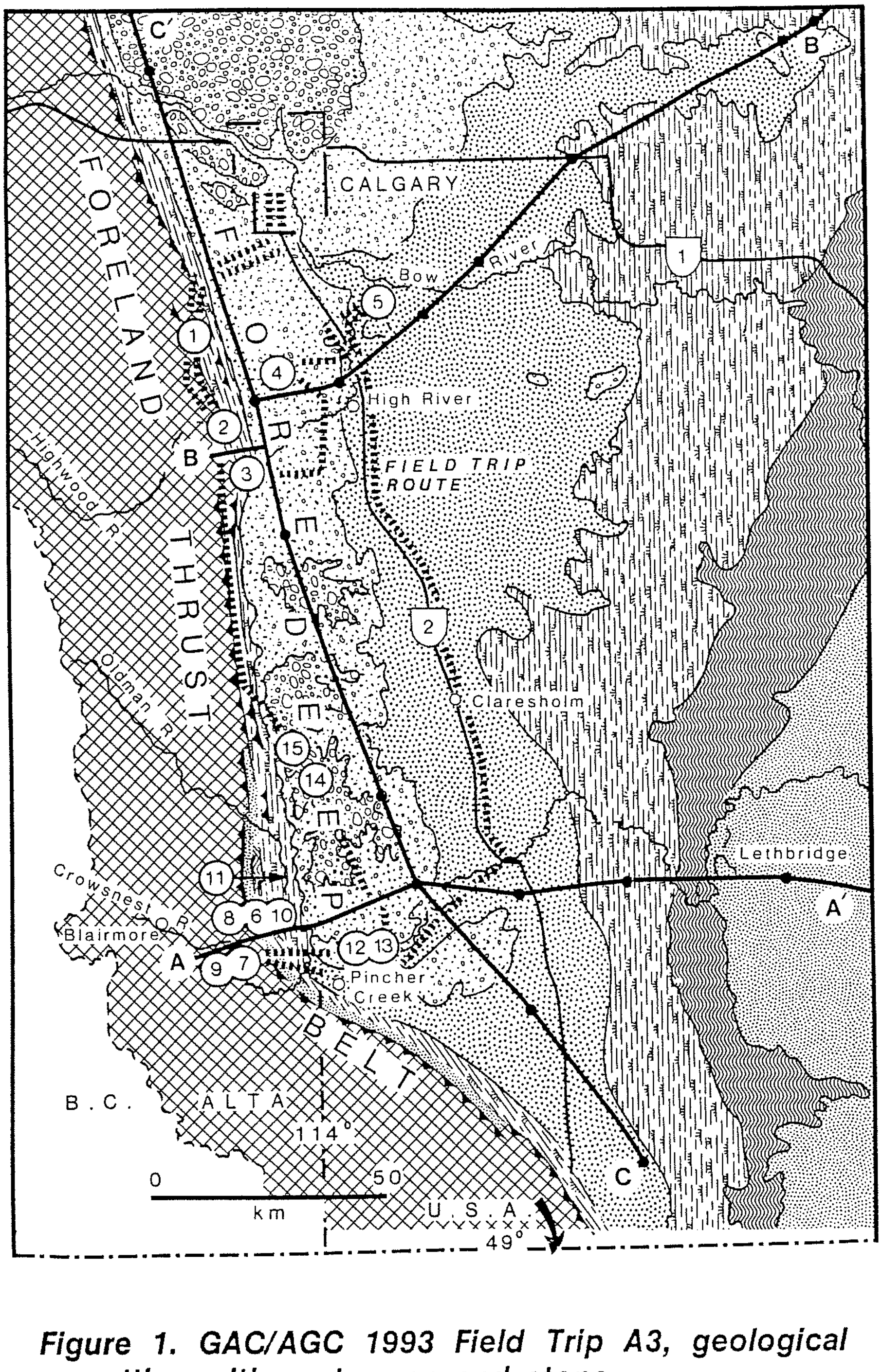


Figure 1. GAC/AGC 1993 Field Trip A3, geological setting with route map and stops.

most partby sediment filling of the foredeep. There is reason to suspect, however, that additional factors may have played an important role in this subsidence (Bally and Snelson, 1980). Otherwise, the foredeep would quickly fill and become plugged with lighter, unconsolidated sediments. The basin axis moved progressively eastward through time in response to the cratonward migration of orogenesis (Armstrong and Oriel, 1965; Bally et al., 1966).

The foredeep was filled by an eastward-thinning wedge of clastic debris derived from erosion of the orogenic highlands. The total thickness of the Upper Jurassic–lower Tertiary sedimentary prism is more than 6 km. The prism is subdivided into subordinate clastic wedges (King, 1959), that were deposited in the rapidly subsiding Foredeep. The Upper Jurassic to lowermost Cretaceous wedge comprises the Fernie, Kootenay and Minnes groups (Stott, 1984; Gibson, 1985). The lower to middle Cretaceous wedge includes the Blairmore Group and stratigraphic correlatives (Norris, 1964; Mellon, 1967). The Upper Cretaceous to Paleocene clastic wedge consists of the marine Alberta Group, with the Wapiabi Formation as its upper part (Stott, 1963, 1984; Wall and Rosene, 1977), overlain by predominantly non-marine deposits (Jerzykiewicz and Sweet, 1988) that are the subject of this Guidebook.

The key to Cretaceous and Paleocene stratigraphy and facies of the Laramide Foredeep is large-scale intertonguing of marine and continental sediments. The pattern of the Cretaceous transgressive-regressive couplets and cycles of Kauffman (1977) and cycles and supercyles of Vail et al. (1987) or Haq et al. (1977) is applicable with limitations resulting from the position of the Laramide Foredeep in the westernmost periphery of the Interior Basin of North America where the influx of terrigenous clastics was dominant. The more than 4 km of post-Wapiabi (post-Colorado) strata are almost entirely nonmarine in the Laramide Foredeep and span more than 20 Ma, between the upper Campanian and Paleocene (Fig. 2). The Wapiabi marine cycle corresponds to the Niobrara marine cycle (Stott, 1984). The Pakowki (or Nomad) marine cycle which corresponds to the Claggett cycle of the Western Interior of the United States is well developed in the southern Alberta Plains and in the central and northern Foothills (Highwood River section and north of it), but has not been identified in the southern Foothills (Crowsnest River section). The last marine cycle of the Bearpaw sea is very pronounced in the southern part of the Western Canada Sedimentary Basin including the southern segment of the foredeep, but it is absent north of Turner Valley.

The post-Wapiabi succession embraces regressive cycles 8–10 of Kauffmann (1987, Fig. 6) and supercyles UZA–4 and TA–1 of Haq et al. (1987). The regressive cycle 8 of Kauffman (op. cit.), corresponding to cycles 4.1. and 4.2 of Haq et al. (op. cit.), is represented by the Belly River Formation of the southern segment of the foredeep (Fig. 2). Regression of the Bearpaw Sea in the early Maastrichtian began the period of continental sedimentation in the Alberta

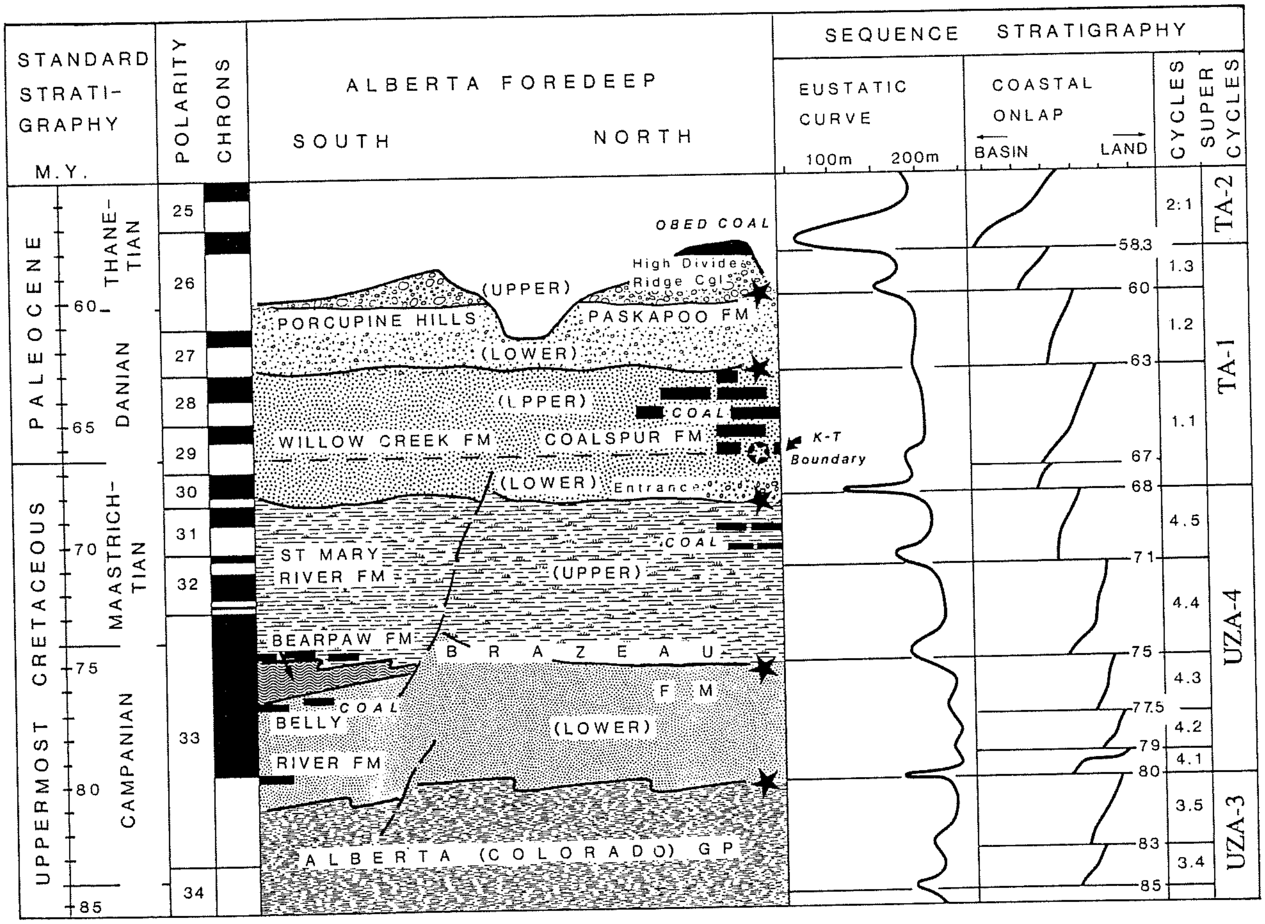


Figure 2. Stratigraphy of the post-Wapiabi (post-Colorado) formations of the Alberta Laramide Foredeep.

Foreland Basin that lasted until the late Paleocene. In the northern segment of the foredeep, where Bearpaw marine sediments are absent, continental sedimentation commenced with the regression of the Nomad Sea in the Campanian.

Biostratigraphy of the post-Wapiabi continental strata of the Western Canada Sedimentary Basin is based on palynology (Srivastava, 1970; Jerzykiewicz and Sweet, 1988; Demchuk, 1990) and vertebrates (Sternberg, 1949; Russell, 1975; Fox, 1990). The stratigraphic correlations of the post-Wapiabi continental formations in the entire Albreta Foothills based on lithology and palynology have been studied in detail by Jerzykiewicz and McLean (1980), Jerzykiewicz (1985), Jerzykiewicz and Sweet (1986a; 1986b; 1988). These studies and subsequent surface and subsurface mapping of the foredeep have led to the recognition of five sequences or subordinate clastic wedges. Each of these subwedges is underlain by a basin-wide break in the stratigraphic record and/or commences with an influx of coarse-grained detritus, heralding major events in the basin (these sequences bounded by breaks in stratigraphic record marked by asterisks are shown in Fig. 2). These events were: 1) regressions of the Wapiabi and Bearpaw seas from the foredeep at approximately 80 and 75 Ma respectively, and 2) drastic changes in lithology at approximately 68, 63, and 60 Ma. These dates correspond to lithostratigraphic boundaries which were mapped surface and subsurface in the entire Alberta Basin (Figs. 4–6). The 68 Ma boundary corresponds to the drastic change in lithology at the St. Mary River–Willow Creek contact in the southern Foothills. This boundary is marked by the Enterance Conglomerate in the central Foothills and by the Kneehills Tuff and/or Battle Formation in the Plains. An unconformity at this boundary was proven in many areas across the basin (Russell, 1983). The Paskapoo and Porcupine Hills formations, that are over 800 m thick in the core of the Alberta Syncline, are subdivided into two members (Figs. 4–6) with their lower boundaries at approximately 63 Ma and 65 Ma (Fig. 2).

The absolute ages of the boundaries between the sequences (subwedges) are approximated on the basis of radioisotopic and magnetostratigraphic data published on post-Wapiabi strata in the Wetern Canada Sedimentary Basin (Folinsbee et al., 1961, 1964, 1965; Lerbekmo, 1989; Lerbekmo et al., 1979, 1990; Lerbekmo and Coulter, 1985; Thomas et al., 1990). The subwedges within the post-Wapiabi (Laramide) clastic wedge differ in external geometry (Fig. 3), and internal distribution of facies across the basin. The Belly River (lower Brazeau in the central-northern Foothills) wedge of Campanian age, and the St. Mary River (upper Brazeau in the central-northern Foothills) of Maastrichtian age were deformed by subsequent thrusting and partitioned into allochthonous and autochthonous segments which differ significantly in facies and thickness. The position of the foredeep at the beginning of the Laramide Orogeny, estimated on palinspastically restored sections of the Belly River formation in the Crowsnest Deflection area is assumed to have been more than 70 km westward relative to the

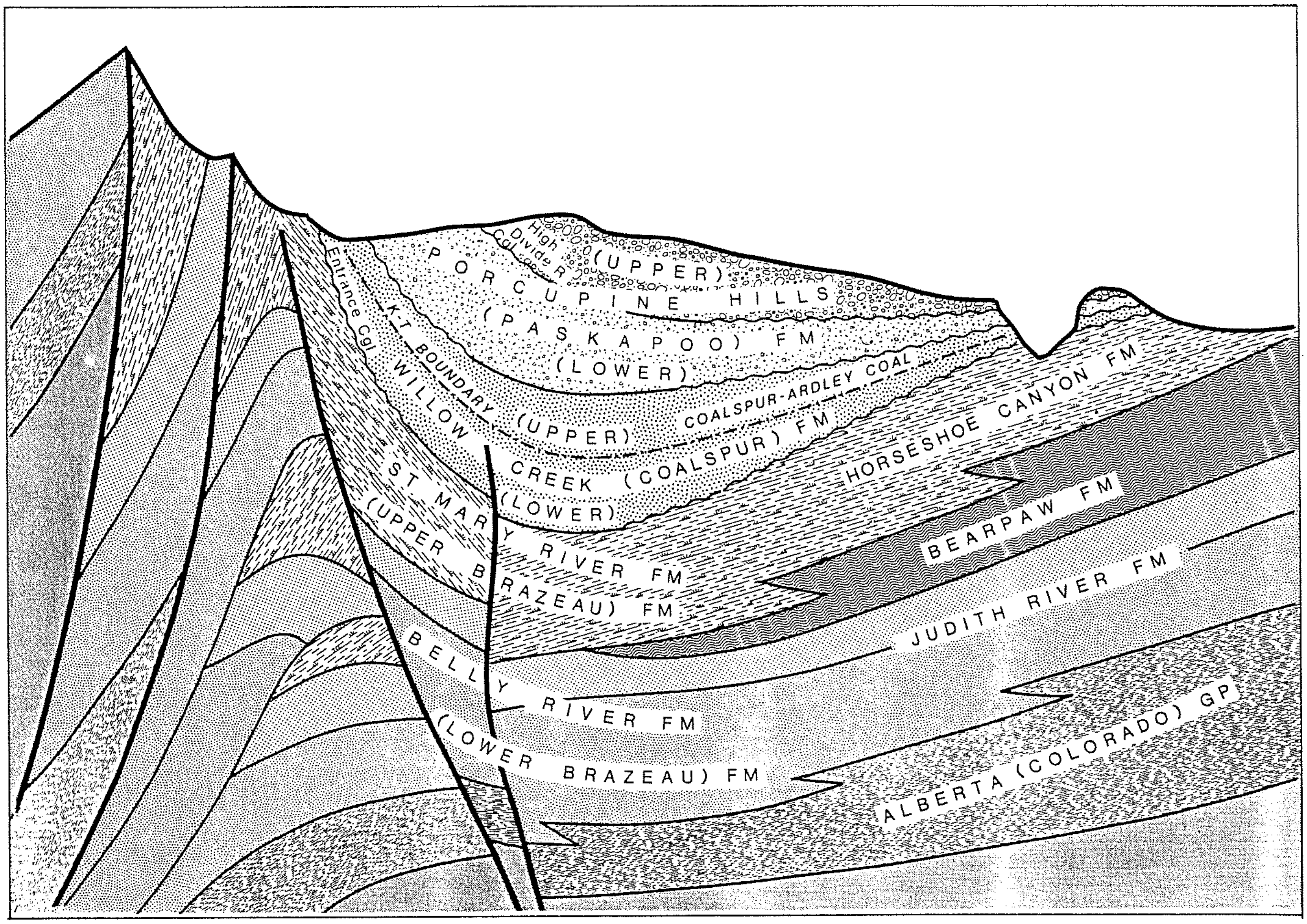


Figure 3. Schematic cross-section of the Alberta Laramide Foredeep.

autochthon of the Alberta Syncline. The uppermost Maastrichtian–lowermost Paleocene sub-wedge (Willow Creek Formation in the southern Foothills and Coalspur Formation in the central-northern Foothills), although compressed in its western part (e.g. Entrance Syncline, Coalspur Anticline), consists of autochthonous and parautochthonous strata with a depocentre east of the Triangle Zone (Gordy et al., 1977). The Paleocene clastic subwedges (Porcupine Hills and Paskapoo formations) are virtually undeformed and their external geometry is established directly from the series of structural cross-sections (Figs. 4–6). Their wedge-shaped geometry is most visible between the Paleocene foredeep, which follows the axis of the Alberta Syncline, and the zone of stratigraphic condensation of the Paskapoo sections in the Plains. The foredeep migration from its most western, distal position in the Campanian to its Paleocene locus along the axis of the Alberta Syncline took approximately 20 m.y., at an average velocity of between 3 and 4 mm per year and was punctuated by the large-magnitude events (see Fig. 2) at approximately 80, 75, 68, 63 and 60 Ma. The sequence of ages for the lower boundaries of the five clastic wedges may indicate tectonic pulses in the orogenic front (McLean and Jerzykiewicz, 1978), although the emerging thrust slices capable of producing proximal sediments were probably separated from the foredeep by a marginal trough (piggyback basin) and the foredeep itself was internally partitioned into discrete drainage domains divided by transverse growth faults.

The largest growth fault zone is documented in the subsurface of the Highwood River section in the vicinity of Longview in the Maastrichtian St. Mary River Formation (Fig. 4). A comprehensive description of this zone requires more subsurface work but the present data, which include marked variations in thickness of the St. Mary River Formation, well developed mudflow facies observed in outcrop and the recognition that this fault zone is a boundary between two distinctly different facies provinces within the Laramide Foredeep (Jerzykiewicz and Sweet, 1988; Jerzykiewicz, 1991) make this zone a particularly interesting target for hydrocarbon exploration. The St. Mary River is observed to double its thickness from 500 m to 1000 m, for example, from one side to the other of the upper detachment to the Triangle Zone in the vicinity of the Cow Creek well, ten km north of Lundbreck (see Fig. 23).

ACKNOWLEDGMENTS

We wish to thank Dr. Stan Dzulynski (Jagiellonian University) for his helpful comments on sedimentary structures. Interpretation of trace fossils from the St. Mary River Formation benefitted from discussion with Dr. Paul Johnston (Royal Tyrrell Museum). We would also like to acknowledge the efforts of A. Czarnecki (well log analysis and drafting), Bill Sharman (photography), M. MacDonald (drafting), Len Wardle (reproduction), Pat Greener and Lisa Cheung (Document Composition) who contributed to the production of this guidebook.

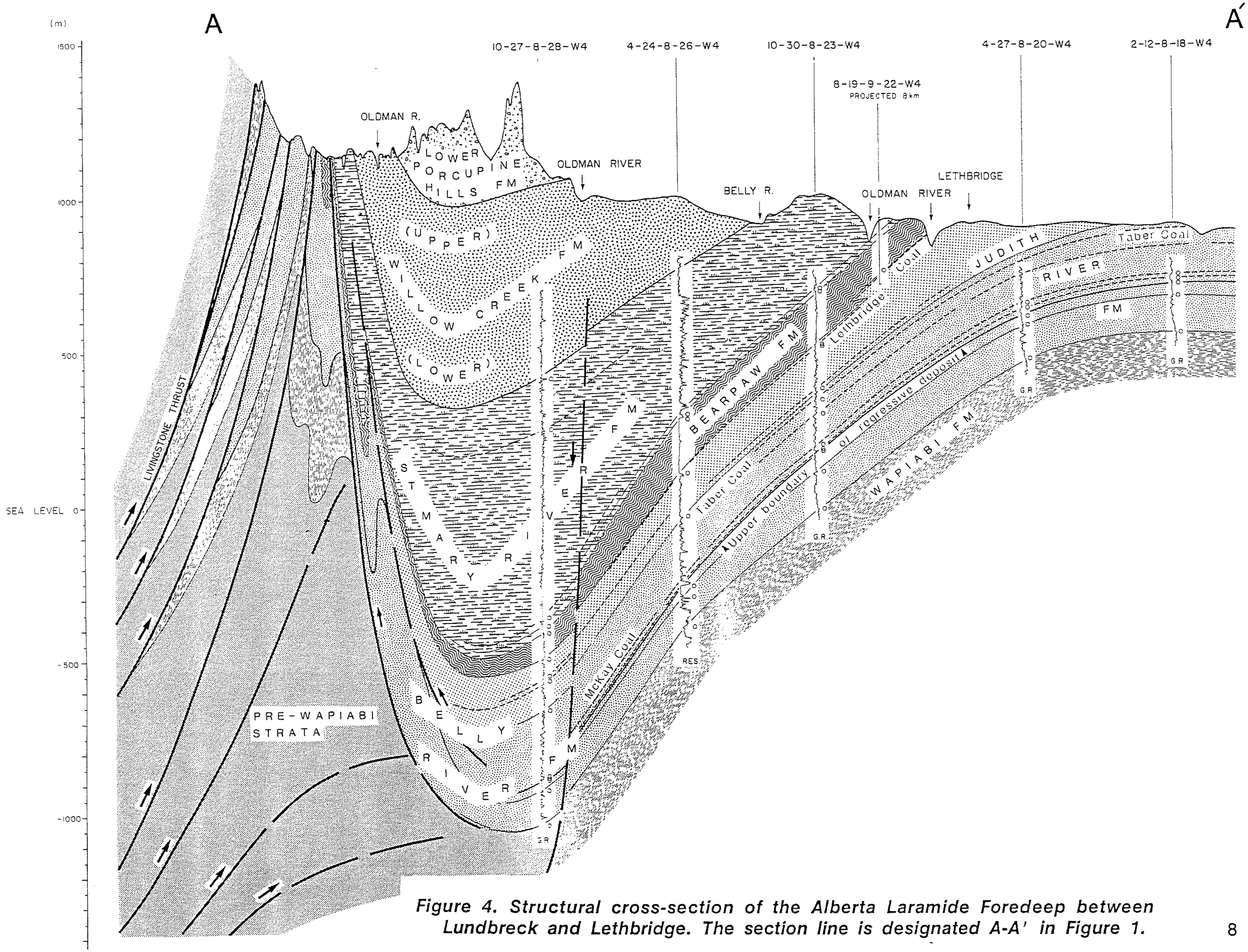


Figure 4. Structural cross-section of the Alberta Laramide Foredeep between Lundbreck and Lethbridge. The section line is designated A-A′ in Figure 1.

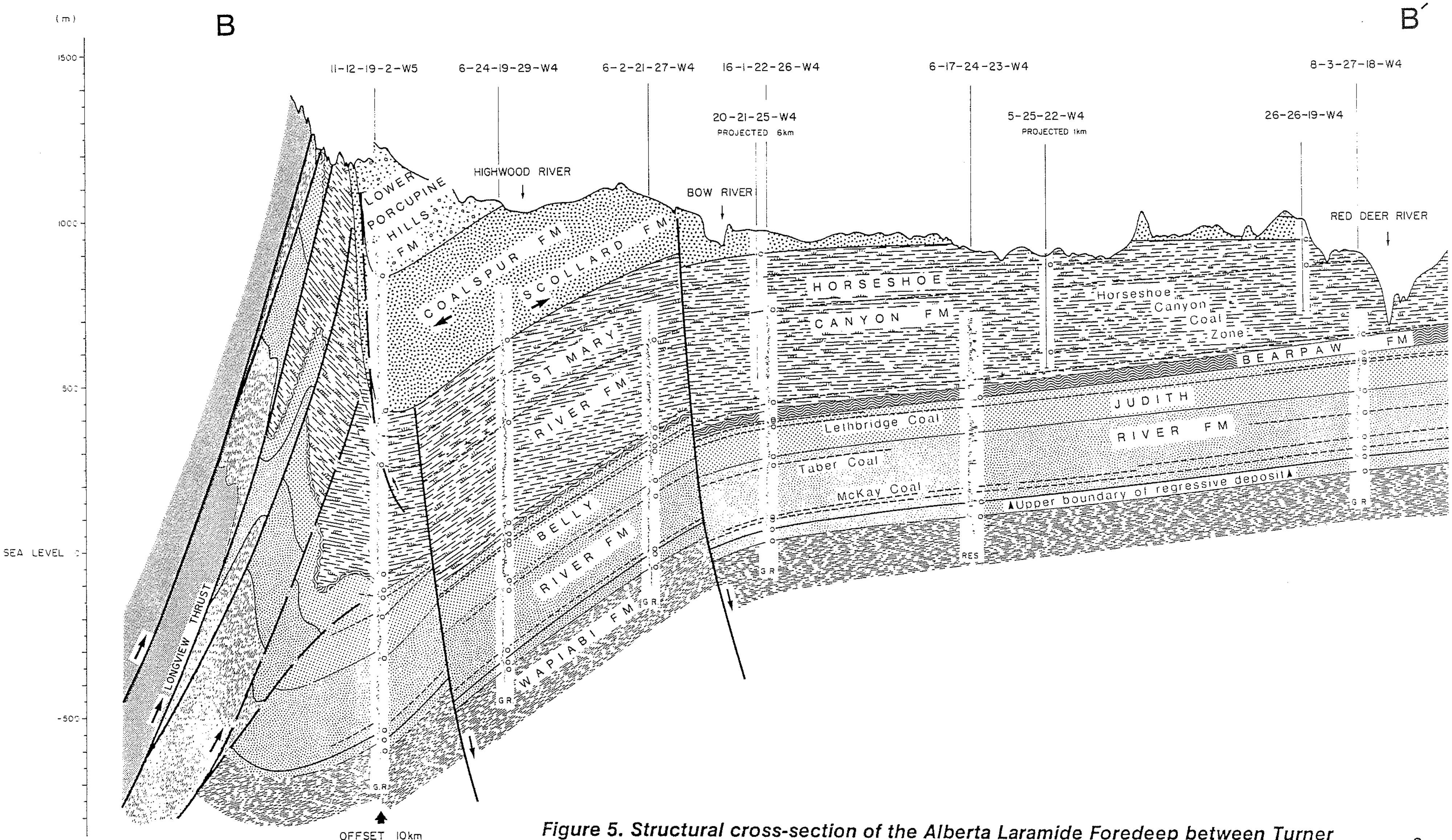


Figure 5. Structural cross-section of the Alberta Laramide Foredeep between Turner Valley and Red Deer Valley near Drumheller. The section line is designated B-B′, in Figure 1.

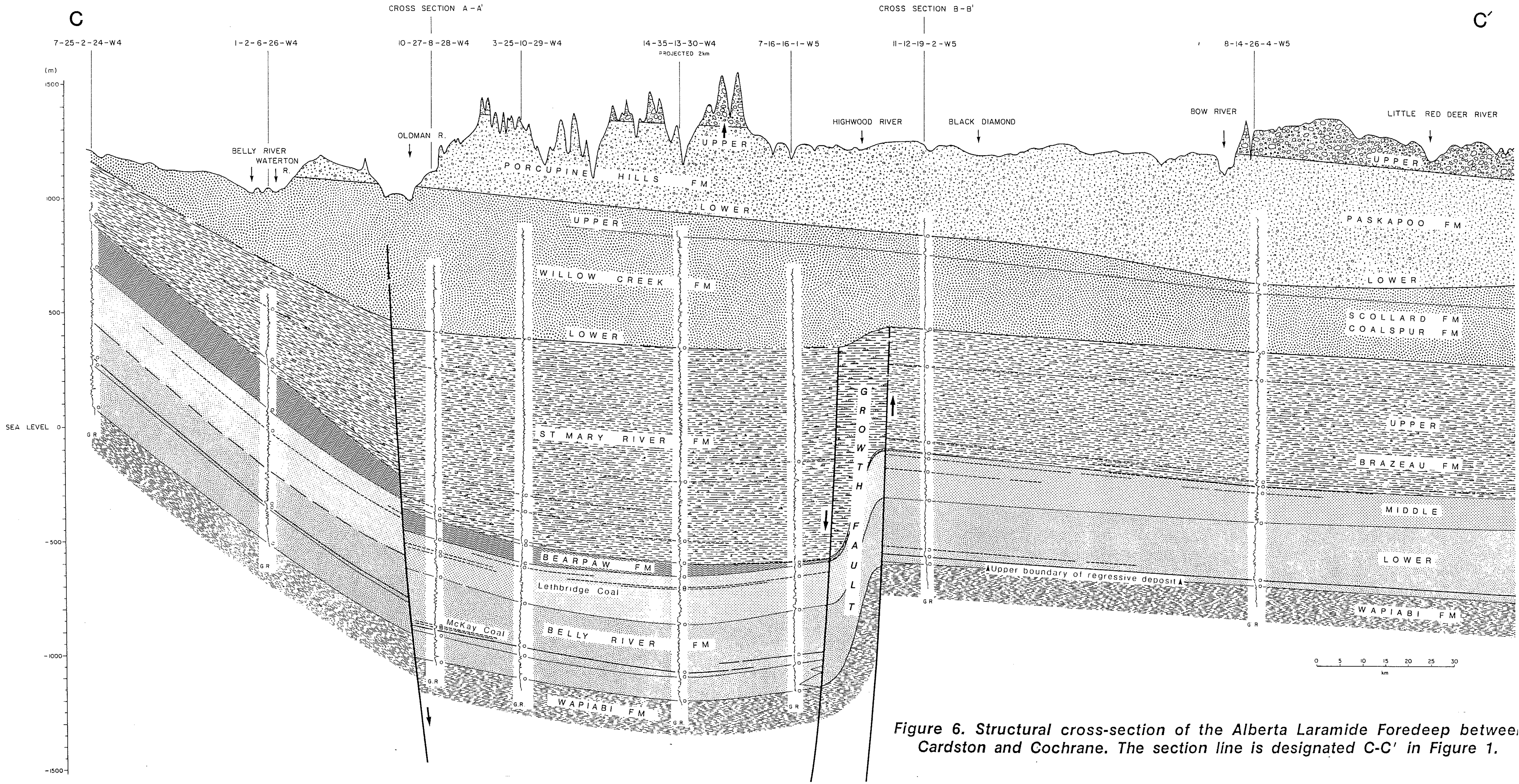


Figure 6. Structural cross-section of the Alberta Laramide Foredeep between Cardston and Cochrane. The section line is designated C-C′ in Figure 1.

II. FIELD TRIP ITINERARY

The route and stops of the field trip are shown on Fig. 1.

DAY 1

Foredeep transect between the Triangle Zone at Longview and the eastern limb of the Alberta Syncline at the Highwood-Bow rivers confluence

Itinerary: Calgary - Turner Valley via Highways 2 and 22 (**Stop 1.** Viewpoint in Turner Valley), Turner Valley - Longview (**Stop 2.** Longview bridge outcrop: St. Mary River - Bearpaw formations contact in the Triangle Zone), Longview - Carroll Canyon Ranch (**Stop 3.** St. Mary River Formation at Carroll Canyon), Carroll Canyon Ranch - Buffalo Springs Ranch via gravel road eastward in the Highwood River valley (**Stop 4.** Buffalo Springs: Porcupine Hills Formation), Buffalo Springs Ranch - Highwood/Bow rivers confluence - via Highways 2A, 2 and 552 (**Stop 5.** Scollard Formation at the Nature's Hideaway Campground) - Pincher Creek via Highway 2.

DAY 2

Parautochthonous Belly River of the Foreland Thrust Belt in the Crowsnest River valley near Lundbreck

Itinerary: Pincher Creek - Lundbreck via Highway 3 (**Stop 6.** Viewpoint for the thrust belt, Triangle Zone, and the Alberta Syncline at Lundbreck - Lundbreck Falls (**Stop 7.** Belly River Formation at Lundbreck Falls) - Lundbreck Falls - Crowsnest River cutbank 1 km northeast of Lundbreck Falls (**Stop 8.** Concretionary member of the Belly River Formation) - Lundbreck Falls - railway track transect through the Belly River of the Foothills Subprovince (**Stops 9a, 9b, 9c, 9d** and **9e**) - Fisherman's Bend 1.5 km northeast of Lundbreck via Highway 3 and gravel road down the Crowsnest River Valley (**Stop 10.** Structure of the eastern margin of the foldbelt and Bearpaw-St. Mary River formations contact) - Pincher Creek via Highway 3.

DAY 3

Autochthonous Willow Creek and Porcupine Hills formations of the Alberta Syncline

Itinerary: Pincher Creek - Cowley cemetery via Highway 3 (**Stop 11.** Red beds of the Willow Creek Formation in the Crowsnest River cutbank at the western end of the Oldman River reservoir), Cowley - Oldman River Dam Site (**Stop 12.** Geological setting of the Oldman River Dam, and **Stop 13.** Porcupine Hills Formation at the Oldman River Damsite), - Porcupine Hills Fire Lookout via Highway 785 and Beaver Creek Road - Heath Creek Road (**Stop 14.** Upper Porcupine Hills sandstone and a viewpoint for the Porcupine Hills, Livingstone Range and other more remote Front Ranges of the Rocky Mountains) - Skyline Drive (**Stop 15.** Upper Porcupine Hills Formation in the road cut and a view of the Front Ranges of the Rocky Mountains) - Calgary via Longview - Black Diamond - Okotoks (Highways 22 and 7).

III. FIELD TRIP STOPS DESCRIPTION

DAY 1

Foredeep transect between the Triangle Zone at Longview and the eastern limb of the Alberta Syncline at the confluence of Highwood and Bow rivers

Stop 1. Turner Valley viewpoint and history of exploration

The Turner Valley structure has attracted the attention of geologists since the pioneering work of R.G. McConnell more than a century ago. The original discovery of hydrocarbons here was based upon gas seeps on Sheep Creek in the core of a surface anticline. The first commercial gas production was in 1913 from Lower Cretaceous (Blairmore) sandstones near the crest of the anticline. In 1924 gas-naptha was discovered in the underlying Mississippian section and extensive exploration of the gas cap ensued. In 1930 oil was encountered downdip from the gas cap.

In a regional cross-section, Bally et al. (1966) and Jones (1982) correctly interpreted the Turner Valley structure as a Triangle Zone adjacent to the Alberta Syncline. They indicated, moreover, that the Turner Valley sole fault terminated within the east flank of the zone rather than cut the Holocene surface. Recent detailed mapping, integrated with abundant seismic and well data (MacKay, 1991), has revealed that the Turner Valley structure is really an antiformal stack of thrust plates comprising the Triangle Zone at the leading edge of the Disturbed Belt. According to MacKay (ibidem), the upper detachment is a smooth, east-dipping listric fault that soles out within the autochthonous Belly River Formation of the Plains. It is our view that this upper detachment is within the autochthonous St. Mary River Formation rather than within the Belly River Formation as suggested by MacKay (ibidem). The lower detachment surface cuts upsection toward the east and meets the upper detachment within the St. Mary River Formation. These surfaces form the upper and lower boundaries of the allochthonous wedge that makes up the Turner Valley structure.

Stop 2. Triangle Zone at the Longview Bridge

Exposures of the Triangle Zone at the Longview bridge are ideal to introduce participants of this field excursion to the Laramide Foredeep and the structural style superposed on it by orogenesis in the Late Cretaceous and early Tertiary. The sedimentary succession of the Western Canada Sedimentary Basin is, broadly speaking, a composite, north-trending triangular prism, thickest in the west and tapering to zero along the edge of the Canadian Shield. The prism is constructed of two temporally and genetically distinct sedimentary wedges, a lower and relatively older infrawedge comprisng rocks up to Late Jurassic in age and a higher and younger supra-wedge comprising the remainder of the prism (Norris and Bally, 1972). The major difference between the two wedges is that the infrawedge, resting on the Precambrian basement, is built of platform and shelf deposits shed primarily from easterly sources and prograded westward into an ancestral ocean. The suprawedge, on the other hand, comprises rocks shed primarily from tectonically uplifted areas to the west and prograded eastward into an interior sea.

The Laramide Foredeep, which is the focus of this field excursion, is the exogeocline of the Laramide Orogeny. Oblique compression of the western margin of the ancestral North American Plate resulted in horizontal shortening, vertical thickening and downbuckling of the prism as the deformation front migrated northeastward across the ancestral craton, thereby systematically tectonizing it. The foredeep created in front (east) of the deformation served to trap the sediments shed from the thickening and isostatically uplifting hinterland, thereby recording in one location or another the complete stratigraphic record of Laramide orogenesis. It is apparent, however, that the loading by the eastward-advancing thrust sheets and the sediment filling were insufficient to maintain the existence of the foredeep (Bally and Snelson, 1980) as it was deluged with lighter, unconsolidated clastic debris. Persistent plate convergence and compression were doubtless major factors in maintaining the foredeep during orogenesis.

A prequisite of a Triangle Zone is the presence of an upper, regional detachment into which successive major, blind thrust faults merge as the deformation front migrates in the direction of the foreland (Jones, 1987). The upper detachment(s) for the eastern Cordillera verges westward and, because of the sense of shear along it, associated minor faults and folds can be expected to do the same. The stratigraphic succession comprising the upper plate of the detachment is essentially autochthonous. Thrust-faulted segments of the lower plate, on the other hand, are parautochthonous in the Triangle Zone, undergoing relatively small horizontal translations in contrast with those associated with the major thrusts cutting the remainder of the prism.

The acute folds and thrust faults involving the Upper Cretaceous St. Mary River sandstones and Bearpaw shales at the Longview bridge (Fig. 8) consistently verge westwards, in harmony with their structural position in the hangingwall of the upper detachment (MacKay, 1991).

Stop 3. St. Mary River Formation at Carroll Canyon

Introduction

Structurally, the Carroll Canyon section lies on the eastern limb of the Turner Valley Anticline and/or the western limb of the Alberta Syncline, east of the Triangle Zone, some 3 km south-east from the Longview bridge (Fig. 7). The continuous section of the Carroll Canyon, which is the main subject of our visit to the area lies a few hundred metres down river from the farm buildings but the lower member of the St. Mary River Formation crops out near the farm buildings (brief stop). Here, the oyster bed of the lower member of the formation is exposed in the core of the Turner Valley Anticline. The bulk of the St. Mary River Formation is visible in the steep banks of the river where the strata dip 30° east.

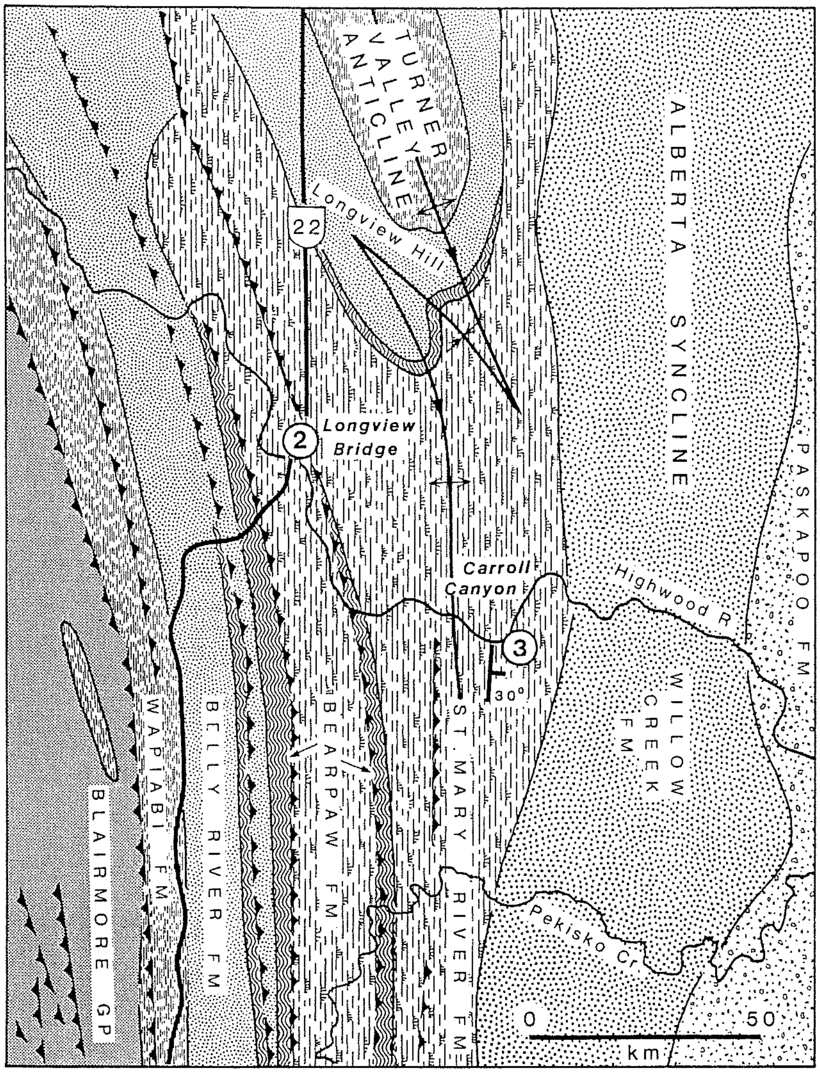


Figure 7. Geological sketch-map of the Longview area. Geology based on Hume (1931, 1949) and Jerzykiewicz (unpublished data).

The St. Mary River Formation in the Turner Valley area was initially mapped as Edmonton Formation (Hume, 1931), and subsequently identified and mapped as the St. Mary River Formation by Hume (1949), and described on the Highwood River by Tozer (1956). Following the definition of the formation by Dawson (1883), its lower boundary is placed at the base of the first prominent sandstone above the marine Bearpaw shale, and the upper at the top of the mudstone, immediately below cliff forming, prominent channel sandstone of the Willow Creek Formation (Fig. 9).

Following the stratigraphic subdivision of the St. Mary River Formation in other areas along the Foothills (Hage, 1943; Douglas, 1950, 1951; Williams, 1949), the

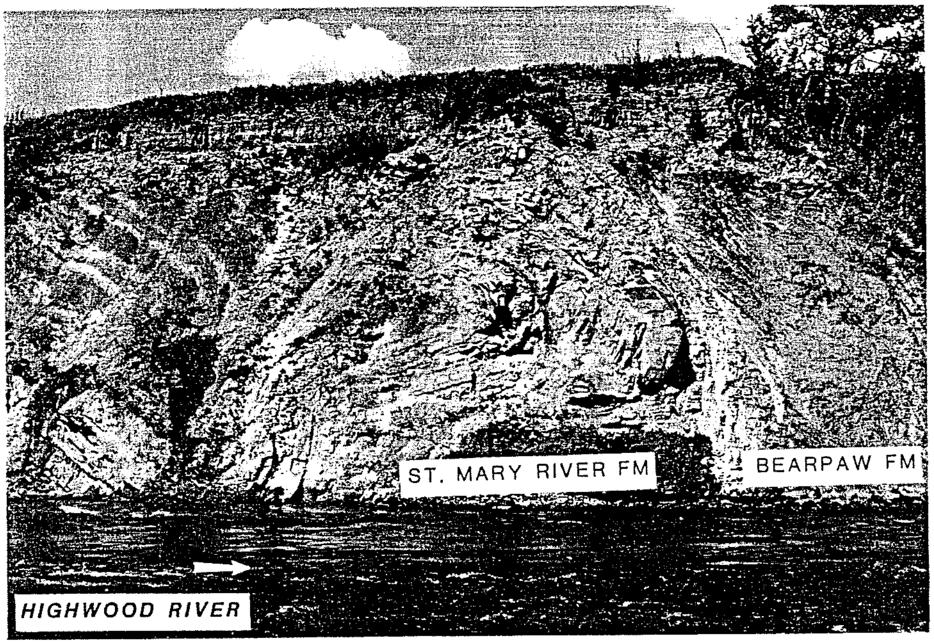


Figure 8. Faulted and folded contact between the Bearpaw and St. Mary River formations at the bridge over Highwood River at Longview.

formation on Highwood River is herewith also subdivided into two members. The basal (brackish) member, up to 100 m thick, consists of fine- to medium-grained flaser- and wavy-bedded, rusty weathering sandstone, coquinoid limestone, siltstones, organic-rich mudstone, coaly shale and/or thin coal beds. The upper (fresh-water to terrestrial) member of the formation is up to 600 m thick, and consists of nonmarine facies, largely mudstone, siltstone and fine-to-medium grained sandstone. Some very thin coal beds and limestones are also found.

Fauna

The basal member of the St. Mary River formation contains brackish and fresh-water faunas. The following species have been identified: *Ostrea glabra* Meek and Hayden, *Anomia gryphorhynchus* Meek, *A. perstrigosa* Whiteaves, *Corbicula cleburini* White, *Plesielliptio* sp. indet., *Viviparus mokowanensis* sp. nov., *Lioplacodes limnaeformis* Meek and Hayden, *Lioplacodes* sp. indet., *''Melania'' wyomingensis* Meek, *Goniobasis webbi* Dryer (Tozer, 1956). Interpretation of this mixed assemblage composed of brackish and fresh-water species may be twofold. Either the common occurrence of fresh-water species (e.g. *Viviparus mokowanensis* Tozer) with the brackish species (e.g. *Corbula*) is a result of the adaptation of usually fresh-water animals to somewhat brackish-water conditions (Tozer, 1956), or the mixed assemblage is a result of redeposition.

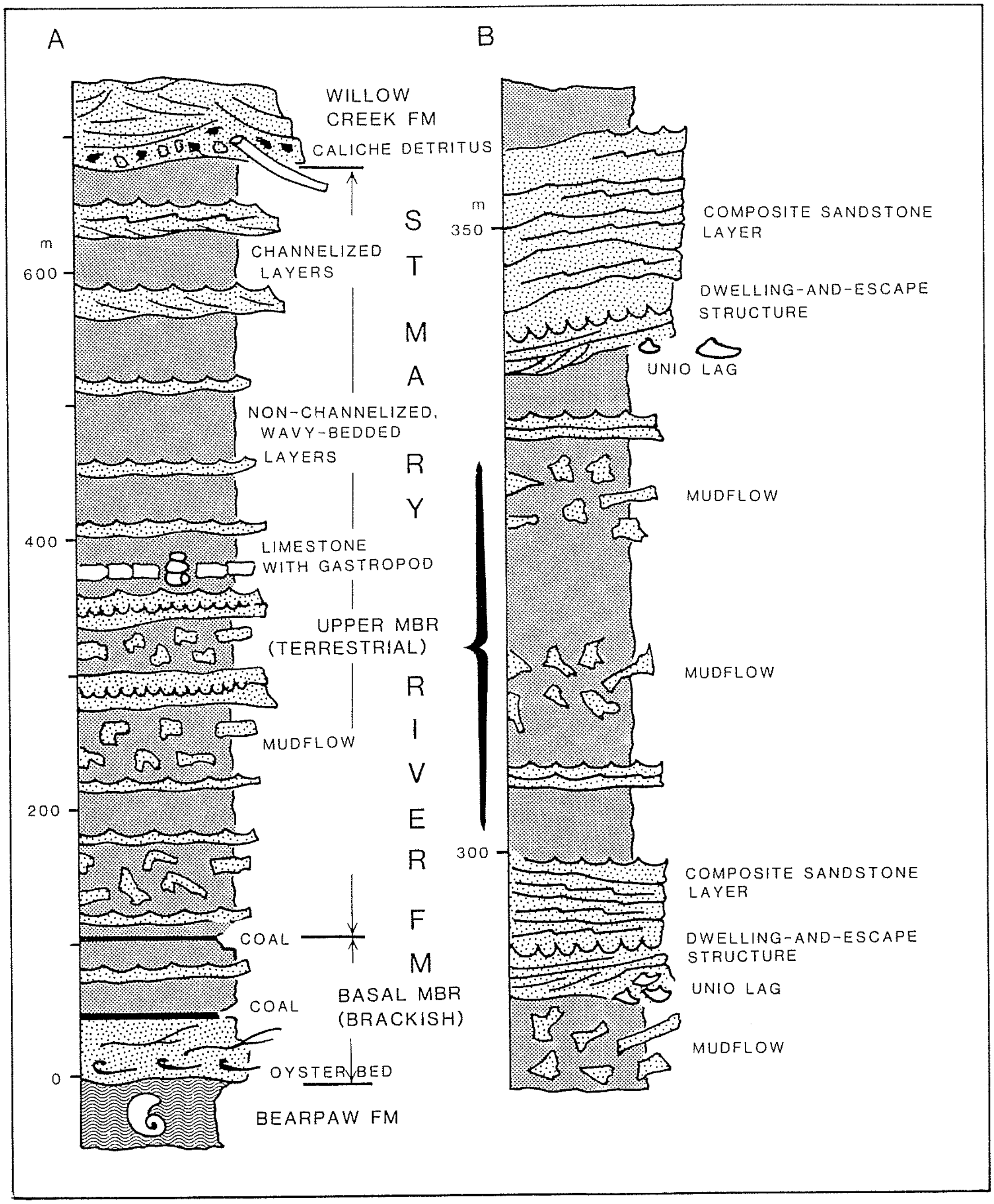


Figure 9. Stratigraphic columns of the St. Mary River Formation exposed on Highwood River in the vicinity of Longview.

A. *A standard composite stratigraphic column of the formation exposed in the Carroll Canyon Ranch area.*

B. *A fragment of the upper, freshwater to terrestrial member of the formation containing a mudflow deposit and dwelling-and-escape structures.*

The upper member of the St. Mary River Formation contains both fresh-water and terrestrial faunas described from the Highwood River section by Tozer (1956). Many samples have been checked for micropaleontology in order to establish the stratigraphic range of the marine influences in the section. According to J.H. Wall (written communication, 1988), no marine microfossils have been recovered from the Higwood River section above the second thin coal bed some 100 m above the oyster layer (Fig. 9), thus these strata are considered as non-marine. This is consistent with micro-paleontological data from other Bearpaw–St. Mary River transitions of the southern Foothills (J.H. Wall, written communication, 1988). The fresh-water and terrestrial faunas from the upper member of the St. Mary River Formation contain several species of molluscs and six species of terrestrial gastropods (Tozer, 1956, Table I). They may represent a wide range of environments from the pond, paludal, through fluviatile and littoral-lacustrine to sublittoral-lacustrine settings (Hanley, 1976). Most of the faunas belong to thin-walled species and the mudrock in which they were found are of pond and/or paludal origin. Thick-walled unionid bivalves of fluviatile association (Hanley, 1976) are represented abundantly in the sandstones of the St. Mary River Formation by *Unio stantoni* White (Fig. 10).

Sedimentology

Sedimentologically, the Carroll Canyon section can be viewed as a succession of mudrock interbedded by thickening upward sheet-like sandstone layers. The sandstone layers are laterally continuous and nonchannelized in the lower part of the section. In the middle part of the Carroll Canyon escarpment, the sandstone layers are vertically stacked forming composite layers that are internally subdivided by extensive erosional surfaces. Some of these erosional surfaces possess a concave shape of very broad and shallow channels (Fig. 11). The sharply based sandstone sheets in the lower, mudstone dominated part of the section are largely fine-grained, horizontal-to-low-angle cross-stratified and/or ripple-to-wavy bedded. Individual sheets usually show a simple coarsening upward trend from fine- to medium-grained sand but some layers also possess thin bottom lag deposits containing abundant unionid shell detritus (Fig. 9). Such layers show thin graded interval above the lower erosional surface and the coarsening trend in the rest of the layer. The vertically stacked, broadly channelized sandstone layers of the middle part of the section are slightly coarser in their lowermost part. Their basal parts contain lag deposits, composed of large usually broken but sometimes whole shells of unionid bivalves (Fig. 10B), and medium grained cross-bedded sandstone. The basal part of the composite layers is thin and the bulk of composite layers consist of fine, horizontal-to-low-angle cross-stratified and/or ripple-to-wavy bedded sandstone.

Mudstone, which is volumetrically the predominant lithology of the formation, especially in the lower part of the Carroll Canyon section, appears largely structureless although some mudstone intervals show a structure characteristic

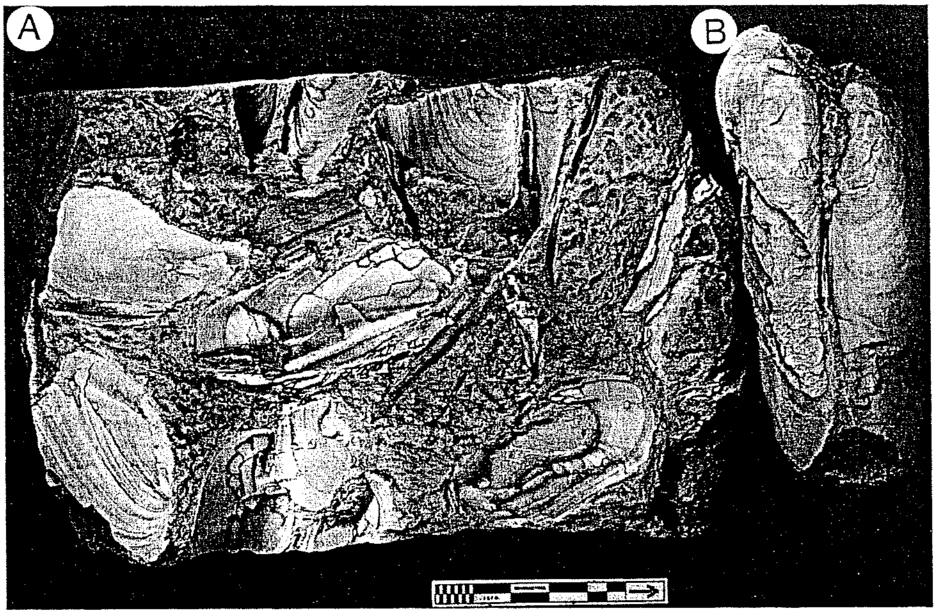


Figure 10.** Unio stantoni **White. Carroll Canyon section, Highwood River.

***A.** Redeposited shells at base of a composite sandstone layer derived from the place indicated by the arrow in Figure 11A.*

***B.** A complete shell of* Unio stantoni *White.*

of debris flow deposits (Figs. 11, 12). These mudstones contain poorly sorted and subangular to subrounded fragments of intraformational sandstone and siltstone. The size of the individual clasts ranges from pebbles to blocks up to .5 m in diameter, or even larger fragments of transported layers of local derivation. The clasts may be rather densely packed in the mudstone matrix or may "float" individually within the supporting muddy matrix. These debris flow layers may be described in terms of mudflow i.e. a mud-supported variety of debris flow. The term mudflow is herewith used after Sharp and Nobles (1953, p. 550): ". . . mudflow is simply a variety of debris flow in which mud, although not necessarily quantitatively predominant, endows the mass with specific properties and modes of behaviors which distinguish it from flows of debris devoid of mud". Surging flows of muddy debris are common on the surface of alluvial fans after rapid melting of deep winter snow and/or after a major flood event (Blackwelder, 1928; Sharp and Nobles, op. cit., Curry, 1966).

The layers of mudflow origin are found in three different mudstone intervals of the Carroll Canyon section (Fig. 9). The upper mudflow interval is associated with composite sandstone layers of the middle part of the section. A sharp contact between the mudflow and the overlying fine-grained, ripple-drift sandstone layer indicates a rather sudden change in the depositional regime from viscous, subaerial sedimentation into subaqueous rhythmic transport of fine-grained, well sorted sand. This change can be attributed to a change from debris flow conditions to a stream flow regime as the debris flows are often followed and partly eroded by flood water (Blackwelder, 1928; Sharp and Nobles, 1953).

The lower surfaces of some sandstone beds are covered with bulbous-shaped burrows of benthonic organisms (Fig. 13A). The burrows are arranged in closely spaced patterns and may cover large surfaces (Fig. 13B). In the Carroll Canyon section the bulbous burrows are found at several stratigraphic horizons. Perhaps the best examples are preserved in the composite sandstone layers in the middle part of the section. There, the burrows can be traced along the internal erosional boundaries of the sandstone beds over a distance of several metres. Limited size of the outcrop precludes the possibility of the assessment of the full size of the structure i.e. the size of the sediment surface primarily covered by the communities of benthonic organisms. From the fragments of the sandstone soles available for examination in situ, and from the size of the slumped blocks covered with the bulbous burrows, it appears that the size and density of the animal population must have been large. The shape and size of discrete burrows corresponds closely to a shell of large fresh-water unionid bivalves. Of three, similar in size and shape, species identified in the St. Mary River and Edmonton formations by Tozer (1956), namely: *Unio stantoni* White, *Unio sandersoni* Warren, and *Plesielliptio* sp. (Tozer, *op. cit.*, Pl. I, figs. 1, 2 and 5), the *Unio stantoni* is most likely the generator of the bulbous burrows because only its shells are abundant in sandstone and mudstone of the Carroll Canyon section (Fig. 10).

The thick-walled unionid bivalve of the *Plesielliptio* association are characteristic of flowing-water habitats (McMichael and Hiscock, 1958). The straight to slightly sinuate ventral shell margin suggests a habitat in relatively swift water in small streams or rivers (Eagar, 1948). The unionid bivalve of *Plesielliptio* association in the Eocene lacustrine and fluviatile Green River and Wasatch formations of Wyoming, Colorado and Utah occupied a river or stream habitat in the lowland adjacent to a lake (Hanley, 1976). According to Hanley (*op. cit.*, p. 250) unionids require fresh, clean, oxygenated, shallow, calcium-rich, permanent water habitats containing a current, pH greater than 7, stable substrate, food source, and at least seasonally warm temperatures. The modern faunal analogue is found in many streams in Virginia, which are characterized by a low-diversity, high-abundance fluviatile molluscan association dominated by *Elliptio complanatus* (Lighfoot), (Hanley, 1976). Modern unionids lack siphons and consequently are shallow burrowers with about a half to a third of the shell length exposed above the sediment/water interface (Trueman, 1968; Thoms and Berg, 1985). In life, these animals show a preferred orientation with the sagittal plane of the shell parallel to current flow and the exhalent area of the shell margin on the downstream side of the inhalent area to avoid recycling of expended

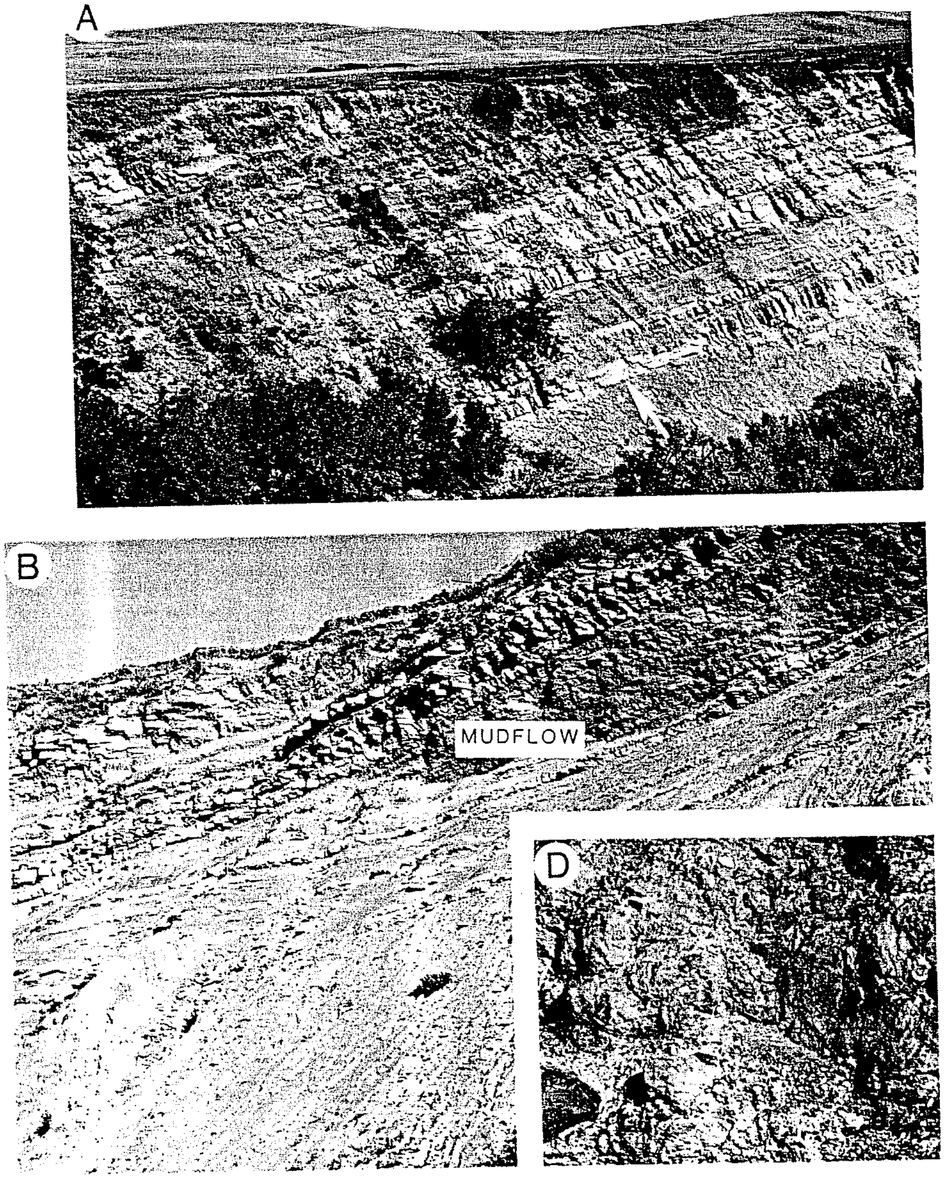
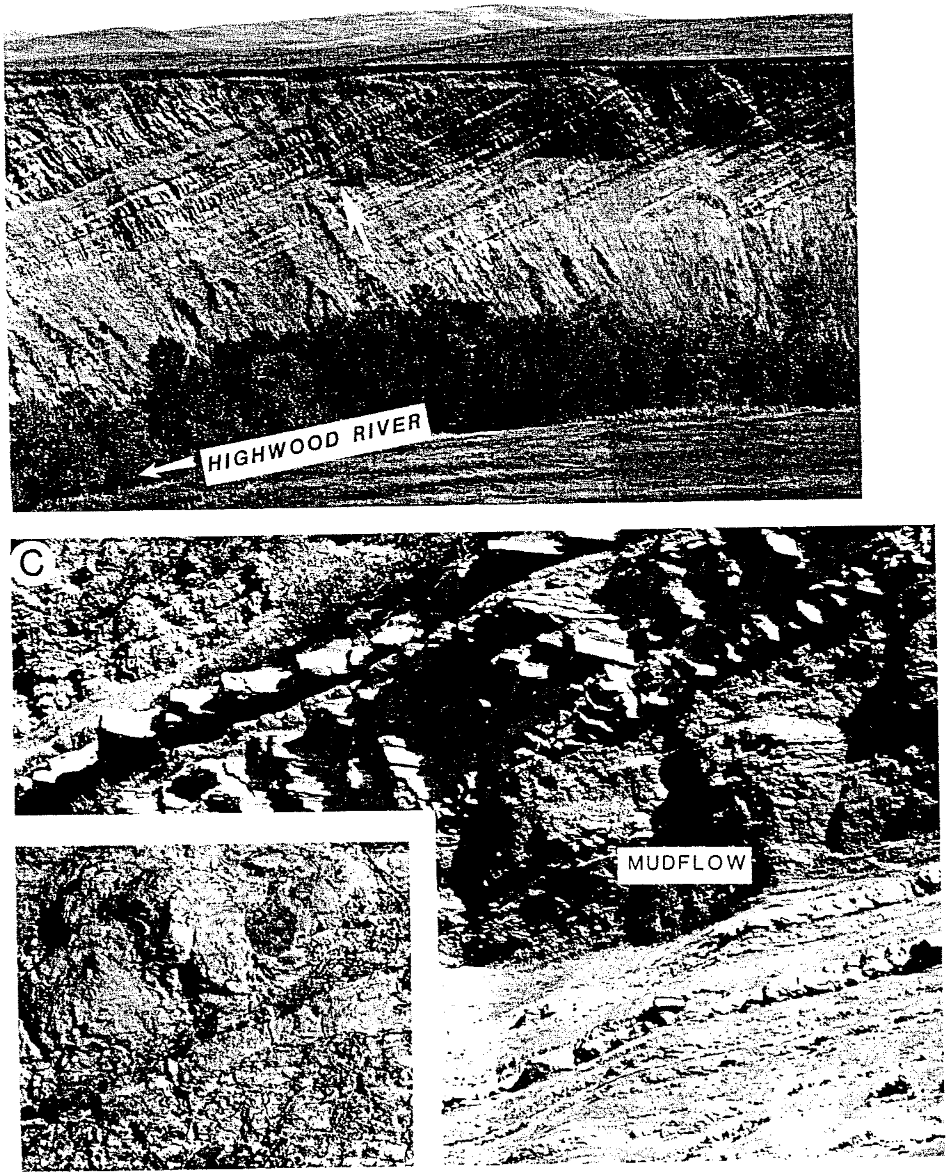


Figure 11. Carroll Canyon Section.

- ***A.*** *General view of the Carroll Canyon section. The mudflow deposits are indicated by arrows.*
- ***B.*** *Upper part of the Carroll Canyon section.*
- ***C.*** *Close up view of the mudflow layer.*
- ***D.*** *The mudflow layer.*



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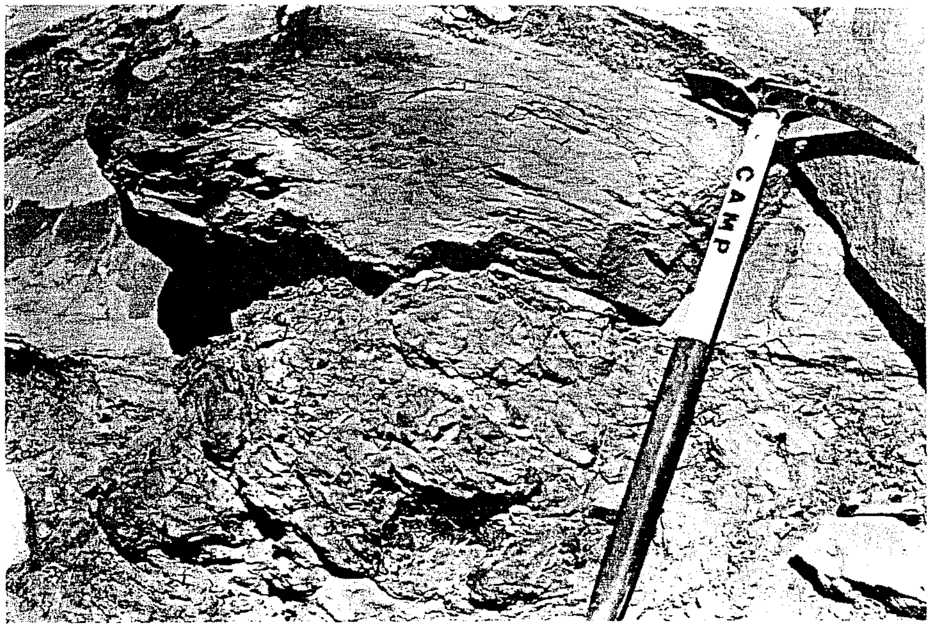


Figure 12. Mudflow overlain by fine-grained, ripple-bedded sandstone of stream flow origin. Carroll Canyon section.

water. Experiments with living unionids show that inundation by sediment prompts an upward escape response achieved by downward thrusts of the foot (Thoms and Berg, 1985). Laminae-filled escape shafts were described for both marine and nonmarine bivalves (Berg, 1973, 1977; Eagar, 1974, 1978; Thoms and Berg, 1974, 1985; Kranz, 1974; Howard, 1975; Hardy and Broadhurst, 1978; Bridges et al., 1986).

Bulbous-shape burrows similar to the St. Mary River examples were described by Koster et al. (1987) from the Judith River Formation of the Dinosaur Provincial Park in the Alberta Plains and interpreted as domichnia (dwelling structures) and the laminae-filled shafts as fugichnia (escape structures) of unionids.

The interpretation of the bulbous-shaped burrows from the St. Mary River sandstone in terms of "dwelling-and-escape" structure is shown in Figure 14.

The upper part of the Highwood River section above the limestone layer contains thin-walled gastropods (Fig. 9) and consists of mudstone interbedded with fine-grained, wavy-bedded sandstone (Fig. 15). In the uppermost part of the St. Mary River Formation, below the erosional contact with the Willow Creek Formation, the sandstone layers change character. The sheet-like layers characteristic of most of the formation are gradually replaced by channelized, compound layers of medium- to coarse-grained sandstone. Their lower parts show features of fluvial channels, i.e. erosional bases, lag deposits, and

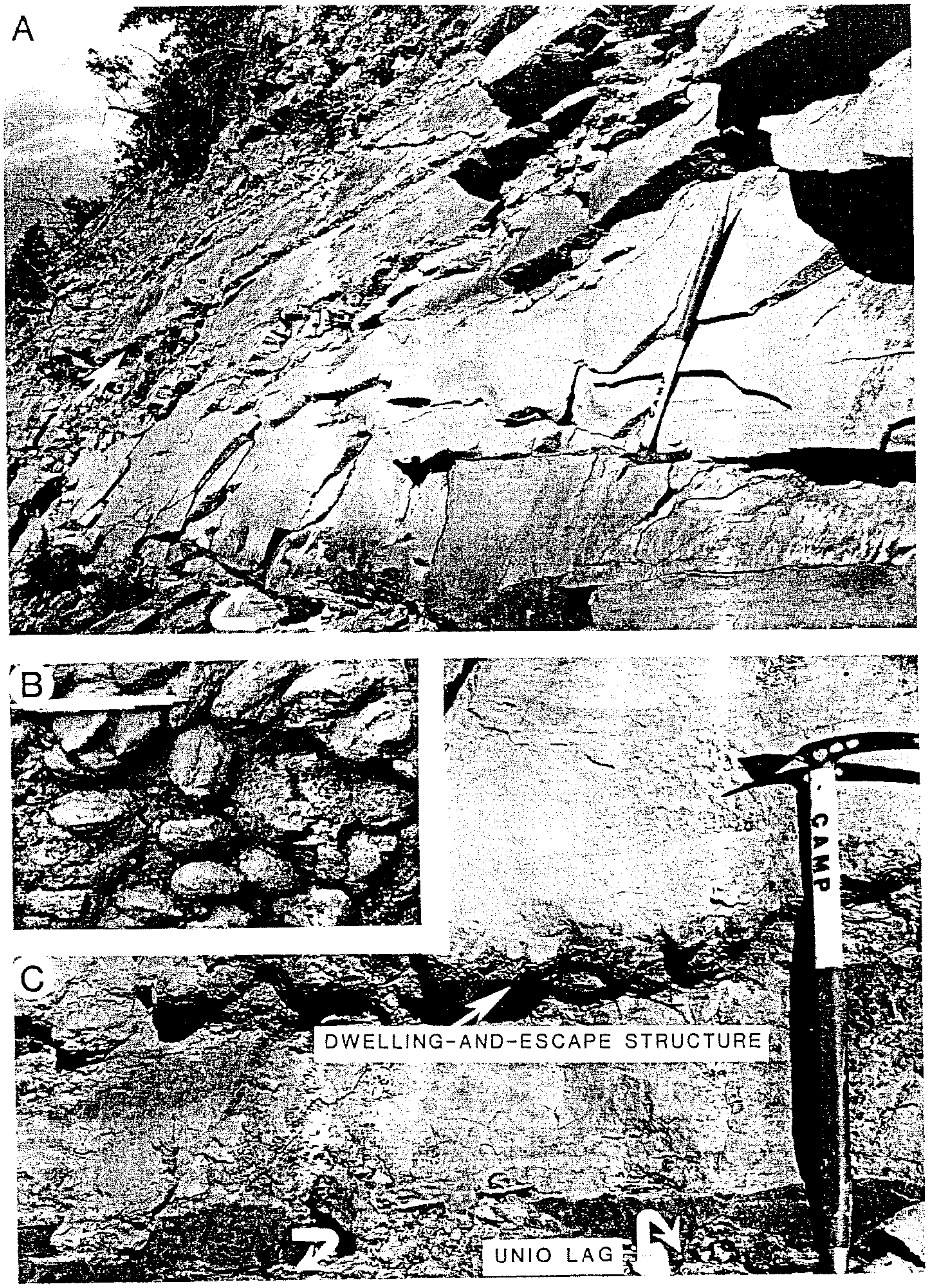


Figure 13. Composite sandstone layers with bulbous-shaped burrows (dwelling-and-escape structures) of unionid bivalves. Carroll Canyon section.

- *A.* *Composite sandstone layer. The straight arrow indicates the position of the dwelling-and-escape structures, the bent arrow points to the Unio lag deposit.*
- *B.* *Dwelling-and-escape structures preserved as a closely spaced pattern of moulds in the sandstone block.*
- *C.* *Close-up view of dwelling-and-escape structures at the sole of an interbed surface of the composite sandstone layer, and of a Unio lag deposit.*

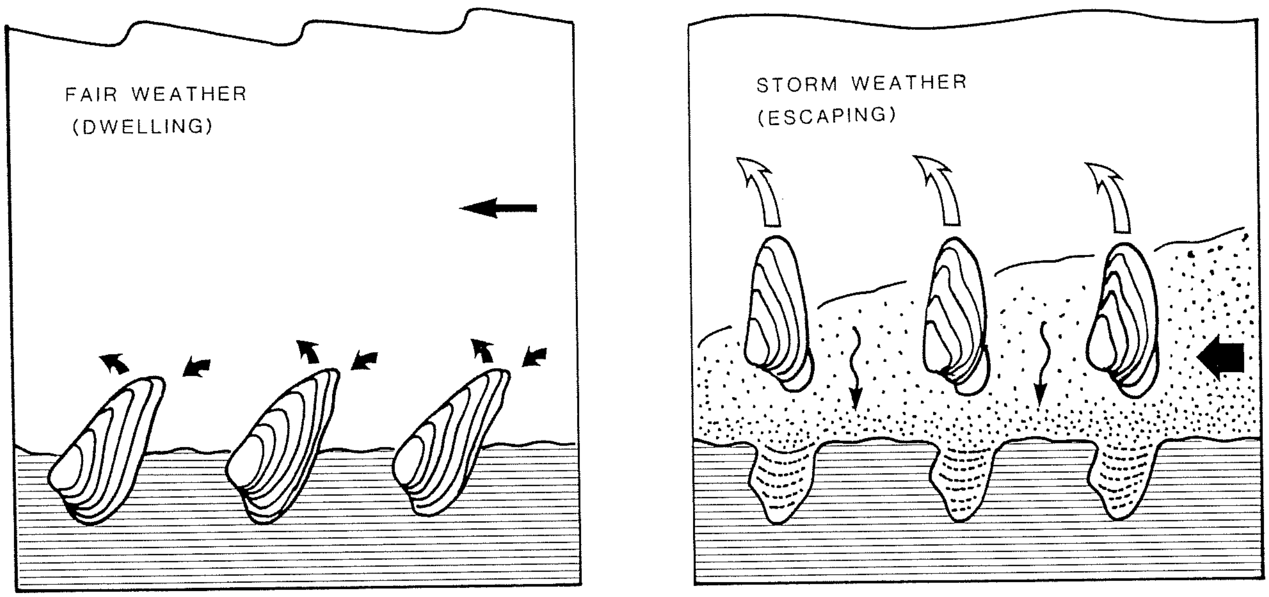


Figure 14. A hypothetical origin of dwelling-and-escape structures in sandstone of the St. Mary River Formation.

A. Community of unionid bivalves living in a flowing water environment during fair-weather. Large arrow indicates the direction of flow; small arrows indicate inhalent and exhalent currents.

B. A storm-induced cloud of detritus prompting the unioids to escape upward through inundating sediment leaving burrows.

large-scale crossbedding; the upper parts are fine-grained and have wave-ripple lamination. These compound layers may represent a distributary-channel/ distributary-mouth-bar transition (Jerzykiewicz, 1991). The upper, wavy-bedded, fine-grained portions of these compound layers were deposited in the wave-dominated nearshore zone of a lake or pond. Similar facies are known from many ancient lakes, as reviewed by Allen and Collinson (*in* Reading, 1986).

Sedimentary Environment

The entire Highwood River section above the open marine Bearpaw shale should be interpreted in terms of the transition from muddy coastal plain into fluvial dominated environment of the lower Willow Creek Formation (Fig. 9).

The succession of facies and sedimentary structures found in the Carroll Canyon section allows for the following interpretation of events. The regressing Bearpaw Sea left in the area a muddy coastal plain with brackish lagoons, ponds and swamps. These mud-dominated environments were initially periodically connected with the sea and episodically were invaded by sand- and shell-laden storm surges (sandstone and oyster shell layers of the lower, brackish part of the St. Mary River Formation). Shallow, muddy ponds and poorly drained swamps dominated the landscape of the early nonmarine sedimentation of the St. Mary River Formation. Rare siltstone and fine-grained sandstone beds were brought into this environment by flood waters. The growing influence of episodic flood events in the area was probably caused by the emerging landmass to the west. Mudflow deposits followed by lobes of sandstones characterize the encroachment of alluvial fans into the environment. Periods of flood events were marked on the fringes of the alluvial fans by mud flows followed by stream flow sandstone marking a waning condition of flow. The distal alluvial fan area was drained into a pond or shallow lake by fluviatile channels. Periods of fair-weather must have had to be maintained over prolonged periods of time since communities of unionids were able to inhabit large areas of sandy shoals near the channel mouths. Clouds of sediments were brought into the environment during episodic flood events, forcing unioids to escape or redepositing their shells as lag deposits at the base of channels.

Sedimentation of the St. Mary Formation in the periphery of an alluvial fan prograding into a lake or series of ponds was probably related to a fault escarpment (thrust?). Rapid thickness changes of the St. Mary River Formation along Highwood River and elsewhere along the Foothills, support the fault controlled alluvial fan model (Heward, 1978) for the St. Mary River. The rapid increase in formation thickness south of the Highwood River, marked in Figure 6 as the growth fault zone, may be genetically related to deposition of the alluvial fans. Weimer and Land (1975) described growth faulting in analogous stratigraphic positions in the Denver Basin. These growth faults which locally are responsible for an increase in thickness of up to 200 feet in the lower Laramie sandstone, appear to have been controlled by recurrent movements of

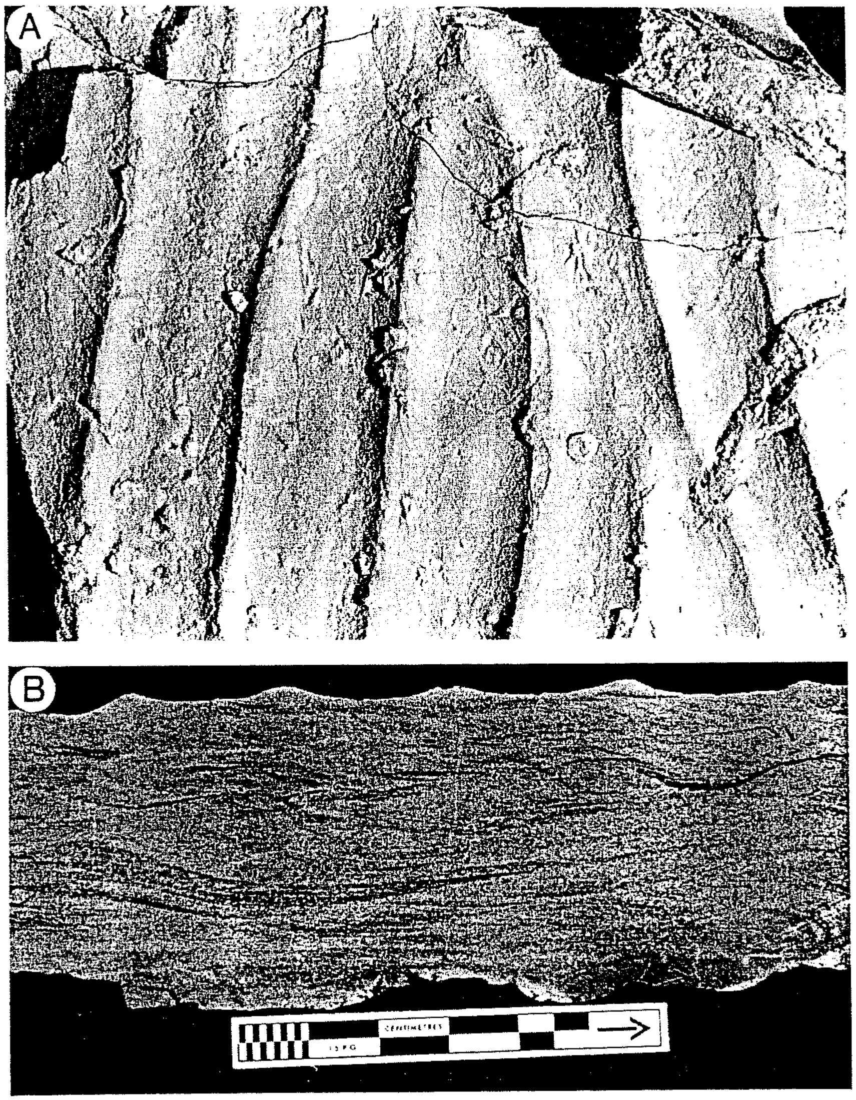


Figure 15. Ripple marks and related wavy-bedding in the St. Mary River sandstone of the Carroll Canyon section.

A. Wave ripple marks. B. Wavy bedding.

deep-seated faults in the Precambrian Basement (Weimer and Land, op. cit.).

Stop 4. Porcupine Hills Formation at Buffalo Springs

The outrop lies some 10 km northwest of High River by the Buffalo Springs farm buildings where a little coulee joins Tongue Creek valley. A group of sandstone hoodoos is visible from the access road to the farm (Fig. 16A), but the entire section is exposed nearby along the Buffalo Springs coulee (Fig. 16B). Structurally, the subhorizontal layers of the Porcupine Hills sandstone, which form the cliff over the Buffalo Springs coulee, lie on the eastern limb of the Alberta Syncline some 10 km east of its axis (Fig. 1).

The bulk of the outcrop is formed by resistant, coarse-to-medium grained, crossbedded, channelized sandstone layers. These layers form the upper part of a laterally persistent, composite sandstone body embedded in the mudstone of the lower Porcupine Hills Formation. This upper (up to 7 m thick) part of the sandstone body consists of vertically stacked, largely trough crossbedded channel sandstone layers. At the base of individual crossbedded units are erosional surfaces and channel lag deposits containing caliche debris. Some layers are structureless and/or subhorizontally- to low-angle bedded. An example of vertically stacked sandstone layers showing upward change in stratification is shown in Figure 17A. Subhorizontally- to low-angle bedded sandstone deposited by high-energy currents is overlain by low-energy, steep-angle bedded channel sandstone.

The lower part of the sandstone body and the boundary with the underlying mudstone is best seen in the coulee (Fig. 16B). The entire section is exposed as are the soles of beds and some diagnostic sedimentary structures. The lower boundary of the sandstone body at the contact with mudstone is an uneven, sharp erosional surface. This surface is covered with sole markings indicating erosion of the muddy bottom by sediment-laden current flow. Both tool marks and scour marks were identified. The most common are groove moulds, striations and flute moulds (Fig. 16D). The groove moulds and striations vary in width from a few mm to several cm. No objects responsible for the production of markings were found in the extension of the grooves and striations. However, the form of the moulds indicates that the objects responsible for their formation might have been twigs and other plant remains carried by sediment-laden current. Mudstone fragments and mollusc shells were also among small objects dragged by the current on the muddy bottom as indicated by fragments of shells found on the surface covered with the flute moulds. Flute marks have been ascribed to the action of vortices on the muddy floor in the strongly turbulent zone near the point of discharge of the turbidity current (Dzulynski and Walton, 1965). Essentially they are produced by the current itself (without an object or tool moving with the current), and belong to scour marks (Dzulynski and Sanders, 1959, 1962). The production of flute marks, however, is significantly facilitated by the presence of small objects in the

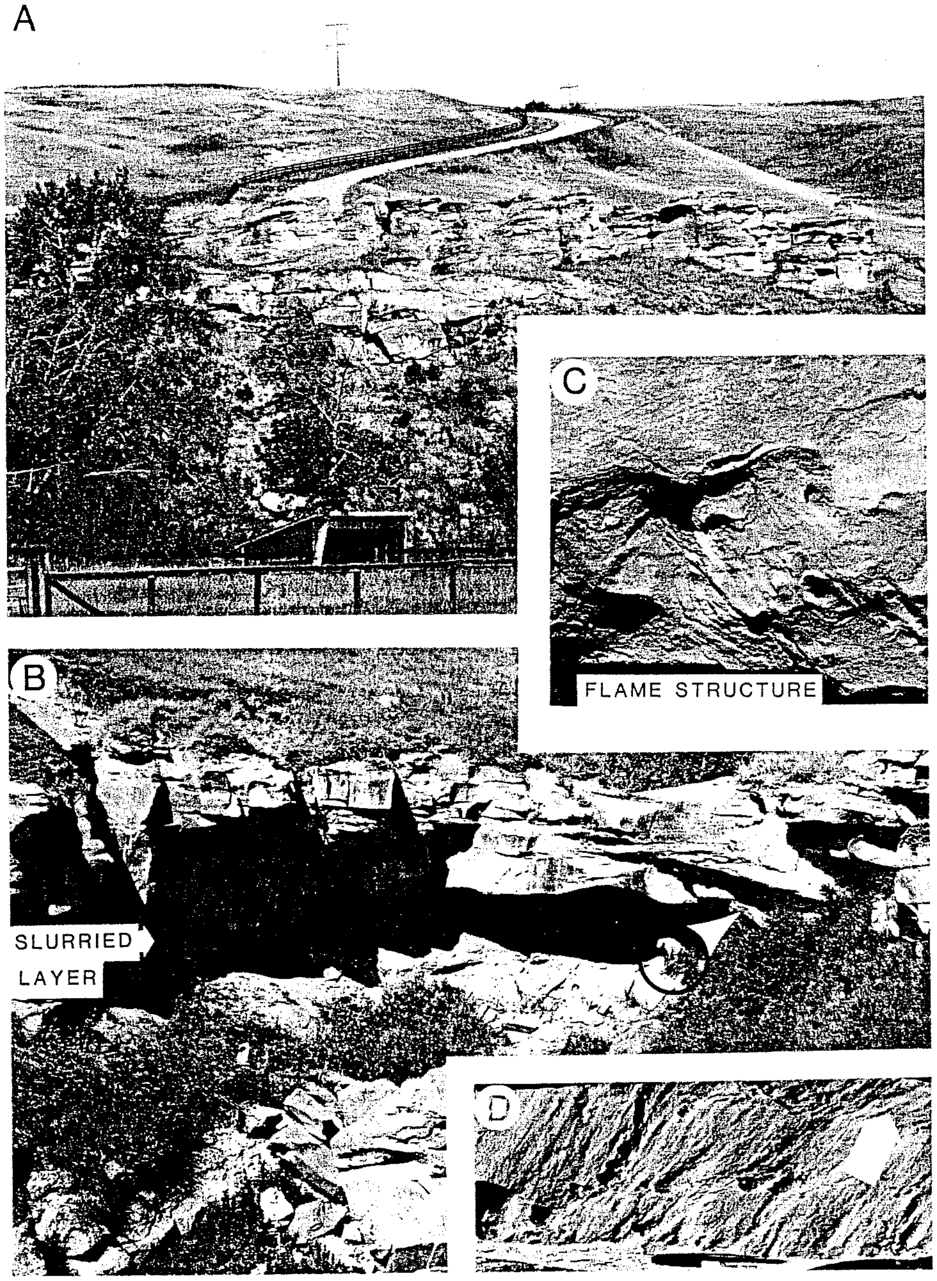


Figure 16. Sand body of the lower Porcupine Hills Formation at the Buffalo Springs locality.

- *A. Buffalo Springs hoodoos viewed from the access road to the farm.*
- *B. Sandstone cliff over the Buffalo Springs coulee. The arrow over the circled man indicates the location of the flame structure shown in detail in the inset (Fig. 15C).*
- *C. Flame structure resulting from penecontemporaneous liquefaction of sand. Note the right angle of the "flames" with the crossbedding in the overlying sandstone bed.*
- *D. Flute moulds on the sole of a sandstone bed. Current direction indicated by the large arrow.*

current. Fragments of shells in the current, for example, may increase the potential for vortices to occur and hence increase the chances for creation of flutes. The forms shown in Figure 16D, were produced by sediment-laden currents carrying small fragments of gastropod shell found in the extension of the flute moulds.

Deposition of the lower part of the Buffalo Springs sand body by high-energy sediment-laden flow is confirmed by other sedimentary structures. The basal sandstone bed immediately above the erosional lower boundary of the sandstone body (Fig. 17A), is graded to sub-horizontally bedded and was deposited by high energy flood-waters. The basal sandstone passes upward into a disturbed, slurried layer which consists of muddy and sandy material (Figs. 17B, 18). This layer consists of sandstone and mudstone fragments which appear to be displaced from their original position. The outlines of the displaced fragments vary from sharp through gradational to diffuse. The mudstone fragments show signs of soft sediment deformation indicating early stages of fragmentation of partially consolidated sediment. Large fragments of sandstone show sub-conformable stratification throughout the disturbed layer which indicates that they were not transported over any significant distance. The displacement of most fragments excavated from the floor must have been minimal.

Another example of soft sediment deformation is visible in the northwestern-most part of the outcrop (Figs. 16B, 16C, 18). Here, large-scale soft sediment deformation is developed in a sandstone layer directly overlying the disturbed layer. A three-dimensional view of this feature shows a large-scale flame structure resulting from penecontemporanous liquifaction of sand. The flame penetrates the overlying sandstone forming a right angle with the stratification (Figs. 16C, 18).

The lower part of the sand body exposed in the Buffalo Springs locality is interpreted as a deposit of a major flood event into the alluvial plain environment in early Porcupine Hills time. Initial sediment-laden, high-energy flood waters produced a wide erosional surface and deposited a graded and horizontal to low-angle-inclined layer of sandstone. Subsequent impact of the sediment-laden flood waters produced a disturbed, slurried layer and large scale bedding disturbances (flame structure). The sedimentation gradually changed from torrential sheet flood type of wide lateral extent to in-channel fair-weather braid-plain (upper part of the Buffalo Springs sandstone).

There is a tendency in the recent geoscientific literature to link the turbidites and other sediment-laden flow deposits with a marine environment. Although marine turbidites are certainly the most often described from ancient sedimentary environments, turbidites were first discovered in modern lakes. Sediment-laden flood waters may possess properties of turbidity currents. It has been proven experimentally that turbidity currents can maintain their density once the sediment-laden flow is no longer laterally confined (Dzulynski and Walton, 1963). The motion of sediment-laden, turbid flood waters in any

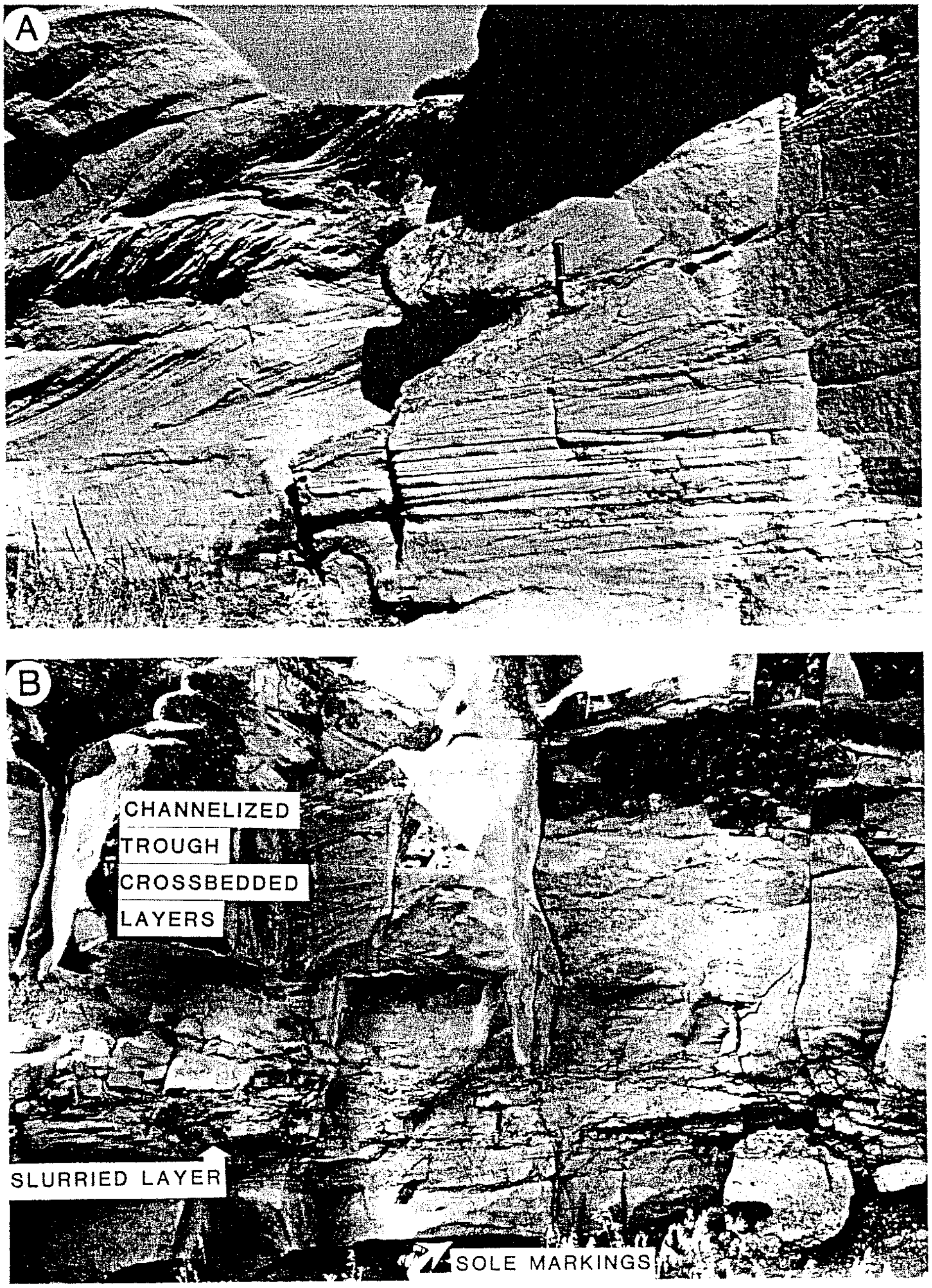


Figure 17. Stratification types of the Buffalo Springs sandstone body (lower Porcupine Hills Formation).

- ***A.*** *Sub-horizontal to cross-stratified upper part of the sandstone body.*
- ***B.*** *Slurried, graded to low-angle stratified, and crossbedded layers of the lower part of the sandstone body.*

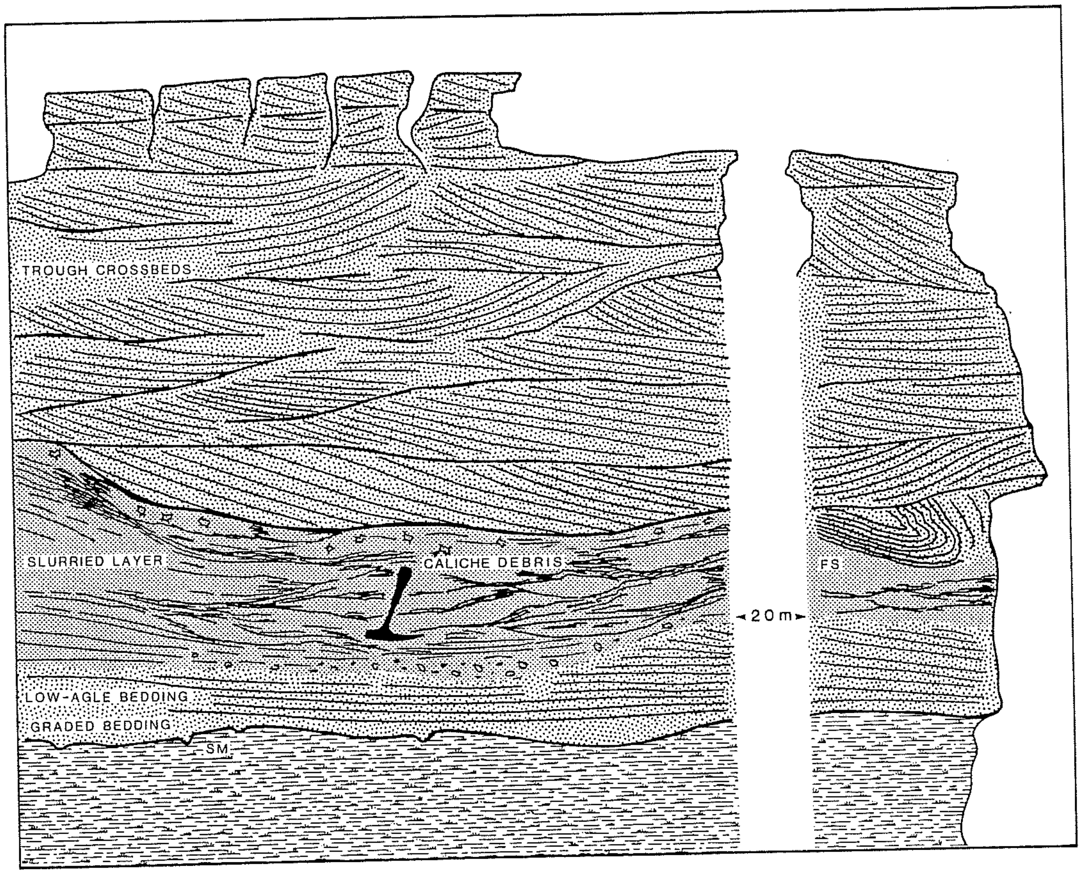


Figure 18. Sketch of the Buffalo Springs outcrop. Note the sole markings (SM) at base of the sandstone, and the flame structure (FS) above the disturbed-slurried layer.

reservoir of water, including shallow lakes and ponds, may produce sole markings and other sedimentary structure described most often from marine turbidites. The sole markings and stratification of the lower (usually graded) parts of layers deposited from sediment-laden currents, however, are not diagnostic of any particular sedimentary environment. The difference between "deep water" turbidite layers (known best from "flysch facies"), and shallow water marine and continental deposits, is detectable usually in the uppermost portion of the unit only. The "deep water" turbidites (i.e. deposited below wave base) possess a gradational upper transition into the indigenous pelagic sediments (transition between the Bouma's intervals Td and Te), as opposed to shallow water turbidites where the upper contact is sharp. The top surfaces of these shallow-water turbidites display features characteristic of shallow-water or even subaerial environmental conditions. The hydraulic properties of sediment-laden flows may be used to explain not only shelf and deep marine sediments but also the features of some very shallow-water and alluvial plain pond and lake deposits (Dzulynski and Walton, 1963).

The lower part of the Buffalo Springs sand body is interpreted in terms of a large magnitude, perhaps cataclysmic, flood event. Sediment-laden turbid, unchannelized flood water deposited the lowermost, graded and low-angle bedded layer and the overlying slurried bed. The slurried bed was apparently deformed by a subsequent surge of sediment-laden flood water shortly after its deposition and before sedimentation of the upper, channelized part of the Buffalo Springs sand body. Similar slurried beds and bedding disturbances were produced experimentally by the impact of heavy suspension flow upon the underlying sediment (Dzulynski and Radomski, 1966).

Paleocurrent readings indicate north-easterly flowing currents during the sedimentation of the Buffalo Springs sand body. The readings were taken on sole markings at the base of the sandstone body, and on trough crossbedding of the upper part of it. Although in both cases the direction of flow was northeasterly, there was a discrepancy of about 30°. The mean azimuth of the axis of the large-scale trough crossbeds was 24°, indicating the direction of braided channels towards NNE, whereas the direction of groove and flute marks shows a more easterly preferred azimuth with the mean at 56°. The sediment-laden flood waters must have come almost directly from the montainous regions located to the southwest from the area of deposition.

Stop 5. Scollard Formation at Nature's Hideaway Campground

Mudstone interbedded with siltstone and thin sandstone layers crops out in a west-facing cutbank of Highwood River about 1 km south of the confluence with the Bow River (Fig. 19). The strata dip westward at a very low angle i.e. towards the axis of the Alberta Syncline located some 35 km to the west. The section lies approximately 70 m below a coarse-grained, resistant sandstone layer several

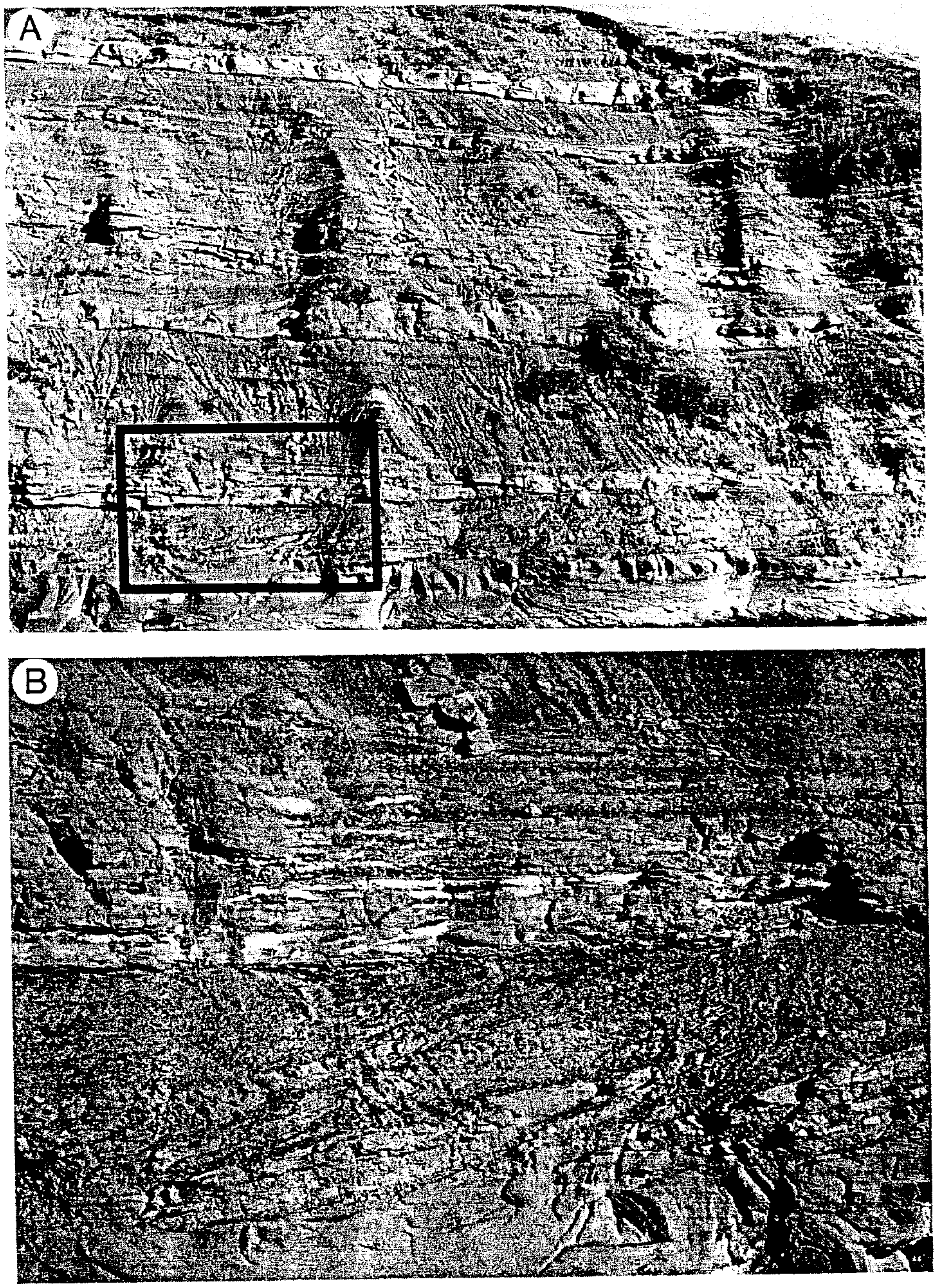


Figure 19. Inclined heterolithic stratification of the Scollard Formation at the Nature's Hideaway Campground near the Bow/Highwood rivers confluence.

- *A.* *Western part of the Highwood River cutbank.*
- *B.* *A fragment of the lower part of the outcrop framed in Figure 19A.*

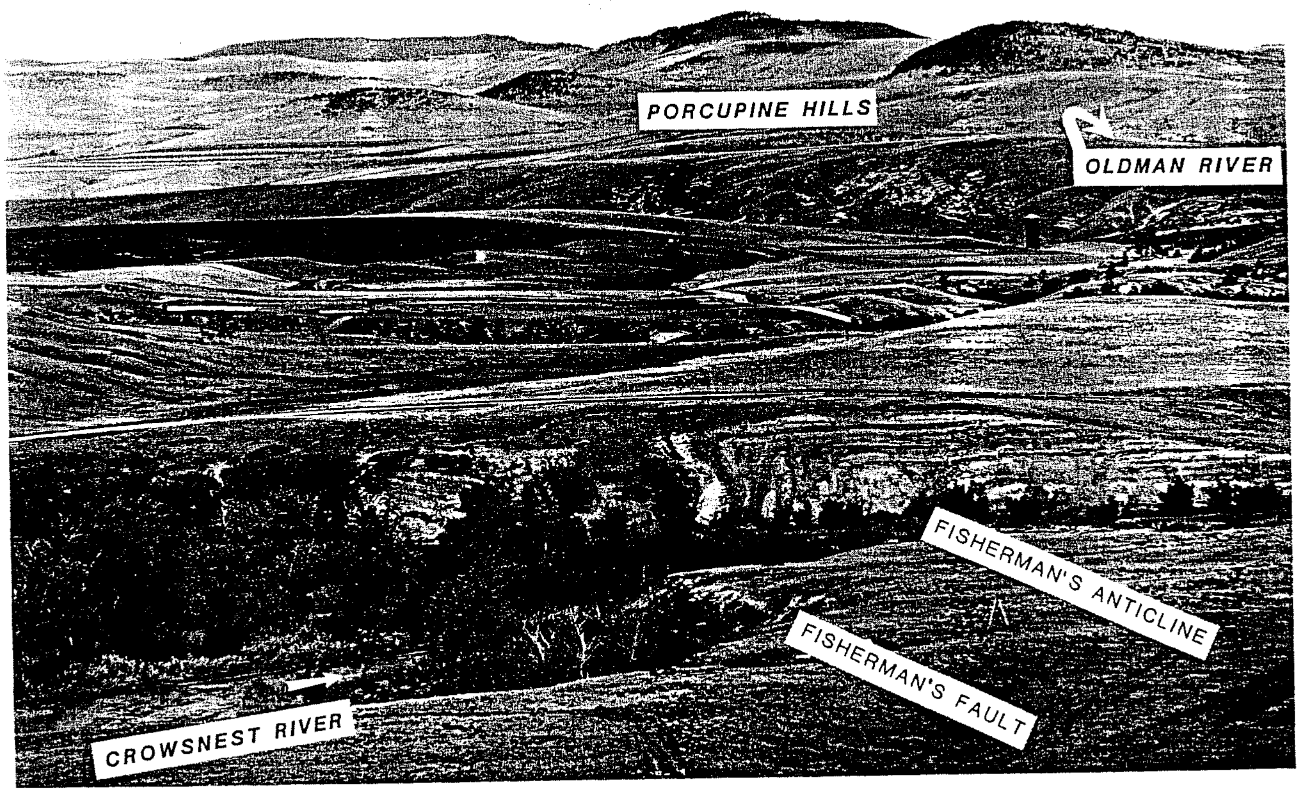


Figure 20. Crowsnest River valley viewed from Highway No. 3 at Lundbreck towards northeast.

metres thick that marks the base of Porcupine Hills Formation in the area (Fig. 5). It is, therefore, in the stratigraphic position of upper Willow Creek, upper Coalspur, and upper Scollard formations of lowermost Paleocene age (Fig. 2). These stratigraphically correlative formations possess a characteristic facies development in the type area. The section along the Bow River, however, is located far from this area and the lithology can be considered as intermediate between that of the coal-bearing upper Scollard (or its Foothills correlative, upper Coalspur), and the upper Willow Creek Formation of the southern part of the basin (Jerzykiewicz and Sweet, 1988) where it is virtually barren of coal. The presence of thin coal beds in the section and the position of the section east of the axis of the Alberta Syncline led us to include it in the Scollard Formation (Gibson, 1977).

The section consists of four sandstone-based fining upward cycles (Fig. 19A). The most conspicuous sedimentological feature is the inclined heterolithic stratification (Thomas et al., 1987). It embraces almost the whole thickness of the individual cycle. The lower boundary of each cycle is an erosional surface of a sandstone unit. The inclined stratification commonly begins immediately above this boundary and extends into the middle and upper part of each cycle (Fig. 19B). The middle parts of the cycles contain inclined interbeds of very fine-grained sandstone, siltstone and mudstone. The upper parts contain subhorizontal layers of siltstone and mudstone and occasionally thin beds of coaly shale and coal (Fig. 19A). The section is interpreted in terms of point bar sedimentation as small channels of mixed and suspended-load meandering streams draining a muddy, alluvial plain.

DAY 2

Parautochthonous Belly River Formation in the Crowsnest River valley near Lundbreck

Stop 6. Foldbelt and Foredeep at Lundbreck

From Lundbreck is a spectacular view giving us a regional appreciation of the tectonic setting of the Laramide Foredeep and the Foreland Thrust Belt. Northeast of us are forested hogbacks (c.f. porcupines?) of the Porcupine Hills Formation. The strata comprising them dip gently eastward on the west flank of the Alberta Syncline. Between the Porcupine Hills and the high line of peaks of the Livingstone Range are the Foothills, a band of imbricated and folded Mesozoic rocks separating the North American Craton from the Front Ranges of the Rocky Mountains, and extending northward in Canada from the 49th to the 60th Parallels.

Lundbreck is located near the eastern edge of the Foothills, a few km west of the apex of the Triangle Zone (Gordy et al., 1977). The reversal in dip of beds from east to west, marking the surface trace of this zone, is evident below us on the banks of the Crowsnest River. Westward across the Foothills, resistant, discontinuous sandstone members of the Upper Cretaceous Belly River Formation delineate folds and west-dipping thrust faults repeating the stratigraphic

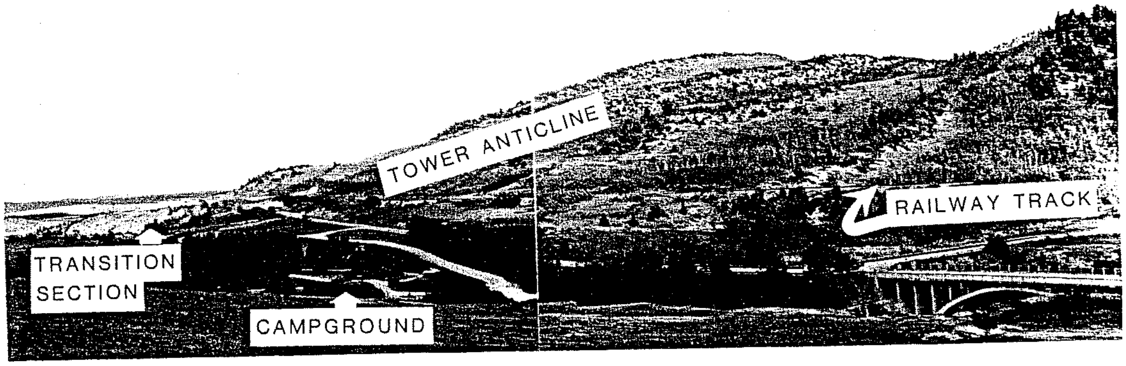


Figure 21. Crowsnest River valley in the vicinity of Lundbreck Falls viewed from northwest.

succession of the Laramide Foredeep. These repetitions will become abundantly evident as we examine successive fault blocks of Belly River strata in this area.

The Upper Cretaceous rocks north and west of us are in the footwall of the Livingstone Thrust. Folds in them attracted early explorers and entrepreneurs to drill them in search of oil and gas, only to be doomed to disappointment. They discoverd that the closures were commonly underlain by folded thrust faults and that their prospective targets were at much greater depths, beyond the reach of their cable tool rigs (Gordy et al., op. cit.).

The Livingstone Range plunges southward toward the Crowsnest River as the Livingstone Thrust beneath it cuts up section to a glide surface in the Jura-Cretaceous Kootenay Group. The resistant Paleozoic succession is eliminated from the thrust plate and the foredeep is once again repeated. Beyond the range is the scar of the giant Frank Slide in Mississippian carbonates of the Turtle Mountain Plate and, in turn, the resistant crags of middle and upper Paleozoic rocks of the Lewis Thrust Plate.

Stop 7. Belly River Formation at the Lundbreck Falls

The Lundbreck Falls section of the Belly River Formation is situated some 12 km west of Pincher Creek in the scenic Crowsnest River valley (Fig. 21). The section is among sites most often visited by geologists as it represents a typical and well exposed transition from offshore marine Wapiabi (Colorado) shale through deltaic lower members of the Belly River Formation to continental Belly River strata (Lerand and Oliver, 1975; Jerzykiewicz and Norris, 1992; Jerzykiewicz and Norris, *in press*). The geological map of the Cowley area (Hage, 1943) was recently updated to show the structure around Lundbreck Falls, utilizing a new stratigraphic subdivision of the Belly River Formation into four members (Jerzykiewicz and Norris, 1992, *in press*). This new map is shown in Figure 22.

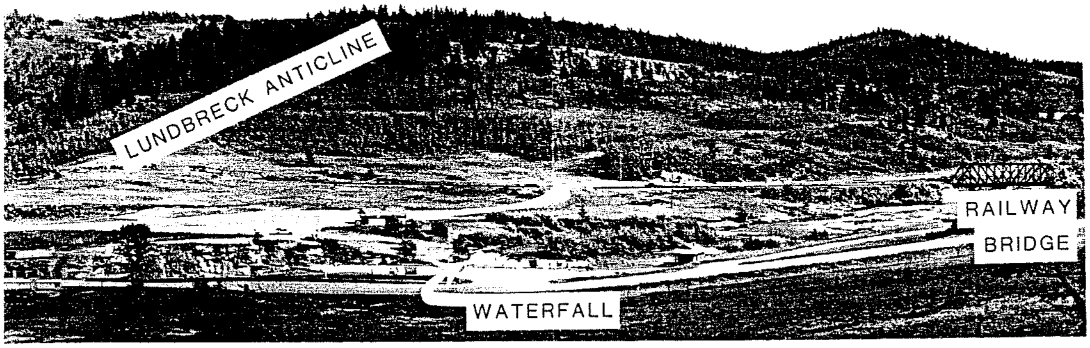


Figure 21. cont'd.

The lower boundary of the Belly River Formation on the new map remains unchanged, in concert with most other published accounts of the stratigraphy of the area (see e.g. Stott, 1963; Lerand and Oliver, 1975). Accordingly, the Lundbreck Falls transition section forms the lowermost member of the Belly River Formation (KBR Ia and KBR Ib on Fig. 22). It is the correlative of the Chungo Member of the central Foothills (Stott, 1963), and does not belong to the Chungo Member of the Wapiabi Formation as interpreted by Rosenthal and Walker (1987). The diachroneity of the Chungo Member along the Foothills and other aspects of the stratigraphy of the Wapiabi/Belly River transition were recently discussed by Sweet and Braman (1989).

The composite stratigraphic column utilized on the map (Fig. 22) is shown in Figure 25. The Transitional Member of the Belly River Formation forms a complete delta sequence that developed in response to the regression of the Wapiabi sea from the Laramide Fordeep in the lower Campanian (Lerand and Oliver, 1975; Jerzykiewicz and Norris, 1992; Jerzykiewicz and Norris, *in press*). Strata of the Belly River Delta were deposited in the Crowsnest Embayment of the Wapiabi Sea between the south and southeast trending legs of the Western Canada miogeocline. Structurally, the delta lies along the eastern margin of the Foreland Thrust and Fold Belt, where the whole of the Cordilleran Orogen east of the Rocky Mountain Trench changes strike from south to southeast (Crowsnest Deflection; Norris, 1968) (Fig. 22). The Laramide Orogeny superposed upon the delta a family of thrust faults and buckle folds that contracted, thickened and repeated the delta succession, allowing access to its several members. In the vicinity of Crowsnest River, where exposures are optimal, the deformed delta can be restored palinspastically to its pre-Laramide configuration within the supracrustal wedge. Horizontal shortening there is on the order of 40%, and the allochthonous part of the delta beneath the Lewis Thrust Plate has been displaced eastward some 70 km relative

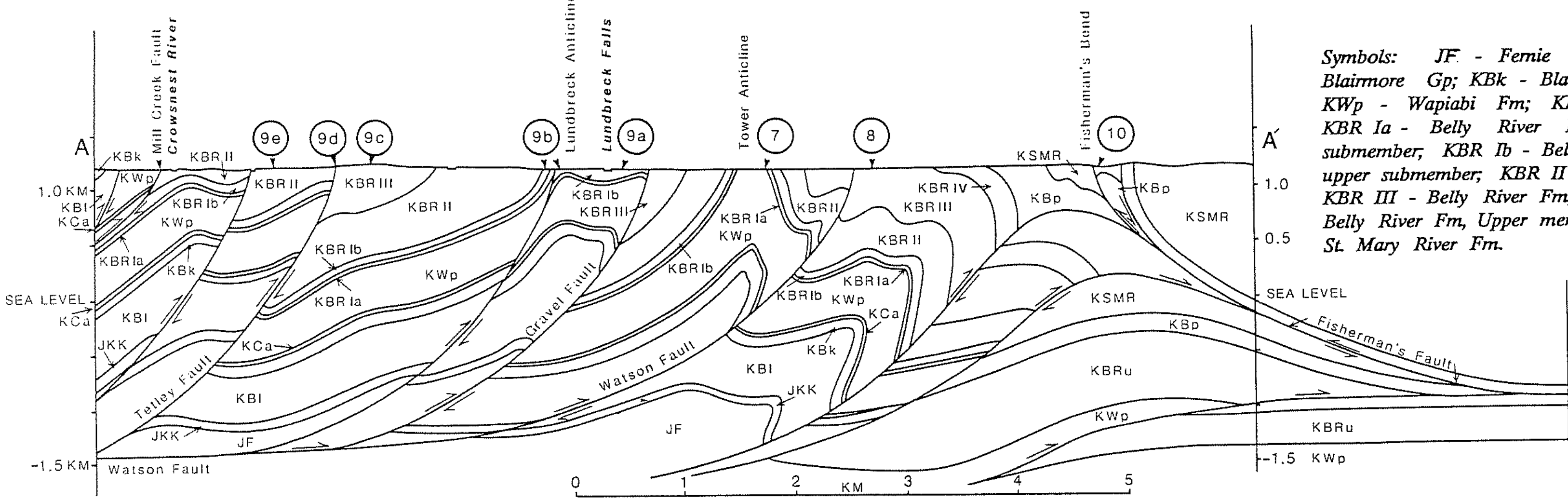
Figure 22. Geological map of the Foreland Thrust Belt in the vicinity of Lundbreck (Geology by C. O. Hage, 1943; T. Jerzykiewicz and D.K. Norris. Compiled by D.K. Norris). For symbols see Fig. 23.

to the autochthon of the Alberta Syncline (Figs. 23, 24).

The Lundbreck Falls transition section was measured by Lerand and Oliver (1975) and interpreted in terms of a prograding delta front environment. This interpretation was subsequently questioned by Rosenthal and Walker (1987) who interpreted the section as a storm-dominated shoreface deposit and gave the following justification for the rejection of the deltaic interpretation: . . . "However, the term shoreface is not very specific environmentally, and one might ask whether the shoreface was attached to a delta, to a strand plain, or even to the seaward side of a barrier. Without knowing the plan view three-dimensional sand body geometry, we know of no reliable way of distinguishing a wave- or storm-dominated shoreface attached to a delta (e.g., the Sao Francisco; Coleman and Wright 1975, pp. 141–142) from a shoreface attached to a strand plain (e.g., the coast of Nayarit, Mexico; Curray et al. 1969). The rare, small channels that cut into or are associated with the Chungo shoreface could be supplying sand either to the strand plain or to a series of deltas. The difference may be largely semantic, related to the *amount* of irregular progradation of the shoreline (delta) versus the amount of along-shore sediment dispersal giving rise to a long, smooth beach and beach ridge complex (strand plain). However, we suspect that the preservation of storm dominated sedimentary structures (swaley cross-stratification) indicates a relatively smooth wave-dominated coastline, that is, a strand plain rather than a delta. There is no evidence that the shoreface was attached to a barrier island." . . . (Rosenthal and Walker, 1987, p. 782).

The purpose of our visit to the Belly River sections in the vicinity of Lundbreck is to demonstrate the external geometry of the sandstone bodies and the internal distribution of facies and sedimentary structures within the Belly River Delta (Jerzykiewicz and Norris, *in press*). Three members of the Belly River Formation (Transitional KBR Ia and KBR Ib, Fluvial KBR II, and Concretionary KBR III) crop out in Crowsnest River cutbanks on both limbs of the Lundbreck and Tower anticlines between the Lundbreck waterfalls and Highway No. 3 bridge (Fig. 22). The Lundbreck Falls transition section is the main purpose of our Stop 7. Here, steeply, east-dipping strata of the Transitional Member of the Belly River Formation (Figs. 26A, 26B) are exposed near the axis of Tower Anticline visible in Wapiabi shale (Fig. 27A). The fluvial channel sandstone of the KBR II member crops out nearby (Fig. 27B), and the overbank facies of this member crops out some 3 km upstream where it will be examined along the railway tracks (Stop 9d).

The Transitional Member is subdivided into two submembers, namely: KBR Ia and KBR Ib (Figs. 21–26). The lower submember (KBR Ia) consists of interstratified mudstone, siltstone and fine-grained sandstone forming a 70 m thick, coarsening upward succession comprising the bulk of the Lundbreck Falls transition zone (Fig. 26). The upper submember (KBR Ib) consists entirely of sandstone showing an upward change in stratification from swaley – through herringbone – to trough crossbedding.



Symbols: JF - Fernie Gp; JKK - Kootenay Gp; KBl - Blairmore Gp; KBk - Blackstone Fm; KCa - Cardium Fm; KWp - Wapiabi Fm; KBRu Belly River Fm, undivided; KBR Ia - Belly River Fm, Transitional member, lower submember; KBR Ib - Belly River Fm, Transitional member, upper submember; KBR II - Belly River Fm, Fluvial member; KBR III - Belly River Fm, Concretionary member; KBR IV - Belly River Fm, Upper member; KBp - Bearpaw Fm; KSMR - St. Mary River Fm.

Figure 23. Cross-section of the Foreland Thrust Belt in the vicinity of Lundbreck (D.K. Norris).

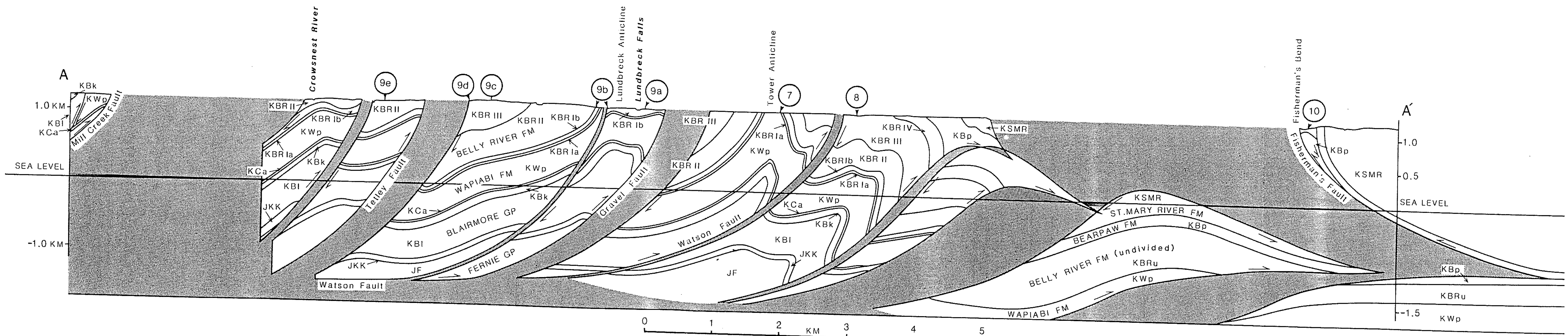


Figure 24. Partially restored cross-section of the Foreland Thrust Belt in the vicinity of Lundbreck (D.K. Norris). For symbols see Fig. 23.

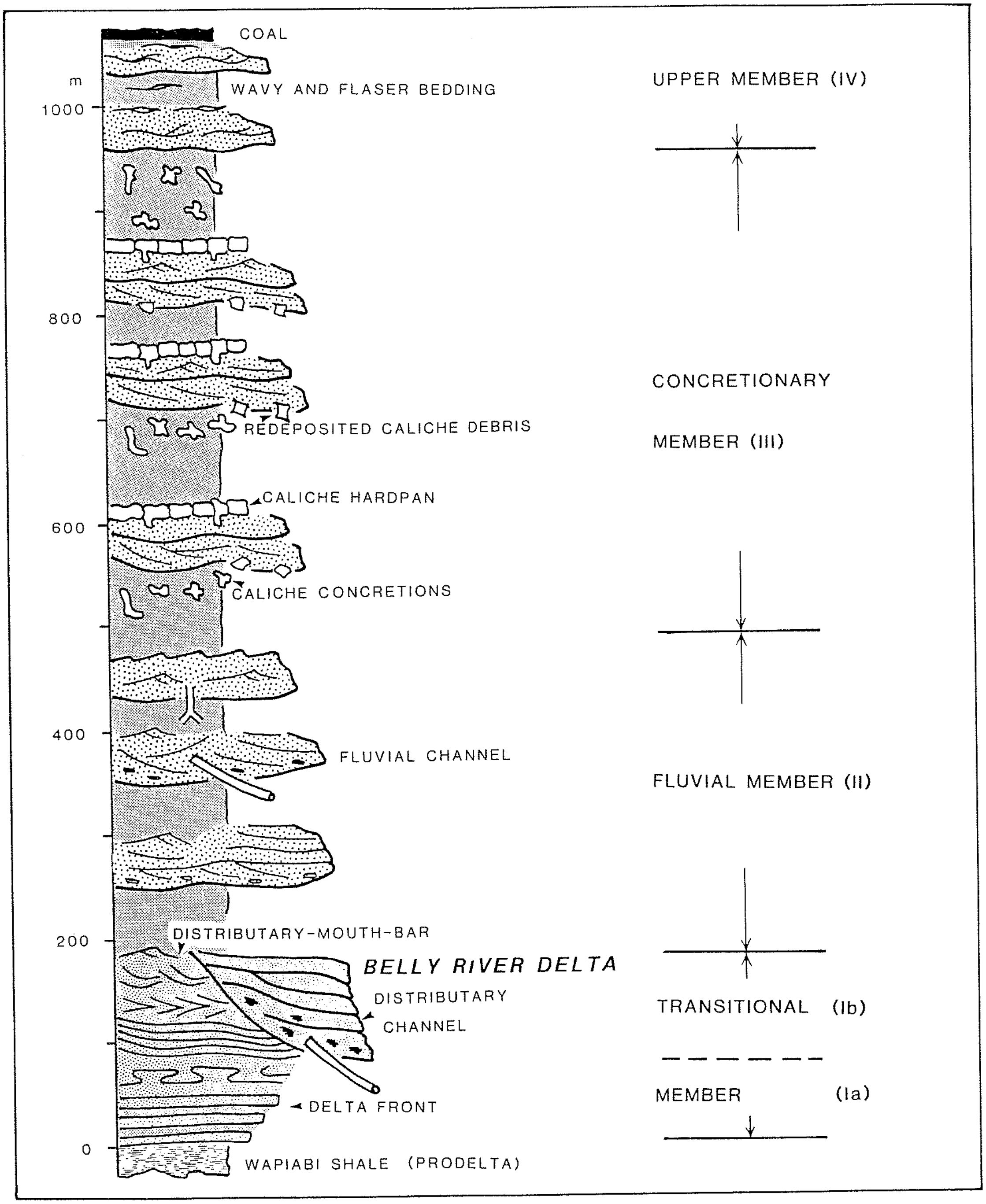


Figure 25. Composite stratigraphic column of the Belly River Formation as measured along the Crowsnest River in the area of Lundbreck Anticline.

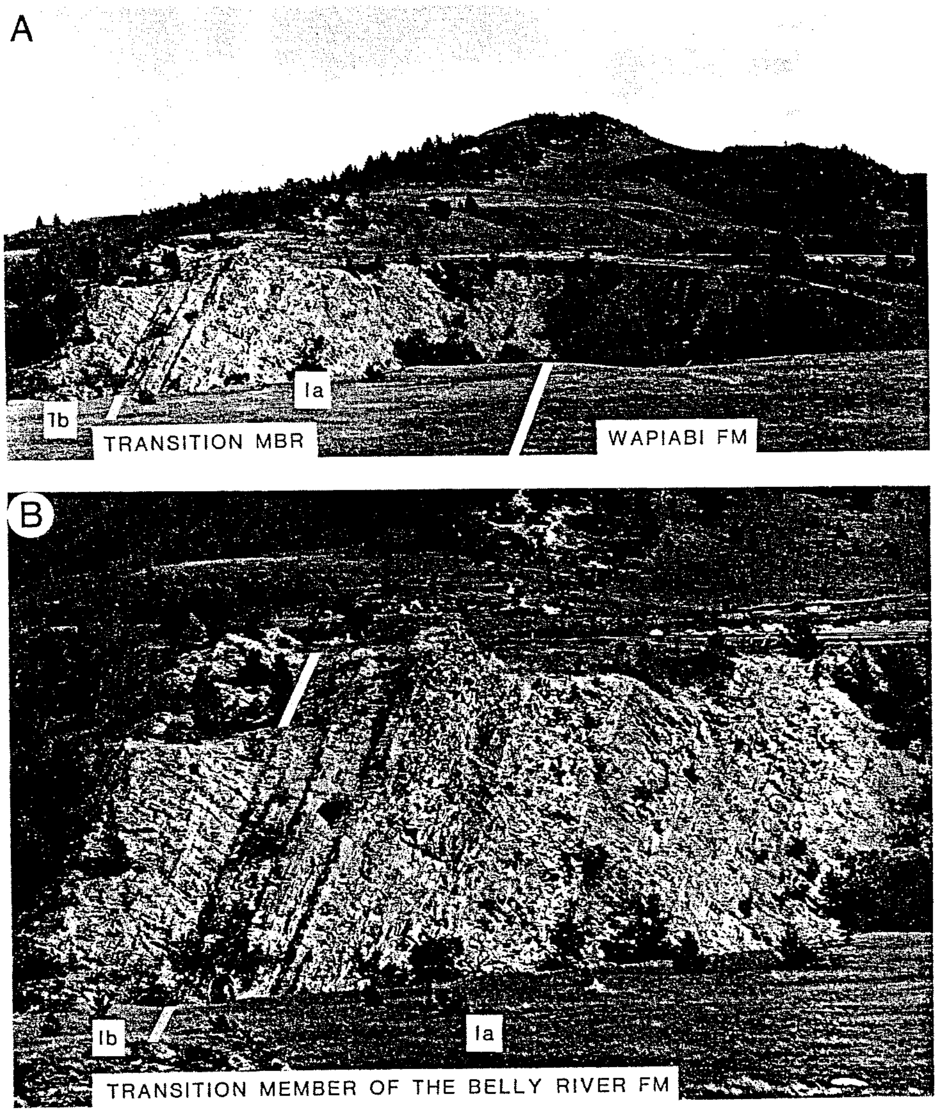


Figure 26. Lundbreck Falls transition section.

A. *The entire section of the Transitional Member of the Belly River Formation on the northeast limb of the Tower Anticline.*

B. *Close up view of the Transitional Member of the Belly River Formation. Note the position of the boundary between the submembers.*

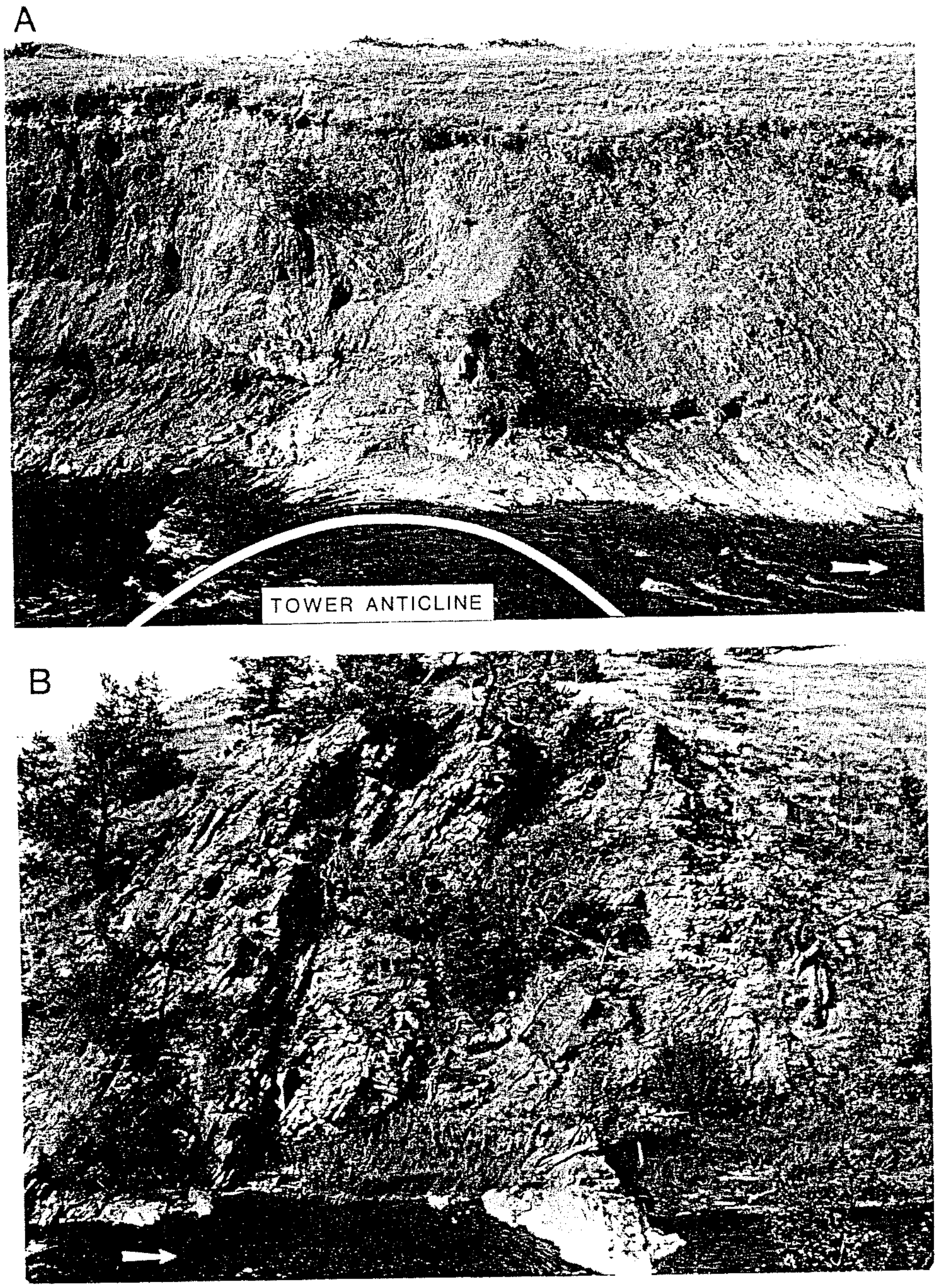


Figure 27. Isolated outcrops of the Wapiabi and Belly River formations in the Crowsnest River cutbank between the Lundbreck transition section and the waterfall cliff.

A. Wapiabi shale in the core of the Tower Anticline.
B. Channel sandstone of the Fluvial Member (KBR II) on the southwestern limb of the Tower Anticline.

The lenticular geometry of the sandstone bodies within the upper submember makes its thickness vary from about 30 metres in the Lundbreck Falls transition section to nil on the south-western limb of the Tower Anticline (Fig. 22).

The KBR Ia submember consists of two intervals that differ in the amount of sandstone beds in relation to mudstone. The lower interval (Fig. 26B) contains turbidite beds interstratified with pelagic mudstone. Most sandstone beds are of the Tb and/or Tc type (Bouma, 1962), being composed of parallel- and ripple-cross lamination intervals (Fig. 28A). The mudstone, according to Rosenthal and Walker (1987), contains the following trace fossils: *Ophiomorpha, Gyrochorte, Cosmorhaphe, Teichichnus, Paleophycus, Cochlichnus,* and *Planolites*. These authors interpreted ". . . the background mudstone as the deposit of a quiet basin at or below wave base.", and sandstone beds as turbidites rather than storm deposits (Rosenthal and Walker, 1987, p. 775).

The amount and thickness of sandstone beds increases upward and sandstone becomes the main lithology within the upper interval of the KBR Ia submember. This interval contains numerous hummocky cross-stratified sandstone beds (Fig. 28B), which were interpreted by Rosenthal and Walker (1987) as storm deposits rapidly emplaced into an area of quiet mud and sandy mud deposition. The upper part of this sandstone interval is characterized by large-scale, soft-sediment deformation (Figs. 29A, 29B) attributed to loading by Rosenthal and Walker (1987). Such disturbed bedding or sedimentary folds may result from an impact of heavy suspensions upon a soft, stratified substratum as evidenced by experiments and numerous examples from the Carpathian flysch (Dzulynski and Radomski, 1965).

Sandstone of the submember Ib differs from the underlying sediments in grain size and type of stratification. These sandstones show significant lateral facies changes in the area as they represent different settings within the delta environment (discussed below). In the Lundbreck transition section the lower part of the member consists of subhorizontal- to swaley cross-stratified layers of fine-grained sandstone. The sandstones are well sorted and have a high quartz content characteristic of high wave-energy settings. The thickness of the swaley cross-stratified interval varies from about 10 metres in the Lundbreck Falls transition section (lower part of the unit 13 of Lerand and Oliver, 1975, Fig. 3), up to 25 metres in the Connelly cliff section of the Lundbreck Anticline (Figs. 30A, 30B; Fig. 33B). The upper part of the Ib submember in the Lundbreck Falls transition section consists of herringbone cross-stratified cosets of medium-grained sandstone passing upward into trough crossbedded sandstone units. In the Connelly cliff section of the Lundbreck Anticline, this upper part of the submember Ib also contains angle-of-repose, planar cross-stratified cosets of sandstone (Fig. 31).

The swaley cross-stratification was described in the Lundbreck transition section by Rosenthal and Walker (1987) and interpreted after Walker (1982),

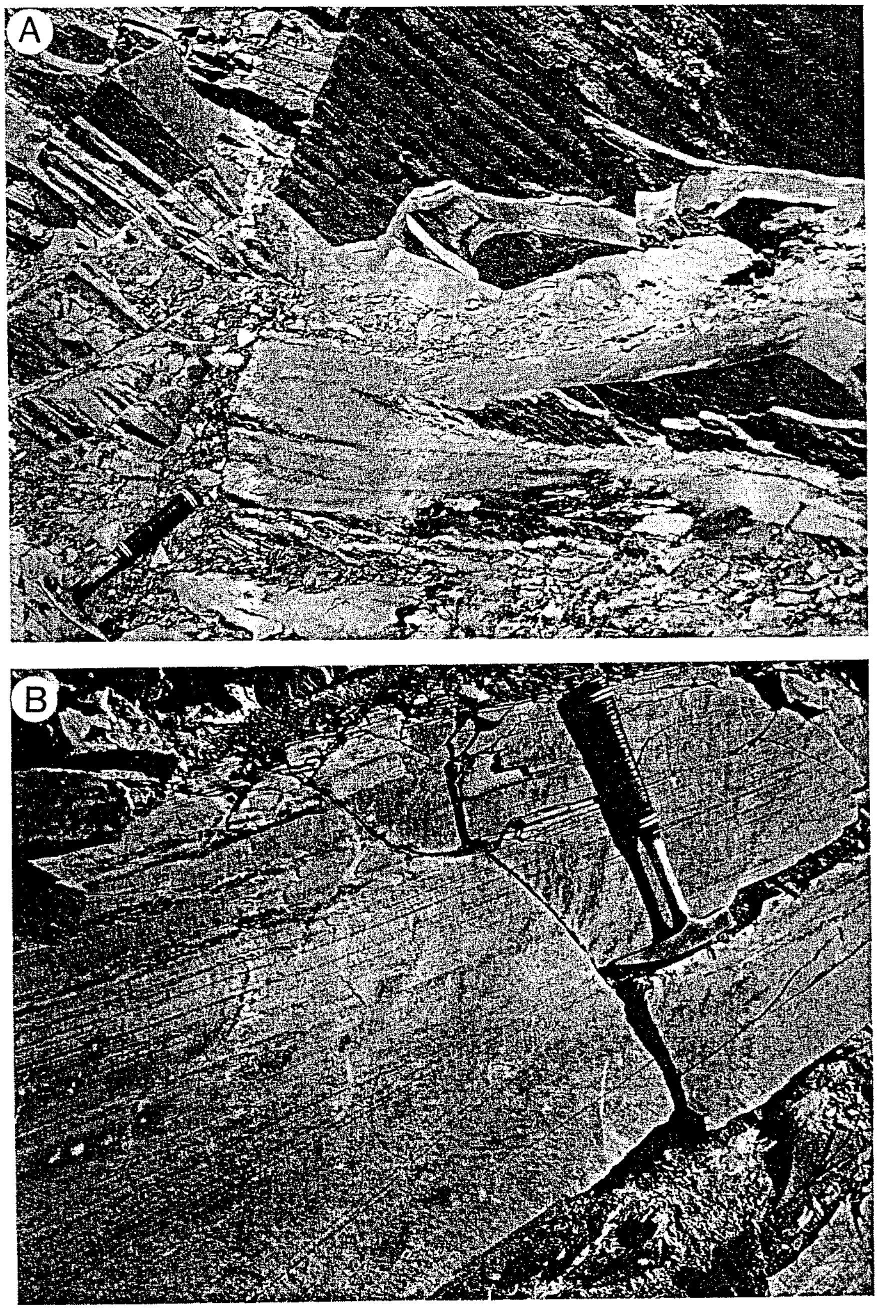


Figure 28. Types of bedding in the lower interval of the Ia submember of the Belly River Formation.

A. Parallel- and ripple-cross-laminated (Tb and Tc) turbidite sandstone beds.

B. Part of a hummocky cross-stratified unit of sandstone.

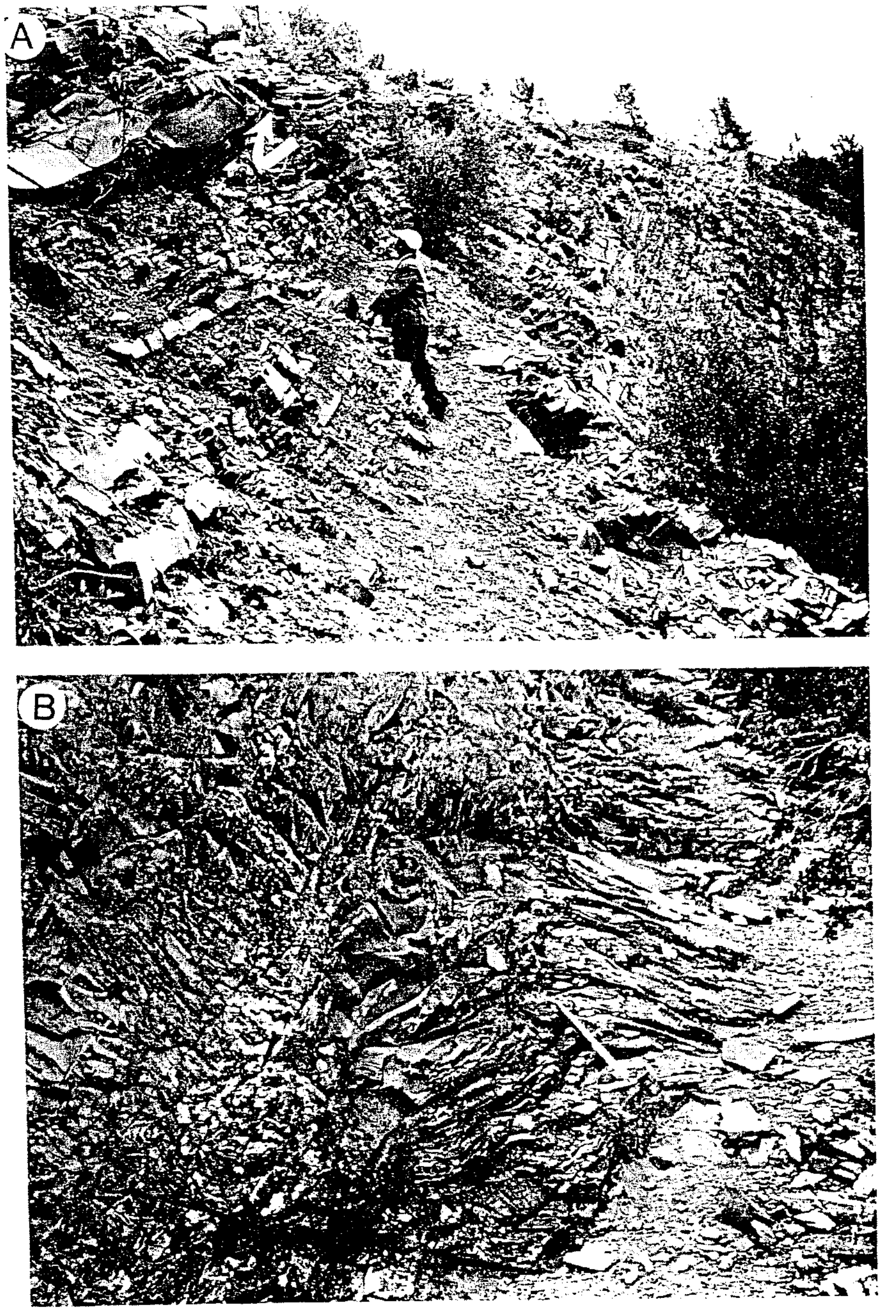


Figure 29. Large-scale soft-sediment deformation in the upper interval of the Ia submember of the Belly River Formation.

A. Disturbed bedding (indicated by the arrow) above subparallel sandstone and mudstone beds.
B. Sedimentary fold resulting from an impact of heavy suspension upon a soft, stratified substratum.

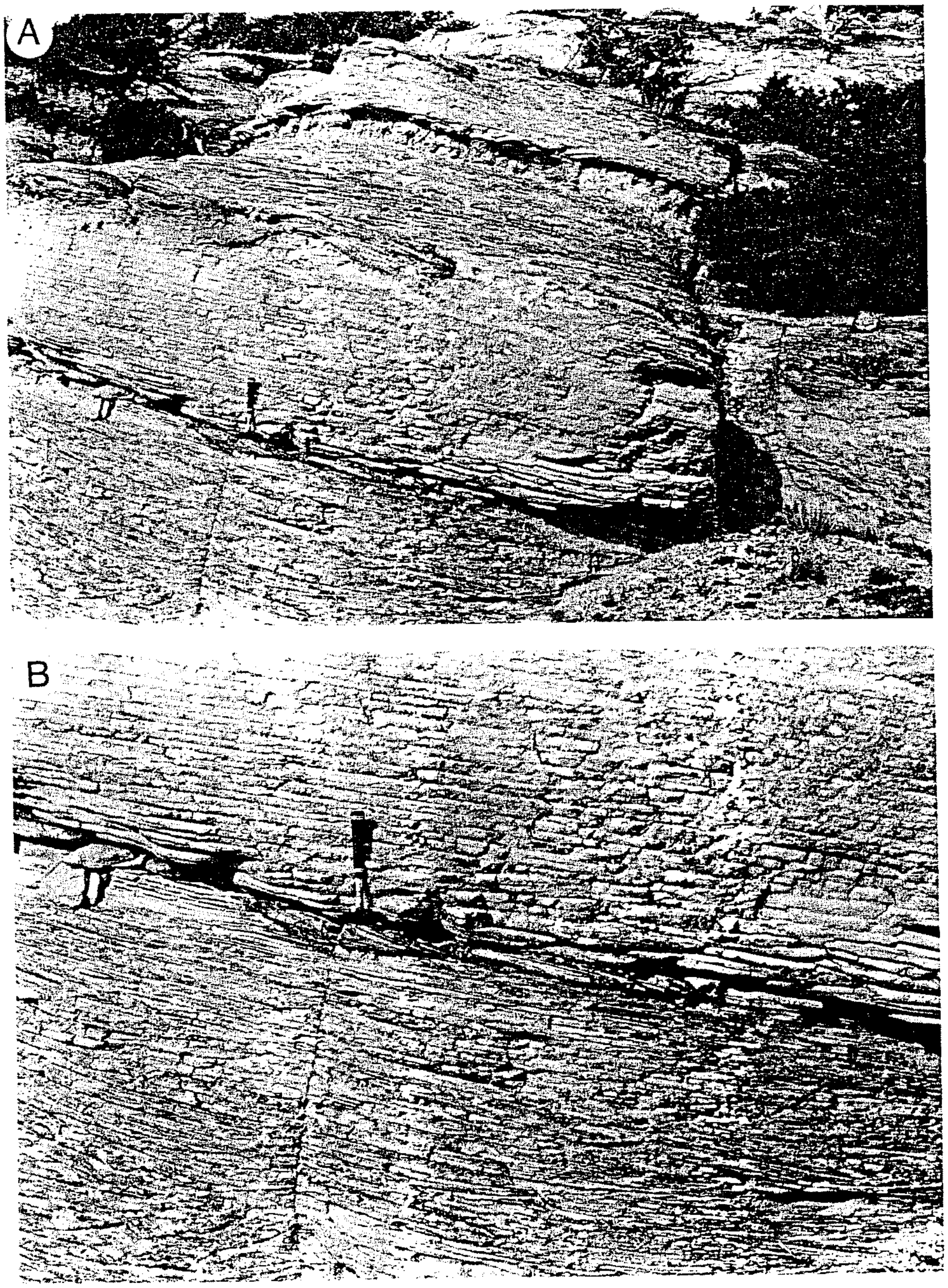


Figure 30. Stratification of the distributary-mouth-bar deposit of the Belly River Delta. Connelly cliff. I.

- *A. Swaley cross-stratification of the KBR Ib submember of the Belly River Formation.*
- *B. Close-up of the lower part of the cliff shown in Figure 30A.*

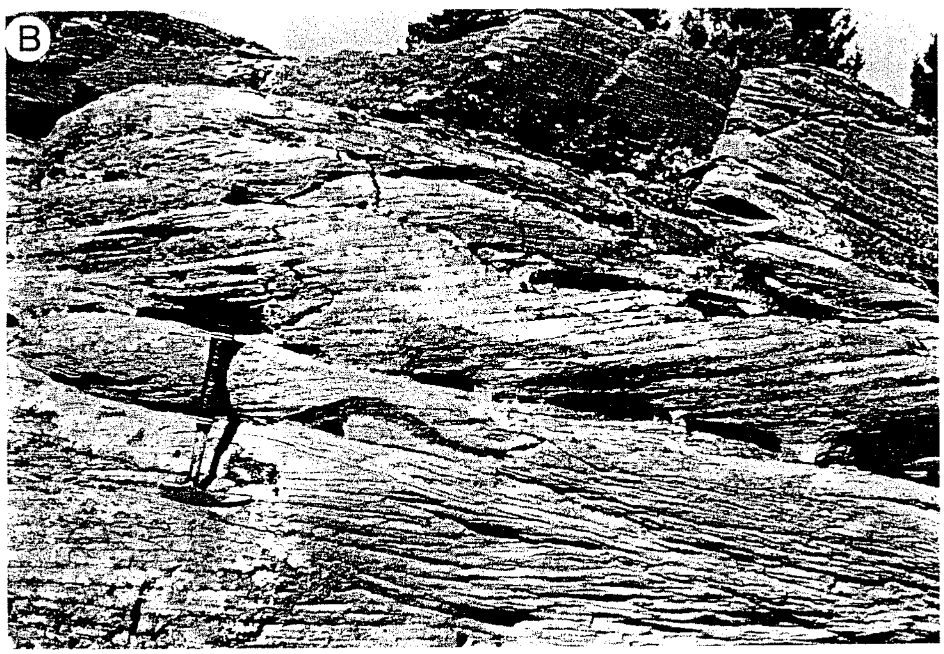


Figure 31. Stratification of the distributary-mouth-bar deposit of the Belly River Delta. Connelly Cliff. II.

A. Herringbone cross-stratified cosets of sandstone passing upward into angle-of-repose planar and/or trough cross-stratified cosets, and subhorizontally bedded units at top.

B. Close-up of the upper part of the cliff shown in Figure 31A.

Lackie and Walker (1982), and McCrory and Walker (1986) in terms of ". . . storm-formed feature based on its similarity to and association with hummocky cross-stratification . . ." (Rosenthal and Walker, 1987, p. 778).

The discussion of the depositional setting of the Ia and Ib submembers within the Belly River Delta as well as an interpretation of the sedimentary environment of the remaining members of the formation is included in a later section of this Guidebook (Stops 9a and 9b).

Stop 8. Concretionary Member (KBR III) of the Belly River Formation at Lundbreck

The Concretionary Member (Fig. 25) forms many usually, small outcrops in river cuts and along Highway No. 3 west of Lundbreck. One of the largest exposures of the member is located at the river bend some 2 km northeast of the Lundbreck Falls (Stop 8). Structurally, the section occurs in the immediate footwall of the Watson Thrust, a major northeast-verging fault repeating the Concretionary Member on the northeast flank of the Tower Anticline (Figs. 22, 23). Minor folding of the member in this exposure is deciphered readily by tracing individual beds around the fold axes (Fig. 32).

The Concretionary Member (or caliche member of Jerzykiewicz and Sweet, 1988) can be easily distinguished from other Belly River members on the basis of the colour of the background mudstones containing abundant and very characteristic limestone concretions. The mudstone is greyish-green to pale yellowish-green (10 GY 5/2 to 10 GY 7/2 according to Rock-Color Chart of Goddard et al., 1984) and contains caliche nodules and hardpan (Fig. 32D). The mudstone and silty-mudstone show rubbly weathering and reveal no stratification. Some thin interbeds of siltstone and very fine-grained sandstone are laminated and occasionally ripple crossbedded. Medium- to coarse-grained sandstone forms multistoried layers several metres thick, embedded in caliche-bearing mudstone (Fig. 32C).

The multistoried sandstone layers possess sharp, scoured, erosional bases and show fining-upward trends in grain size and in arrangement of sedimentary structures. Their lower, trough cross-bedded parts are of scour-and-fill type and contain redeposited caliche debris. Some scours contain intraformational lag deposits composed of rip-up-clasts of mudstone and subangular-to-subrounded, large limestone fragments derived from the caliche hardpans (Fig. 32B). Examples of large blocks of hardpan excavated from the floor and refilling the scours are also found. Above the scour-and-fill bedding the multistoried layers are composed of amalgamated units of flat to low-angle, bedded, medium-grained sandstone occasionally passing upwards into ripple bedded, fine-grained sandstone.

The caliche nodules and hardpan layers consisting of coalescing nodules (Fig. 32D) were interpreted in terms of mature, semiarid paleosols (Jerzykiewicz and Sweet, 1988). Some of the hardpan horizons from the Concretionary Member

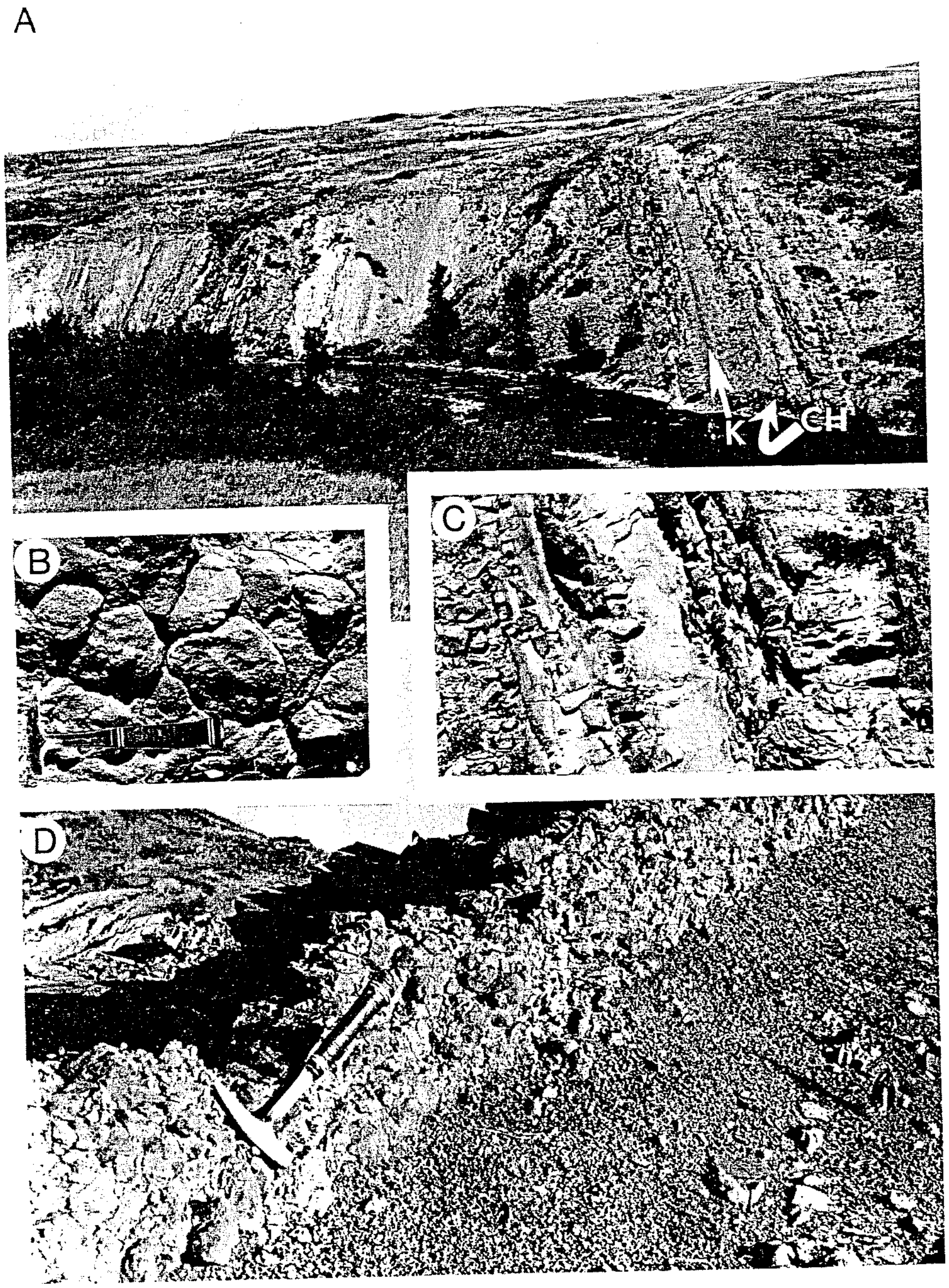


Figure 32. Concretionary Member of the Belly River Formation (KBR III) in the Crowsnest River cutbank near the bridge over Highway No. 3, northwest of Lundbreck.

- *A.* *General view of the section from Highway No. 3. For the exact location of the fold marked by the white tape see Figure 22. Symbols: K stands for the hardpan layer, CH stands for the multistorey channel layer shown in the inset C.*
- *B.* *Channel lag deposit composed of cobbles derived from the caliche hardpan.*
- *C.* *Multistorey channel sandstone.*
- *D.* *Caliche hardpan layer composed of coalescing nodules.*

are very similar to those described by Gile et al. (1966, 1981) from semiarid soil profiles of New Mexico. These hardpans represent stages III and IV of caliche development of Gile et al. (1966, 1981). Stage III caliches are thought to require as much as 50 Ka to develop, and stage IV even longer periods of semiarid conditions (Gile et al., 1981; Holliday and Gustavson, 1988). Pedogenic processes in semiarid conditions operate very slowly. It is reasonable, therefore, to assume a very slow rate of deposition for the mudstone intervals with horizons of caliche concretions and periods of nondeposition for mature hardpans. The semiarid climate, which is characterized by long-lasting droughts interrupted by sporadic but heavy rainfalls, cause episodic flood events. The torrential character of these flood events can be inferred from the nature of the sandstone layers that show signs of very high energy erosion of the hardpan, sudden deposition of large blocks and mostly parallel-bedded sheets of sandstone. The sand bodies embedded by the background caliche-bearing mudstone are interpreted as sudden discharge of ephemeral streams into the semiarid alluvial plain.

The semiarid alluvial plain of late Belly River times was sparsely vegetated as indicated by an impoverished and partly xerophytic palynological assemblage (Jerzykiewicz and Sweet, 1988). The depositional environment of the Concretionary Member of the Belly River can be visualized as a distal alluvial fan, episodically covered by flood waters infilling ephemeral channels, and producing sheets of sandstone and leaving intermittent playas. The playa environment is evidenced by the occurrence of micritic limestone associated with laminated siltstone and ripple laminated, very fine-grained sandstone within the mudstone.

Stops 9a to 9e. Belly River Formation along the railway tracks west of Lundbreck

The Crowsnest River and the railway cuts west of the Lundbreck transition section (Stop 7) provide several outcrops of the Belly River Formation. The locations of the outcrops, from 9a to 9e, that will be examined in a 3 km stretch along the railway tracks westwards from the Waterfall are shown in Figures 22–24. The purpose is to make a transect through the Belly River strata of the Foothills and to demonstrate stratigraphic and facies relationships within the Belly River clastic wedge, its depositional geometry and structure. The significance of a palinspastically restored section of Belly River strata for a paleoenvironmental interpretation of the basin margin (strand plain versus deltaic interpretation of the Belly River shoreline) will also be discussed.

Stop 9a

The Lundbreck waterfall cliff consists of a composite layer of sandstone (Fig. 33A) that is stratigraphically correlative of the Connelly cliff sandstone (Fig. 33B). It belongs to the Transition Member (KBR Ib on Fig. 22) in the core of Lundbreck Anticline where bedding is essentially horizontal.

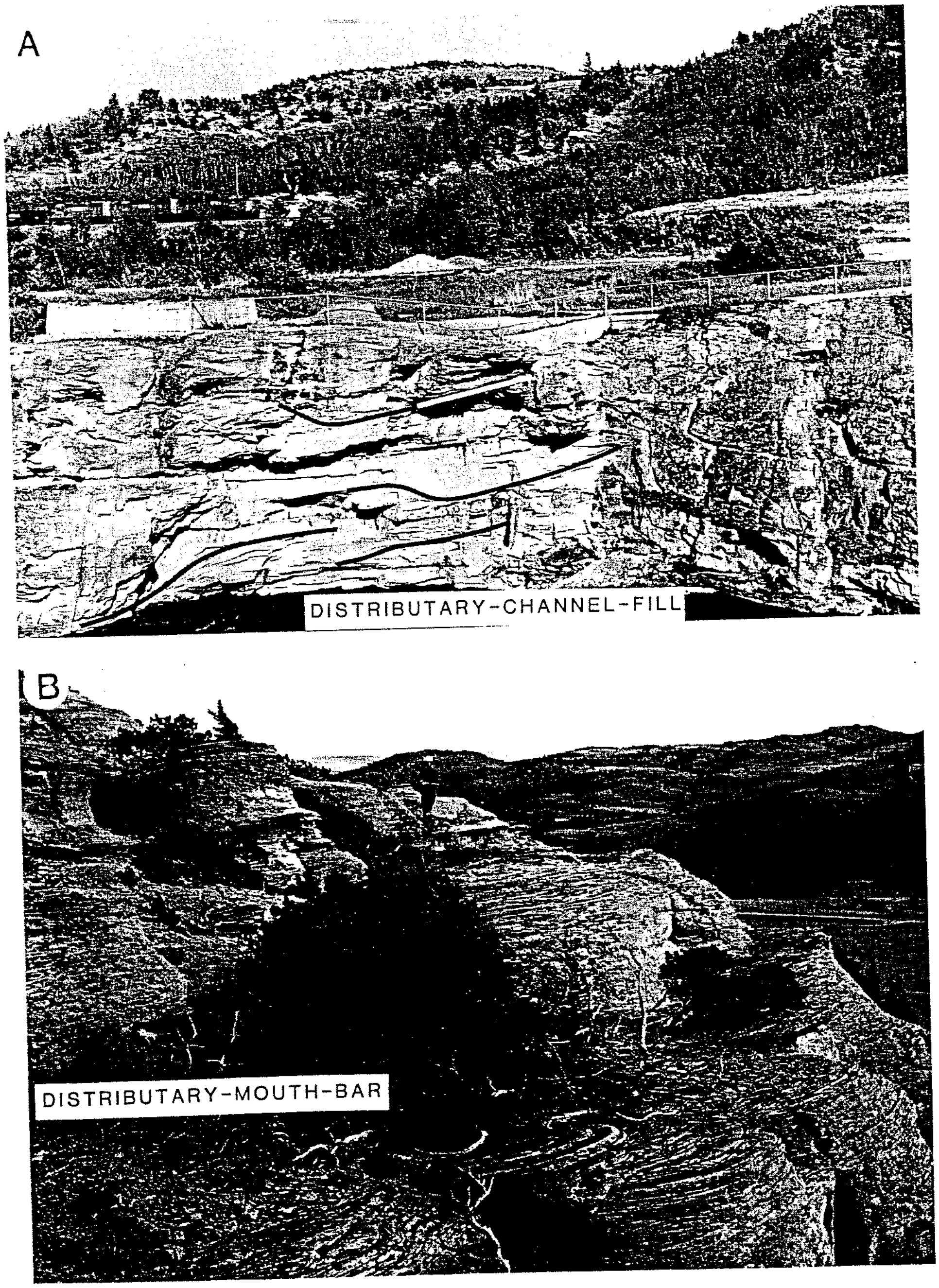


Figure 33. Distributary-channel-fill and distributary-mouth-bar deposits of the Belly River Delta in the Lundbreck Anticline area.

- *A. Large scale trough cross-bedded sandstone at waterfall cliff.*
- *B. Swaley cross-stratified sandstone at Connelly cliff.*

The waterfall cliff and the Connelly cliff sandstone bodies differ in external geometry and internal sedimentary structure. The waterfall cliff is about 10 m thick, and is just the lower part of a 120 m thick sandstone body that forms the core of the Lundbreck Anticline. It can be seen in numerous outcrops in the area (Fig. 21). Channel shape erosional surfaces and large-scale trough crossbedding are the most common sedimentological features of the waterfall cliff (Fig. 33A). The geometry of the entire sandstone body is lenticular. It pinches out in a northwest-southeast direction largely perpendicular to the axis of internal channels outlined by the erosional surfaces (Fig. 33A). Over 30 readings of the trough crossbedding axis indicate a northeasterly paleocurrent direction (mean azimuth towards 64°). The waterfall cliff sandstone body is interpreted in terms of distributary-channel-fill of the Belly River Delta.

The Connelly cliff sandstone body, which is a lateral equivalent of the waterfall sandstone body, is of similar thickness (about 100 m), and possesses lobate external geometry. Swaley cross-stratification is the most conspicuous sedimentary structure (Figs. 30A, 30B, 33B). It passes upward into herringbone-cross-stratification and large-scale trough-to-planar crossbedding in the upper part of the sandstone body (Figs. 28B, 31A). The Connelly cliff sandstone body is interpreted in terms of a distributary-mouth-bar developed sideways at the river mouth (Lundbreck waterfall sandstone body). Unlike the channelized sandstones of the waterfall (the distributary-channel-fill), that are limited to the Crowsnest River sections, the swaley to herringbone cross-stratified layers of sandstones occur in many sections throughout the area. The maximum thickness of the distributary-mouth-bar sandstone bodies varies from about 100 m at the Connelly cliffs to less than 30 m in the Lundbreck transition section. This difference can be explained by the larger distance of the transition section from the mouth of the distributary channel. The extension of the distributary-mouth-bars both perpendicular to the main distributary channel and offshore indicates reworking by littoral currents.

Our interpretation of the Belly River strata in terms of a delta (Jerzykiewicz and Norris, *in press*) does not contradict the previous interpretations i.e. "shoreface" of Rosenthal and Walker (1987), and "deltaic" of Lerand and Oliver (1975). The Belly River Delta, in our opinion, spanned a larger stratigraphic interval than visualized by Lerand and Oliver (op. cit.), and covered a larger area embracing the prograding shoreface of Rosenthal and Walker (op. cit). All of the main depositional processes operating in the deltaic environment i.e. fluvial currents, waves, littoral currents and storm surges as well as the tides seem to be documented by the presence of diagnostic sedimentary structures in various parts of the Belly River Delta (Lerand and Oliver, 1975; Rosenthal and Walker, 1987). Their diagnostic significance, however, is site specific and the type of the Belly River Delta cannot be decided without knowledge of its plan view. Spatial relations of the distributary channel-fill sandstone and of the distributary-mouth-bar sandstone bodies indicate a well developed main distributary channel oriented approximately along the present Crowsnest River (Fig. 34A), with the mouth of the channel immediately northeast of the Lundbreck waterfall cliff (on the basis of the absence of the distributary channel fill facies in the Lundbreck transition section), and with distributary-mouth-bars developed sideways roughly perpendicular to the paleocurrents in the distributary channel.

Stop 9b

A section which occurs on both sides of the railway tracks about 0.5 km west of Lundbreck Falls has been described in the supplement on page 88 of this guidebook.

Stops 9c and 9d

Some 2 km west of Lundbreck Falls, yellowish-green mudstone containing numerous caliche concretions and rhizocretions crop out in a railway cut (Figs. 35A, 35B). The mudstone and silty-mudstone are interbedded with thin, fine-grained sandstone layers. The section belongs to the Concretionary Member of the Belly River Formation already known from Stop 8. A few hundred metres westward, yellowish-green mudstone of the Concretionary Member is thrust over rocks of the Fluvial Member across the Tetley Fault (Fig. 22).

Stop 9e

Overbank, fine-grained facies of the Fluvial Member of the Belly River Formation crop out in a railway cut some 3 km west of Lundbreck Falls (Fig. 36). The dominant lithology is mudstone of various colours from olive-green to dark-grey and almost black. Shells of thin-walled, fresh-water gastropods and bivalves occur sporadically in the mudstone. Thin coaly shales are found in the uppermost part of the outcrop.

The sandstone layers consist of ripple-cross laminated, fine-grained sand and silt. They are interpreted in terms of crevasse-splay deposits into an alluvial plain environment. No major fluvial channels, known from other sections of the Fluvial Member (Fig. 27B), are observed in this outcrop.

Stop 10. Structure of the eastern margin of the Foothills at Fisherman's Bend and the Bearpaw–St. Mary River formations contact

Fisherman's Bend of the Crowsnest River is located some 1.5 km northeast of Lundbreck (Figs. 20, 22). There the river cut exposes the lower St. Mary River Formaton and, in the next cut a few hundred metres downstream, the transition from the Bearpaw shale into the lower St. Mary River Formation is exposed. At Fisherman's Bend the St. Mary River Formation is folded into a strongly asymmetric anticline (Fig. 37A) that verges westward in the immediate hanging-wall of the Fisherman's Fault, the upper detachment of the Triangle Zone at this latitude (see Fig. 23). Just downstream the transition from the St. Mary River into the underlying Bearpaw Formation is readily identified although folded and faulted (Fig. 37C).

A

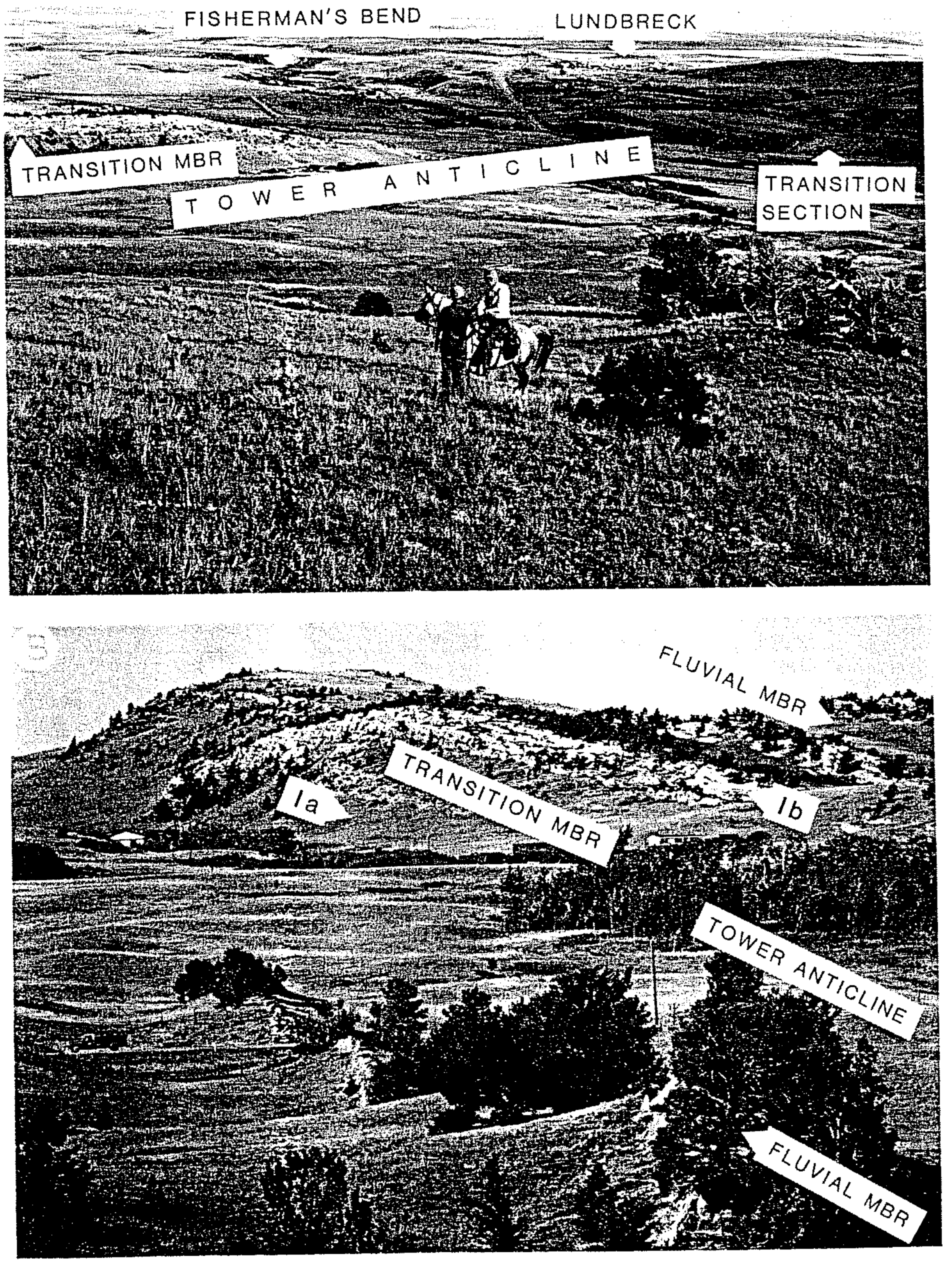


Figure 34. Belly River Delta sandstone bodies of the Tower Anticline.

A. View from the Connelly cliffs towards southeast. Village of Lundbreck is in right background.

B. View from the rapids on Crowsnest River between the Lundbreck transition section and the waterfall cliff to the north.

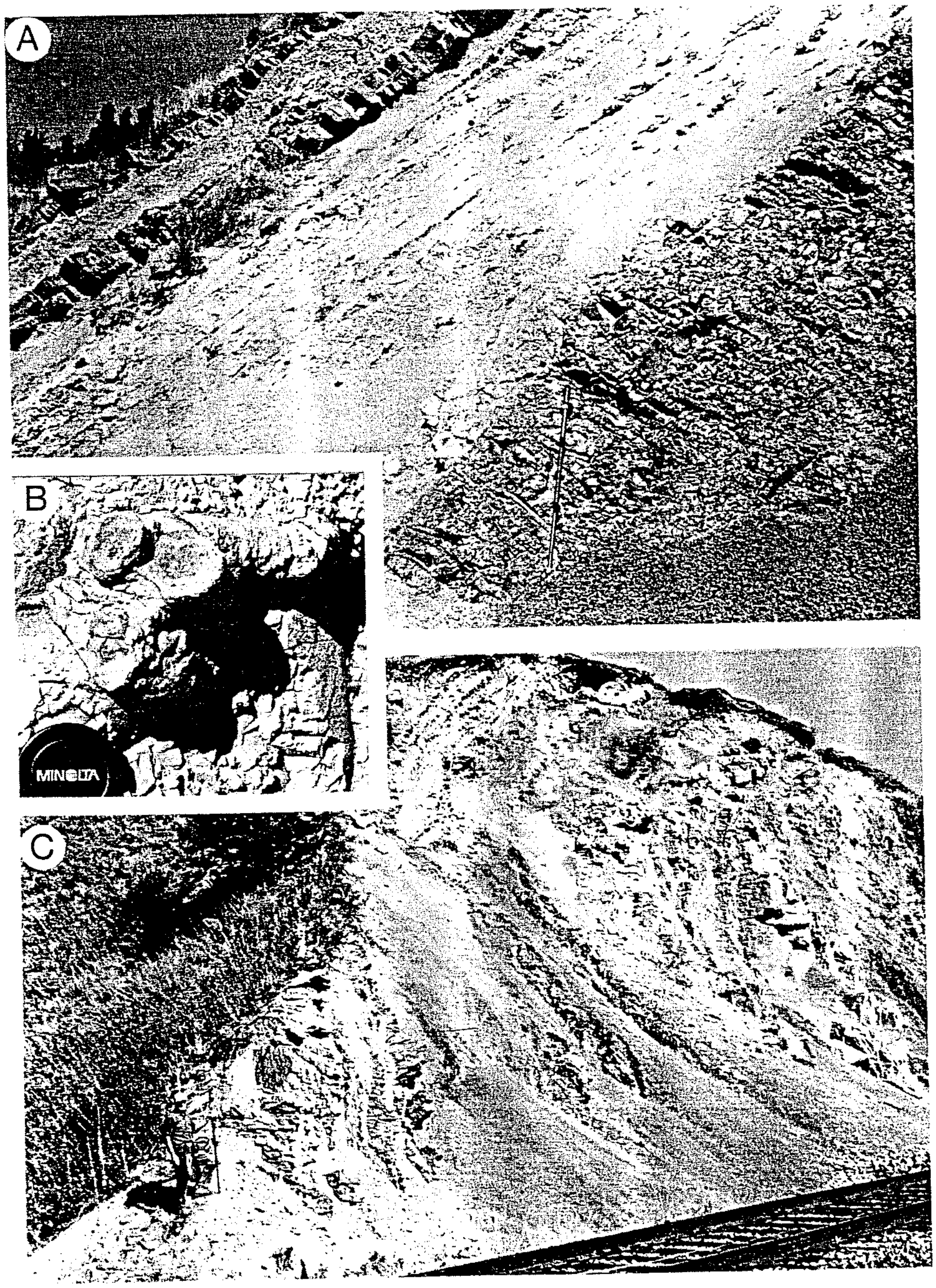


Figure 35. Concretionary and Fluvial members of the Belly River Formation in the railway cut some 2 km west of Lundbreck Falls near the Tetley Fault.

- *A.* *Silty-mudstone and mudstone with caliche concretions and thin sandstone layers of the Concretionary Member.*
- *B.* *Cylindrical- and conical-shaped caliche concretions (rhizocretions).*
- *C.* *Contact of the Concretionary and Fluvial members of the Belly River Formation in the Tetley Fault zone.*

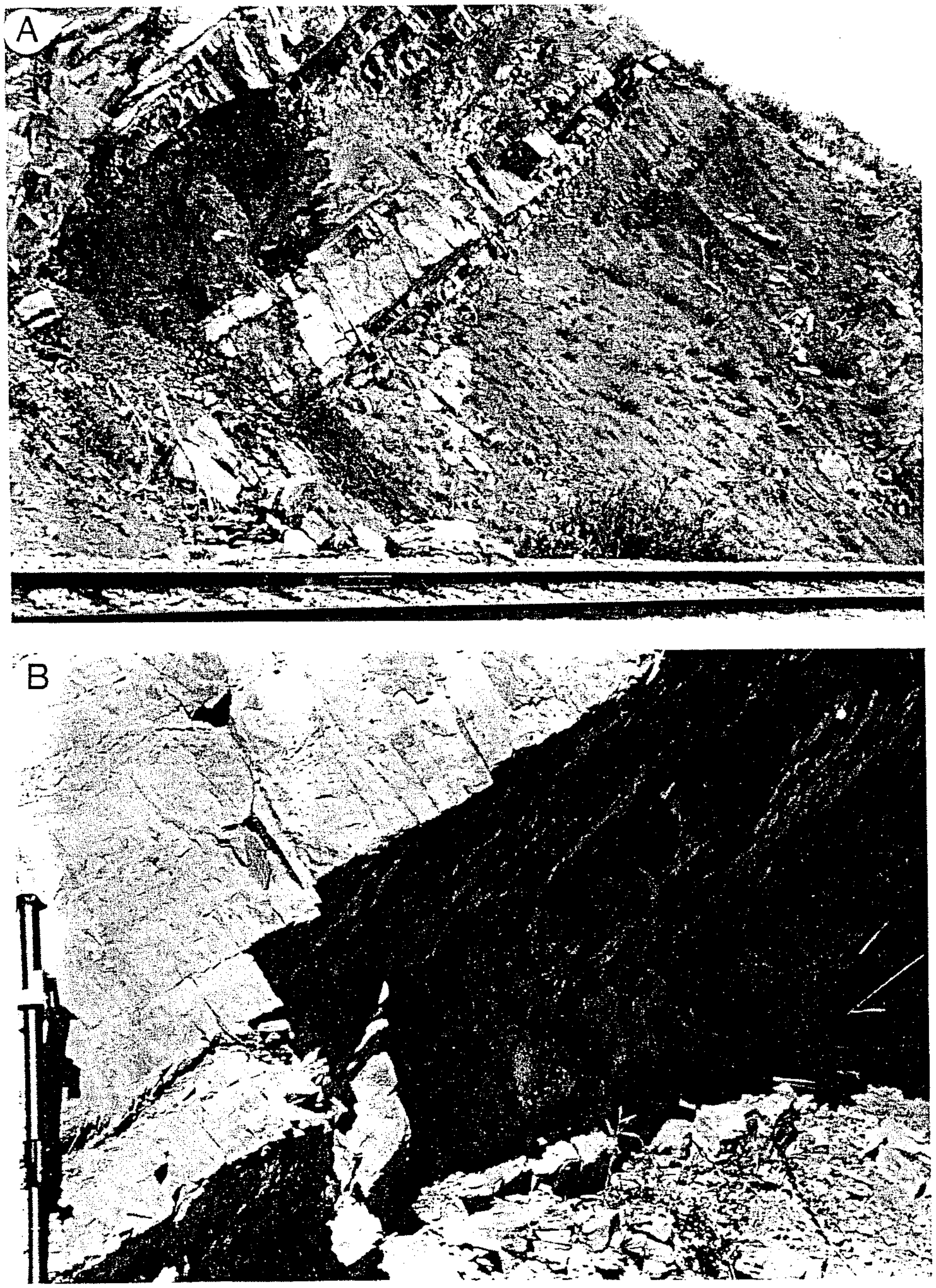


Figure 36. Overbank deposit of the Fluvial Member of the Belly River Formation in the railway cut some 3 km west of Lundbreck Falls.

- *A.* *Ripple-crossbedded, fine-grained sandstone to siltstone layers of crevasse-splay origin interbedded with the overbank mudstone.*
- *B.* *Close-up view of the ripple-cross laminated layer of sandstone*
- *C.* *Contact of the Concretionary and Fluvial members of the Belly River Formation in the Tetley Fault zone.*

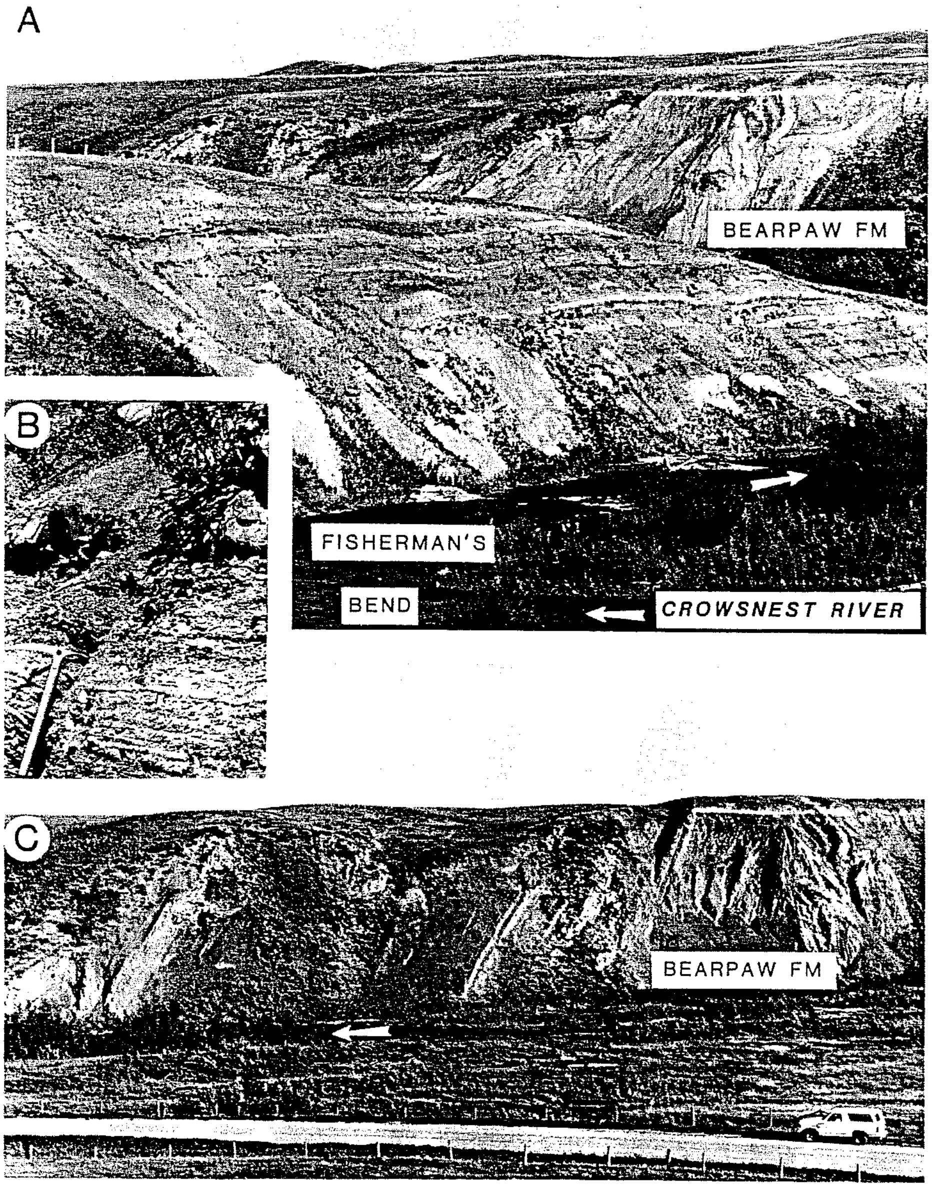


Figure 37. Lower St. Mary River and Bearpaw formations at the Fisherman's Bend.

- *A.* *Fisherman's Anticline in lower St. Mary River Formation in the immediate hangingwall of the upper detachment of the Triangle Zone.*
- *B.* *Stratification of the lower St. Mary River Formation deposit.*
- *C.* *Tectonically disturbed contact between the parautochthonous Bearpaw and St. Mary River formations on Crowsnest River.*

The lower member of the St. Mary River Formation at the Fisherman's Bend shows a sequence comprising several fining-upward cycles. The lowest consists of medium- to fine-grained sandstone with wavy mud drapes in the lower part, passing upward into dark gray mudstone with numerous, large ironstone concretions (Fig. 37B). Several overlying fining-upward cycles are similar to the first one, except that the basal sandstone units are finer. They consist of alternating thin beds of fine- to very fine-grained sandstone showing low-angle inclined lamination marked by mud couples. The uppermost cycle ends with rooted, coaly shale passing upwards into coal.

The lithology of the lower St. Mary River Formation above the Bearpaw shale in the next outcrop downstream is very similar. The sandstone layers contain abundant redeposited oyster shells which are characteristic for lower St. Mary River strata. These marginal marine, lagunal to brackish sediments represent the same regressive shoreline that was examined in Stops 2 and 3 (see description and interpretation of the Carroll Canyon section on pages 13–27).

DAY 3

Autochthonous Willow Creek and Porcupine Hills formations of the Alberta Syncline

Stop 11. Red beds of the Willow Creek Formation at Cowley

The best outcrops of the lower Willow Creek red beds are located some 3 km west of the confluence of the Crowsnest and Oldman rivers on both sides of a former bridge over the Crowsnest River at Cowley. The newly built Oldman River Dam has changed the topography of the Crowsnest River valley in the area. The valley is flooded most of the year and the sections of the Willow Creek red beds form the banks of the reservoir (Figs. 38, 39). What used to be called the Cowley bridge section of the lower Willow Creek (Fig. 39A) is aproached from the Cowley Cemetery along the southern bank of the Oldman Reservoir.

Structurally, the sections are situated east of the Triangle Zone on the western limb of the Alberta Syncline some 13 km west of its axis. The strata dip 20° northeast. The lower Willow Creek Formation lies unconformably above the St. Mary River Formation and below the Cretaceous–Tertiary boundary which marks the base of the upper part of the Willow Creek Formation (Jerzykiewicz and Sweet, 1988). The lower contact of the Willow Creek Formation with the St. Mary River Formation is nowhere exposed in the Foothills (Russell, 1965). The closest outcrop of this contact to the Disturbed Belt was described in the Plains by Tozer (1956) in the Oldman River cut west of Lethbridge. There, the St. Mary River and Willow Creek formations are separated by a regional stratigraphic marker, the Kneehills Tuff. The lower Willow Creek Formation is the correlative of the lower Coalspur Formation in the central Foothills, and of the lower Scollard in the central Foothills and Plains (Fig. 2). The Late Maastrichtian age of the lower Willow Creek is proven by palynology (Jerzykiewicz and Sweet, 1986), and by the presence of dinosaur bones. The bone bed found in the coulee opposite Stop 11, on the opposite bank of the Oldman Reservoir yielded tyrannosaurid and hadrosaurid bones including one complete skeleton of *Tyrannosaurus rex* (Fig. 38).

The most conspicuous features of the lower Willow Creek mudstone are its pink to red colour and the common occurrence of caliche nodules. These strata, described in terms of the Caliche Member of the Willow Creek Formation (Jerzykiewicz and Sweet, 1988), were mapped along the Foothills belt as far north as Nanton. Farther north, in the Turner Valley area, lower Willow Creek strata are devoid of red beds and caliche nodules in mudstone, but channel sandstone still contains fragmented and redeposited caliche debris.

Recessive mudstone is the dominant lithology. At Stop 11 it is interbedded with two compound, channelized sandstone layers (individual channel units are up to 1 m thick), and some thinner (less than 30 m thick) sandstone sheets. Both the lower and the upper compound sandstone layers are well exposed in outcrop so that the internal geometry and the relationships between individual channels can be seen. The lower compound layer is composed of two vertically stacked channel units and shows complex internal erosion surfaces with truncated trough crossbedding (Fig. 39C). The axis of the trough cross-bedding indicates northeastern paleo-currents (mean azimuth from 29 readings is 51°). The channel lag contains mud-chips and redeposited caliche debris (Fig. 39D).

The recessive intervals consist of varicoloured mudstone to silty and/or sandy mudstone containing caliche nodules and hardpan. Some thin beds of ripple-drift stratified sandstone alternating with mudstone are also present. The pink to red coloured (5 R 7/4 to 5 R 6/6) mudstone seems to be the most distinctive for the lower Willow Creek Formation, although the greyish olive-green and brown varieties (5 GY 3/2 to 5 Y 4/1) are equally common.

The caliche nodules are clearly of accretionary origin and result from a process of calcium carbonate accumulation in a subaerially exposed diagenetic environment (Esteban and Klappa, 1983). Calcium carbonate accumulation may have begun at plant roots, as indicated by rhizocretions (caliche concretions of root shape) found in the position of growth (Fig. 12 *in* Jerzykiewicz and Sweet, 1988). The nodules grew by precipitation from downward-percolating soil water enriched in calcium carbonate. The septarian crack pattern developed by case-hardening of the nodule exterior and shrinkage by dehydration of the interior ("irreversible chemical desiccation" of Pettijohn, 1949). The process of nodule formation requires several alternations of calcium carbonate dissolution and reprecipitation and is characteristic of soil profiles in semiarid climates (Gile et al., 1966; 1981). The most favorable conditions for caliche formation exist in regions where the annual rainfall is between 400 and 600 mm (Goudie, 1983). Essential for caliche formation also appears to be the sporadic distribution of rainfall, i.e. alternation of periods of rainfall and long-lasting droughts (Woolnough, 1930).

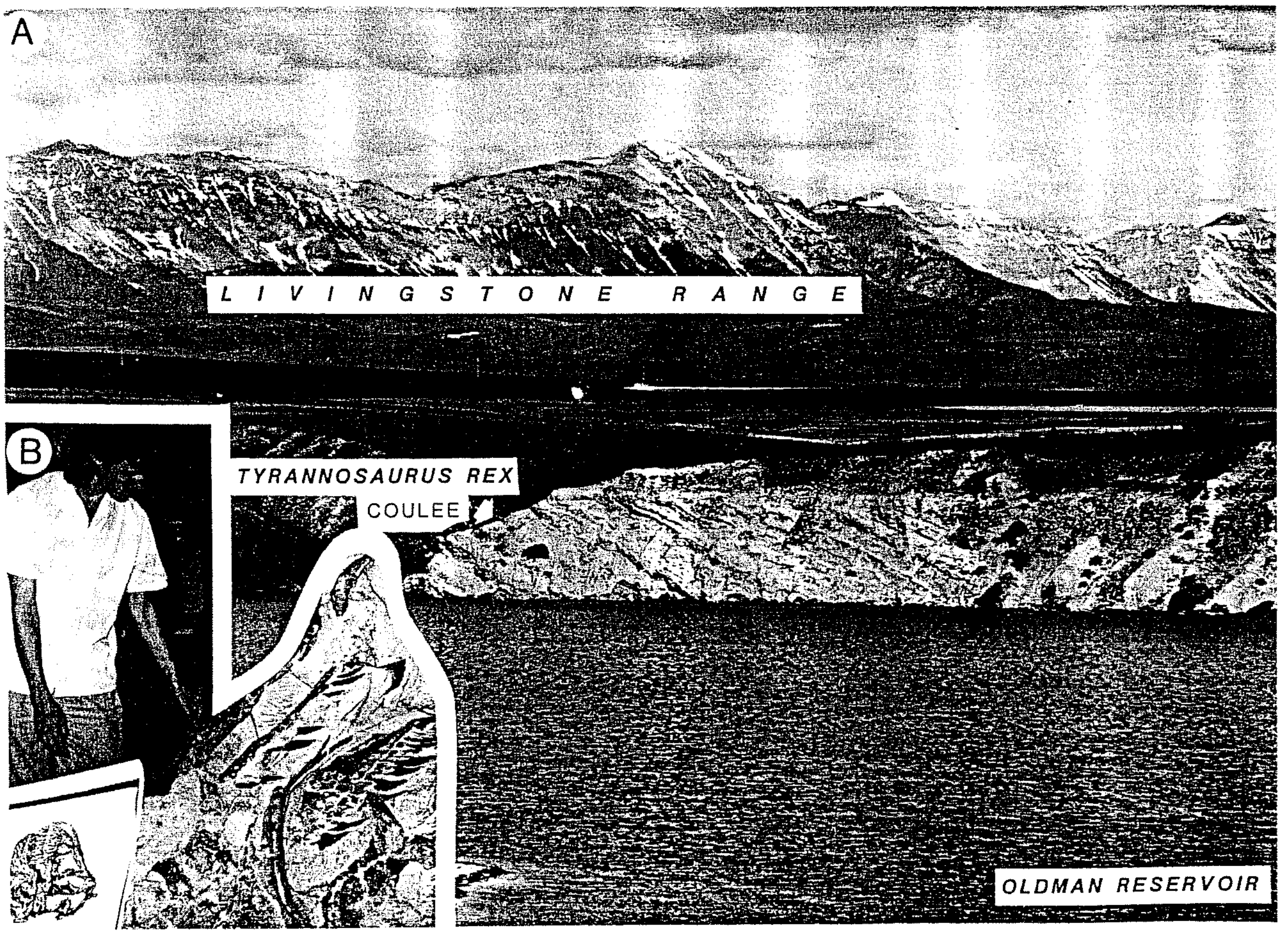


Figure 38. Tyrannosaurus rex coulee at Cowley.

A. Location of the Tyrannosaurus rex coulee in the Crowsnest River valley at Cowley flooded by the Oldman River Reservoir.

B. Skull of Tyrannosaurus rex from the lower Willow Creek at Cowley in preparation at the Royal Tyrrell Museum of Paleontology in Drumheller.

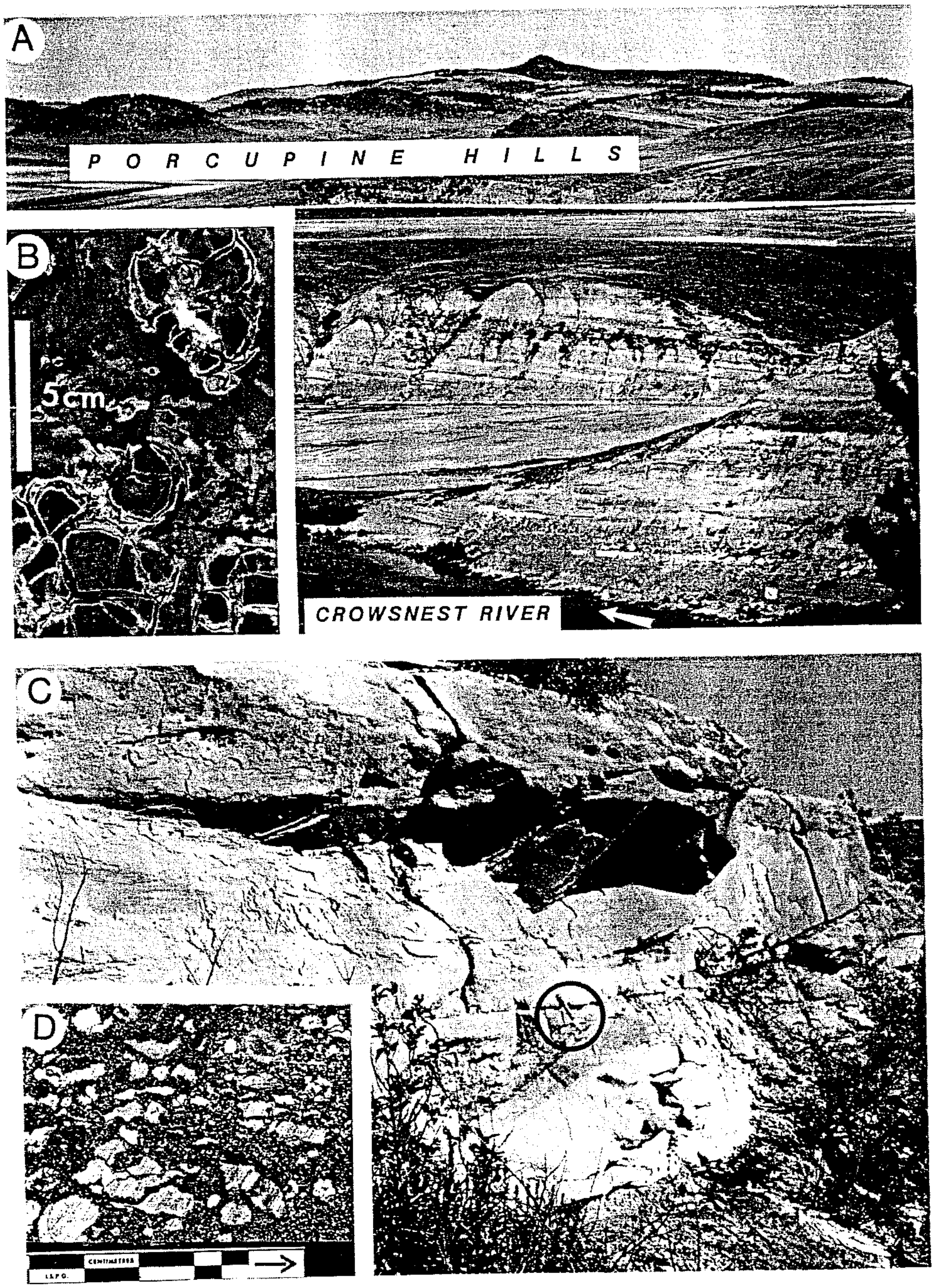


Figure 39. Lower Willow Creek Formation in the type section at Cowley.

- *A. Sections of lower Willow Creek strata on both sides of the Crowsnest River at time of low water level in the reservoir.*
- *B. Septarian structures of coalescent caliche nodules.*
- *C. Compound layer of channel sandstone.*
- *D. Redeposited caliche debris at base of a channel sandstone.*

It has been shown also that the depth of the caliche zone in the soil profile depends on the amount of annual rainfall (Jenny and Leonard, 1939). With increased annual rainfall, the zone of caliche formation moves to a greater depth and finally disappears when the annual precipitation (in temperate regions) exceeds 1000 mm (Blatt et al., 1980).

It is reasonable, therefore, to assume that the caliche nodules and hardpan of the Willow Creek were formed in a soil profile that developed in semiarid conditions where rainy seasons succeeded long-lasting periods of drought (similar conditions are also assumed for the Concretionary Member of the Belly River Formation as indicated on p. 51 of this Guidebook).

Some of the caliche nodules in the lowermost interval of the section exposed at Stop 11 are redeposited and mixed with large fragments of silty mudstone and siltstone within the background mudstone. These recessive intervals in the lower part of the section consist of structureless mudstone that contains subangular to subrounded sandstone and siltstone fragments of local derivation. The size of these redeposited clasts is up to 20 cm in diameter. The clasts "float" within the supporting muddy matrix. These layers are interpreted in terms of a mudflow deposit (Sharp and Nobles, 1953). The mudflow layers are capped by sandstone sheets and/or ripple cross-stratified thin beds of sandstone which indicate that the periods of dense and viscous mudflows, triggered by a flood event, were followed by stream flow during waning flood waters.

The association of facies found in the red beds of the lower Willow Creek Formation as well as the wedge-shape external geometry of the entire lower member of the Willow Creek Formation in the southern Foothills (Figs. 3, 4; Russell, 1965), indicate sedimentation in distal areas of alluvial fans in a semiarid climate. Processes of sedimentation that laid down the mudstone are not entirely clear as most of them are structureless. However, the co-occurrence of well developed hardpans and mudflow deposits indicates extreme changes in the rate of accumulation. The presence of mudflow deposits strongly supports the alluvial fan interpretation rather than the alluvial plain one. Long-lasting periods of pedogenesis in semiarid conditions were interrupted by flood events that triggered the mudflows and reactivated the ephemeral braided channels in the lower fan area.

Biological evidence further confirms the alluvial fan interpretation of the lower Willow Creek strata. The recovery of pollen and miospores was very poor and many samples were barren (Jerzykiewicz and Sweet, 1988). Invertebrate fossils are scarce in contrast with the upper part of the Willow Creek Formation which is interpreted as an alluvial plain to lacustrine deposit. Finally, the state of preservation and distribution of dinosaur bones in the bone layer at Cowley, that is correlative with the lower compound sandstone layer exposed at Stop 11, seems to support the alluvial fan interpretation. Abler, who mapped the *Tyrannosaurus rex* quarry, noticed: "...The approximately bell-shaped distribution of bones in the Crowsnest deposit (i.e., sparsest concentration of bones in the top and bottom layers, or levels ONE and SEVEN; densest concentration of bones in the central layer, or level FOUR) further suggests that some random process has indeed operated in the formation of the deposit."... (Abler, 1984, p. 13).

Stop 12. Oldman River Dam viewpoint

The effects of geological setting upon the design and construction of the Oldman River Dam (by H. H. Hartmaier, Acres International Limited, Calgary)

Introduction

Constructed between 1986 and 1991, the Oldman River Dam provides flow regulation and on-stream storage of water for irrigation and multi-purpose use in southern Alberta. In the future, the hydroelectric potential of the site may also be developed as a secondary benefit. The site is located near the confluence of the Oldman, Castle and Crowsnest River; hence, the site was originally referred to as the Three Rivers Site.

The principal project structures include a 76 m high-zoned earth and rock-fill embankment dam, a low earth-fill dike 1.5 km long, twin 6.5 m diameter concrete-lined diversion tunnels 900 m long, 1.5 km of drainage tunnels 3 m in diameter in both abutments and a 25 m high spillway structure comprising a 110 m wide headworks transitioning into a 40 m wide chute and flip bucket energy dissipator. Figures 40–42 show the general project layout and cross-section through the dam.

Bedrock

The dam site is founded on fluvial sediments of Paleocene age belonging to the Porcupine Hills Formation (Fig. 2). The underlying late Cretaceous Willow Creek Formation occurs at a depth of 50 m below river level.

For engineering purposes, the rocks at the dam site have been subdivided into three major units:

- Upper Mudrock Sequence
- Basal Sandstone Sequence
- Lower Mudrock Sequence.

As shown in Figure 43, the Upper Mudrock Sequence forms both abutments of the dam. The Basal Sandstone Sequence is exposed in the valley floor and forms the foundation of the dam in the center of the valley. In general, there are four main rock types: claystone, siltstone, sandstone, (overbank facies) and sandstone (channel facies). Gradational varieties are common, i.e., silty claystone and sandy siltstone. Collectively, the claystone and siltstone units are referred to as mudrocks.

The Upper and Lower Mudrocks have similar engineering properties; therefore, the exact location of the Porcupine Hills/ Willow Creek contact was not critical in the design of the project. Unconfined compressive strengths range from 0.6 MPa for some claystones to 130 MPa for massive sandstones. Siltstones are quite variable, ranging between 8 and 110 MPa depending on clay content and degree of cementation.

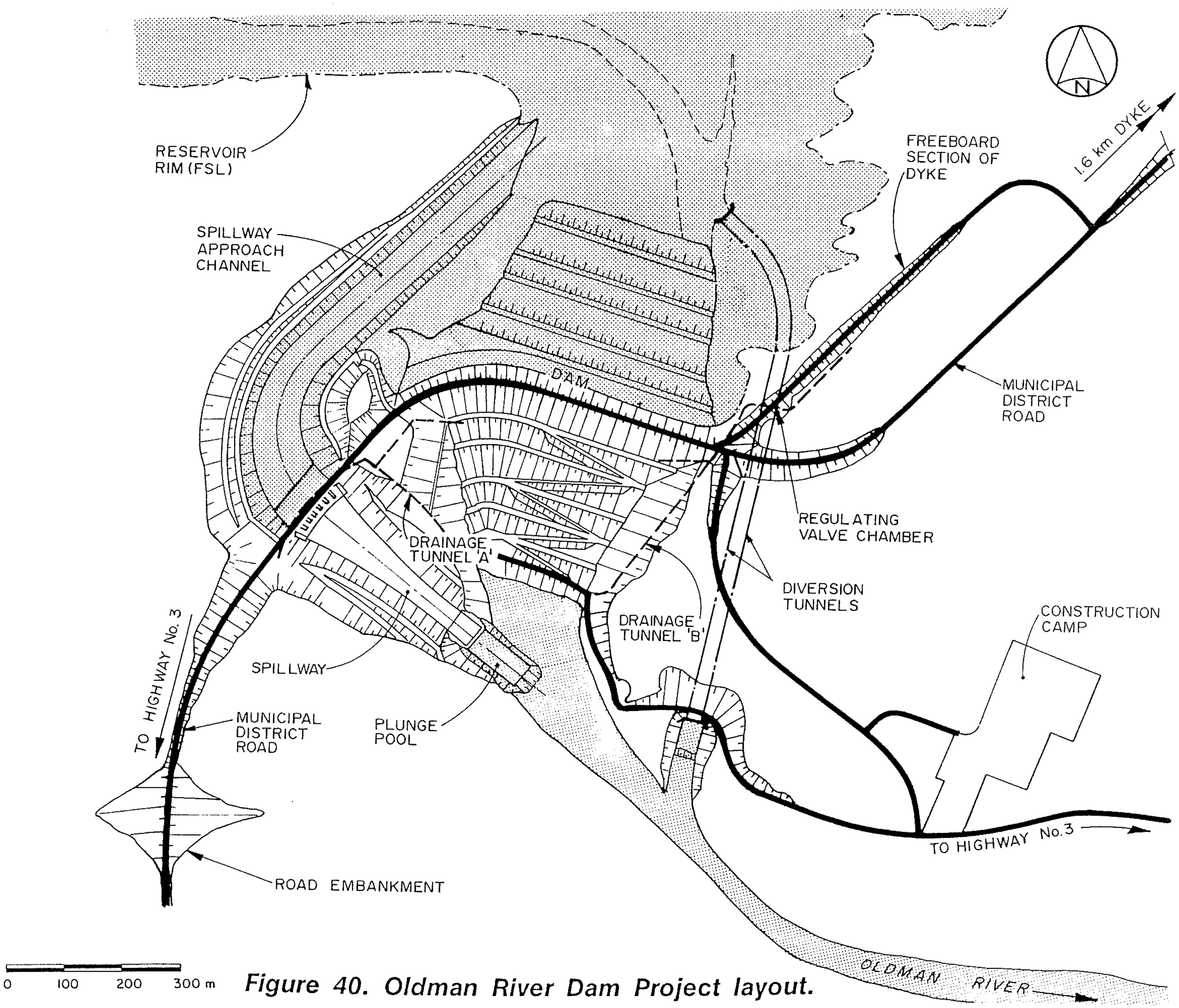


Figure 40. Oldman River Dam Project layout.

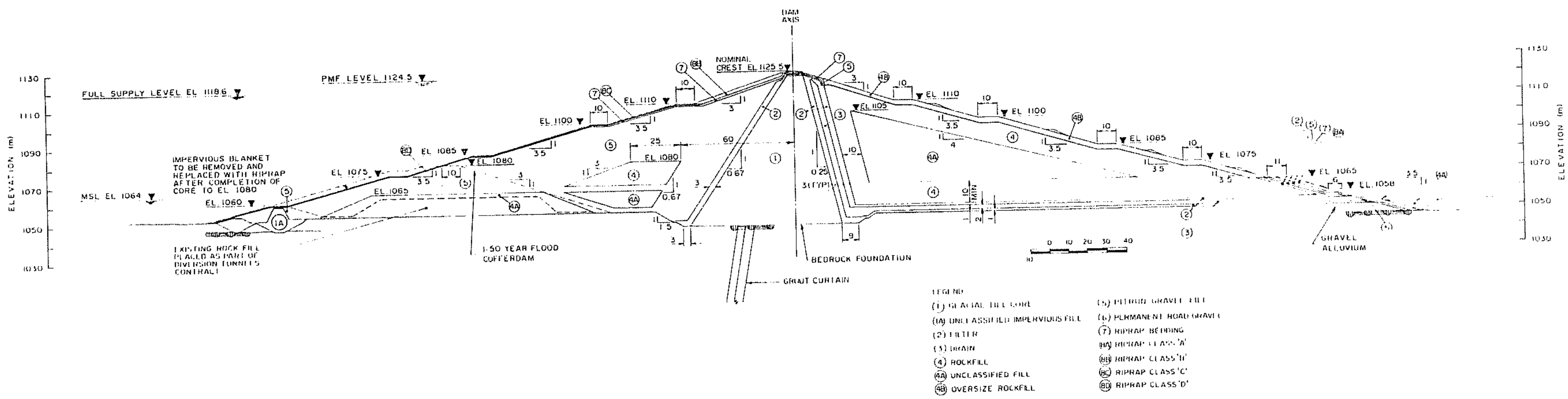


Figure 41. Oldman River Dam cross-section.

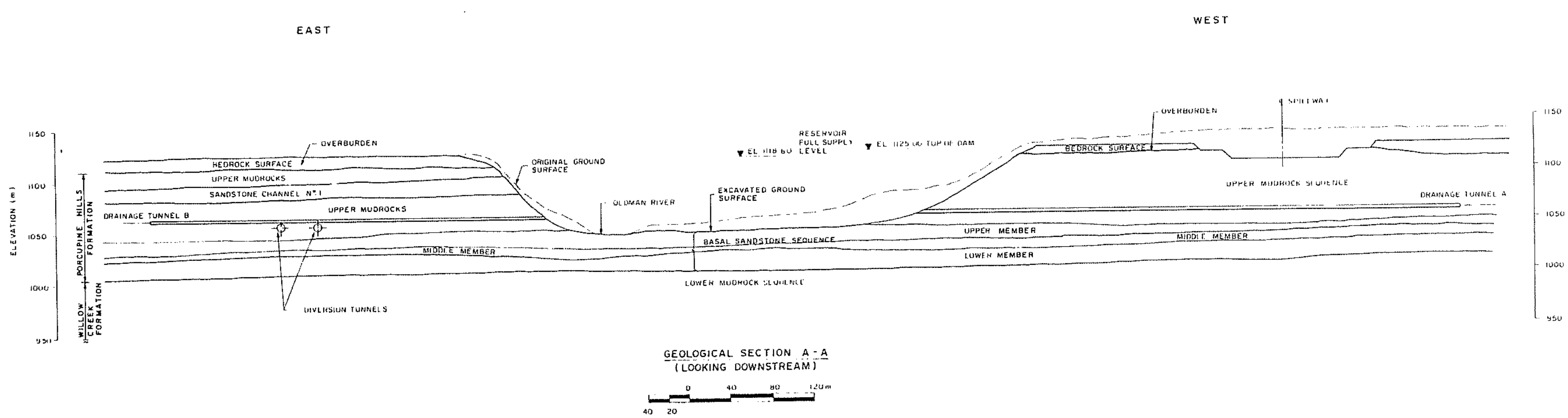


Figure 42. Geological cross-section along the axis of the dam.

Typically, beds are uniform in thickness (0.3 to 2 m) and continuous over great distances, although lateral facies variations occur. Rhythmically bedded sequences of mudrocks, including overbank facies sandstones are typical within the Upper and Lower Mudrock sequences.

Thin black or dark gray carbonaceous claystone and siltstone beds occur throughout the stratigraphic section. These were used as marker beds to correlate stratigraphy and subdivide the Upper Mudrock Sequence into at least five members (Fig. 43).

Beds dip at about 0.6° in a N17°E direction, reflecting the proximity of the dam site to the axis of the Alberta Syncline about 2 km to the east.

Four sets of sub-vertical joints, forming two distinct orthogonal conjugate pairs were found at the site with the following strike directions:

1. east–west,
2. north–south,
3. northeast–southwest, and
4. northwest–southeast.

Sets 1 and 2 are the most predominant. Sets 3 and 4 are locally non-existent. Strike directions may vary locally by ±20°. Although joints are found in all rock units, they are best developed in the sandstones and more resistant or calcareous siltstones. Typically, joints are spaced one or two times the bed thickness. In the clay-rich, less resistant mudrocks, joints are poorly developed and more closely spaced (10 to 30 cm). Horizontal continuity of joints may exceed 20 m in sandstone, whereas vertical continuity is usually more limited with joints terminating at a bedding plane contact with adjacent mudrock units.

Overburden

Successive glacial events during the Pleistocene left a thick covering of glacial drift (Buffalo Lake Till) overlain by glaciolacustrine silts and clays (Lake Caldwell sediments) in the upland area adjacent to the dam site. Alluvial silt, sand and gravel deposits occupy terraces and the floodplain of the Oldman River. The valley slopes are mantled by colluvium.

The Buffalo Lake Till is up to 35 m thick at the site and comprises brown, medium to high plastic clay and silt, 5% gravel with cobbles and boulders. This material was used to construct the impervious core of the dam (Fig. 41).

Glacial Lake Caldwell sediments, 4 to 16 m thick comprise laminated (varved) clay, clay and silt and silt with local silty sand. Clays are typically medium to high plastic. Glaciolacustrine silty clay was used in the construction of the 1.5 km long dike on the left abutment.

Engineering Geology

Experience with other dams constructed in Western Canada in similar geological settings indicated the need to evaluate the following areas of concern:

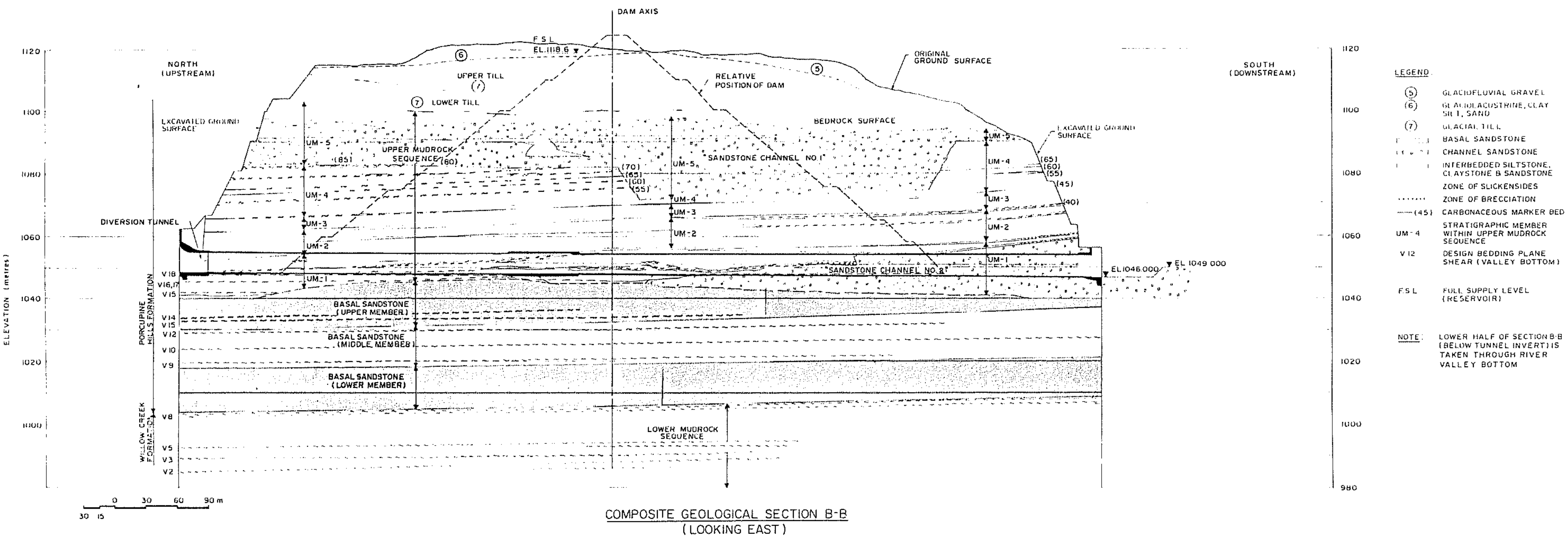


Figure 43. Geological cross-section perpendicular to the dam axis.

- presence of low shear strength structural features in the bedrock units,
- implications of valley rebound and stress relief phenomena,
- wide range of strength and mechanical properties of bedrock units,
- hydraulic conductivity of the dam foundation, and
- slake durability of mudrock units upon exposure in excavations.

Detailed field investigations (Davachi et al., 1991) revealed the presence of bedding-planeshears in the mudrocks. These features of relative weakness and low shear strength were found at all structure locations and occur throughout the stratigraphic section. Special emphasis was given to identification and description of these features since their presence strongly influences foundation shear strength. Six vertical shafts, 1 m in diameter and up to 60 m deep, were drilled into the foundations of the dam and spillway to examine the bedding plane shears in situ. Each shaft was geologically mapped in detail. Samples of clay-filled bedding plane shears were then obtained using a 20 cm diameter coring bit mounted in a special cage which allowed horizontal cores to be taken from the walls of the shaft. The characteristics of the bedding plane shears can be summarized as follows.

The bedding plane shears usually occur along the contacts of relatively strong and weak rocks such as sandstone and claystone or in claystones sandwiched between stronger siltstones or sandstones. They may occur either as a single shear plane less than 2 mm thick, filled with clay and silt, or as a group of closely spaced sub-parallel shear planes. Brecciated zones, up to 20 cm thick, containing angular rock fragments in a matrix of silt and clay gouge are also common. Horizontal continuity is generally in the order of tens of metres. However, the most critical bedding plane shears have been traced over hundreds of metres; therefore, they extend over the base width of the structures constructed on them.

Bedding plane shears are common features in interbedded claystone and siltstone sedimentary rock sequences in western Canada and elsewhere (Ferguson and Hamel 1981; Imrie 1991). Their development is related to the following general mechanisms:

- tectonic activity,
- glaciotectonic activity, and
- valley rebound and stress relief.

Each of these mechanisms may be responsible for the development of bedding plane shears at various times in the geologic history of the Oldman River Dam foundation.

A total of 22 continuous bedding plane shears was identified by correlation of borehole data and exposure mapping. Laboratory determined effective angles of shearing resistance ranged between 8° and 30°.

The clay-rich rocks were subjected to a number of soils type index tests by "blenderizing". Atterberg limit determinations indicate that most of the claystones are of medium plasticity. The dominant clay mineral is kaolinite. Similar properties were noted for the clay fillings in the bedding plane shears supporting the idea that the filling material was generated by shearing rather than infilling from foreign sources. No bentonite seams were found at the Oldman River Dam site.

Slake durability testing indicated that the sandstones are well indurated and cemented siltstones are the most resistant to slaking. Claystones or clayey siltstone are the most susceptible, typically retaining 0 to 20% after three slaking cycles.

The low shear strength available along the continuous bedding plane shears had a major effect on the design and layout of the dam and all other project structures (Davachi et al., 1991). A wide dam base was required for stability. This in turn determined the length of the diversion tunnels, spillway and its approach channel.

Stability of rock excavations and rock support requirements were also dictated by the shear strength of the bedding plane shears. Stress relief and excavation rebound effects were taken into account in the design of the spillway headworks. Approximately 40 m of soil and rock were excavated at the headworks which will result in an estimated 140 mm of differential heave across the excavation. Therefore, the piers of the headworks were designed with a vertical seam to accommodate differential movements across the structure.

Valley rebound effects are also evident in the distribution of rock mass permeabilities and grout takes in the dam foundation. In the valley bottom, hydraulic conductivities ranged from 6×10^{-3} cm/sec to 3×10^{-5} cm/sec, versus 4×10^{-4} cm/sec to 5×10^{-6} cm/sec in the abutments.

Open, sub-horizontal bedding planes in the valley bottom and sub-vertical stress relief joints parallel to the valley sides in the abutments were the major discontinuities which required treatment. The entire dam core trench bedrock foundation was blanket grouted to a depth of 5 m to seal any open fractures. Grout take averaged 72 kg/m of grout hole.

The bottom of the two line grout curtain was established within the relatively impervious Lower Mudrock Sequence to form an impervious seal across the dam foundation. Grout takes averaged about 26 kg/m of hole across the 1300 m length of the grout curtain.

Recharge from the reservoir will raise the groundwater table in the abutments. To prevent excess seepage water from affecting the stability of the dam abutments and to reduce uplift pressures on the base of the spillway, drainage tunnels were constructed into both abutments. Inclined drain holes will intercept both sub-horizontal and sub-vertical water-bearing fractures.

The poor slake durability of the mudrocks presented a problem in maintaining sound rock in the excavations. Shotcrete application was required within 24 hours of exposure of the final excavation grades to protect the mudrocks. This was carried out in all foundation excavations including the dam core trench in the abutments. In the tunnels, the walls were shotcreted and the invert was covered with a concrete mudslab.

Stop 13. Porcupine Hills Formation at the Oldman River Damsite

Excavation works in the Oldman River dam site area in late 1980-ties exposed excellent sections of the Porcupine Hills Formation. The entire channel and large sections of overbank mudstone were available for close examination in the area of the present diversion tunnel (Figs. 44A, 40C). Until flooded by the reservoir waters, these sections were the best source of information about the lithology of the formation. Sandstone cliffs scattered on the slopes of the Porcupine Hills and river cuts reveal only fragments of channels and very little overbank sediments.

The geometry of the Porcupine channel was studied near the present diversion tunnel of the dam (Fig. 44A). The Porcupine channel is cut into mud-dominated overbank strata and possesses a well defined sharp base and margins. The depth of the channel is about 15 m, and width/depth ratio is 4. It can be classified as of fixed or of ribbon-shape geometry (Miall, 1985). Internally, the channel fill comprises sets of low-angle inclined strata bounded by gently dipping second-order erosional surfaces. In the periphery of the main channel, second order small channels are filled with sand-silt couplets overlain by sand lenses bounded from the top by convex-up internal erosion surfaces (Fig. 44B). There is virtually no vertical trend of decreasing grain size on the scale of the individual sets of strata or the entire channel.

The apparent stacked character of the individual sets of strata bounded by erosional surfaces in a laterally confined main channel incised into overbank mudrock, and the lack of a fining upward trend, point to deposition in a fluvial system dominated by vertical rather than lateral accretion. The lateral, inclined stratfication may have been generated in a braided stream or anastomosing stream environment by lateral migration of side- and inchannel bars (Long, 1978). The presence of thick intervals of floodplain facies separating the channel sandstones also strongly supports the interpretation of the Porcupine Hills Formation in terms of a stable channel fluvial system – termed anastomosed streams by Smith and Smith (1980).

The anastomosed fluvial systems are characterized by an interconnected network of channels, separated by extensive stable islands with pronounced levees and vast floodplains of varies types depending on climate. They may be of wetland type (Smith, 1983), tropical savanna type (Tanner, 1974; Smith, 1986) or semiarid type with caliche development (Rust, 1981; Rust and Legun, 1983).

Lithology of the Porcupine Hills and Paskapoo formations may be explained in terms of a network of anastomosed channels that drained vast floodplains with shallow lakes and ponds. In the central part of the basin (north of Bow River), where the soil moisture regime was subhumid to humid (Jerzykiewicz,

A

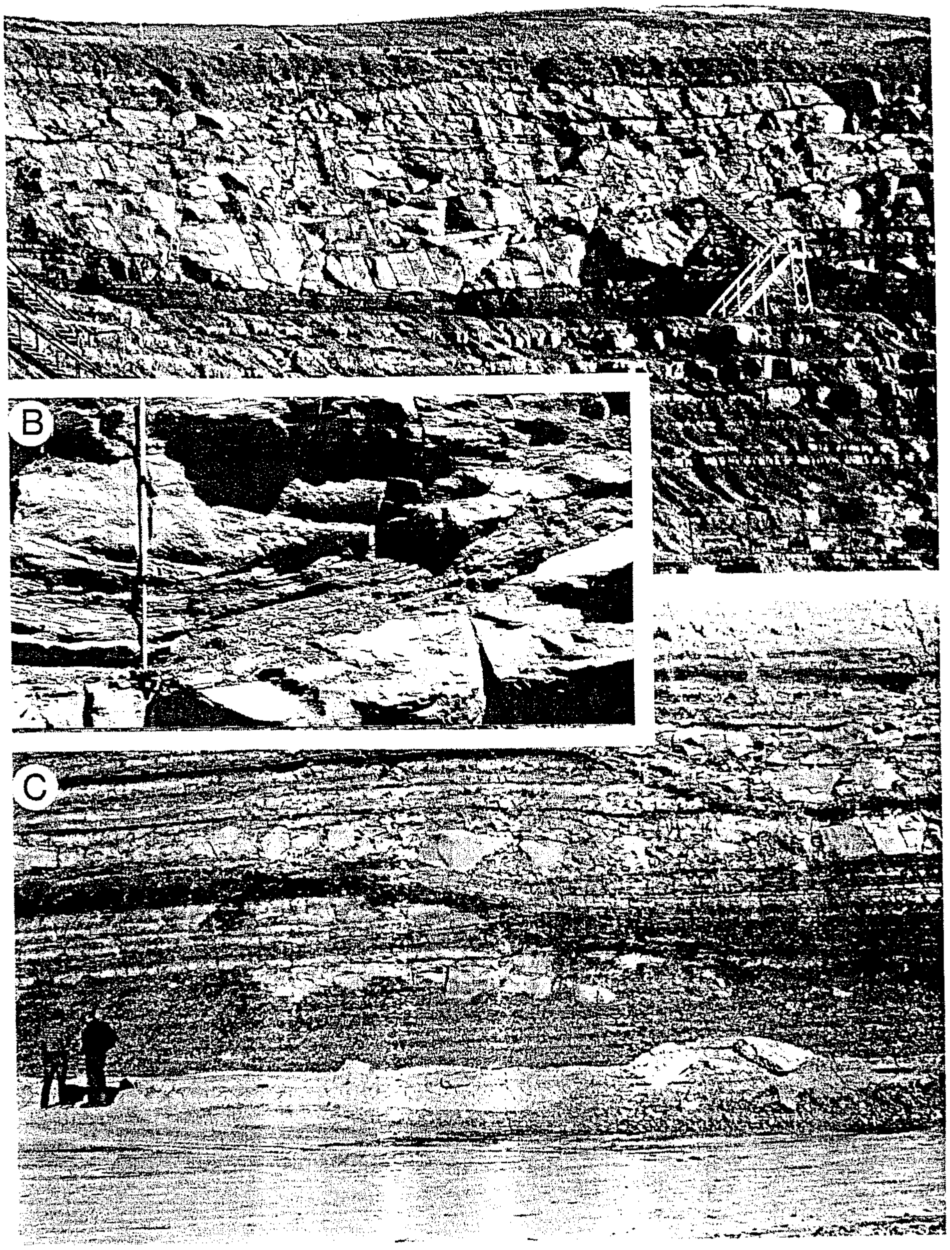


Figure 44. Channel and overbank facies of the Porcupine Hills Formation at the Oldman River damsite.

- *A. A channel incised into overbank facies. Section perpendicular to the flow, near the diversion tunnel of the damsite.*
- *B. A second order channel filled with sand-silt couplets and a sand lens bounded at the top by convex-up erosional surface, at the western periphery of the large channel shown on Figure 44A.*
- *C. Overbank mudstone interbedded with crevasse splay sandstone and siltstone layers at the spillway approach channel of the dam.*

1991) the floodplains, pond and lakes were surrounded by swamps and marshes. The southern part of the basin was much dryer as indicated by the lack of coal in the Porcupine Hills Formation and the presence of caliche debris.

Stops 14 and 15. Porcupine Hills Formation at the Skyline Drive

The Beaver Creek gravel road north- and north-westward from the vicinity of Brocket will lead us to the highest parts of the Porcupine Hills (Fig. 45A). Our intention is to demonstrate both geology and topography of the Porcupine Hills and the adjacent Front Ranges. The route along the Skyline Drive, following the axis of the Alberta Syncline, will give us an opportunity to visit outcrops of the youngest strata in the foredeep, and to enjoy a spectacular view of the Front Ranges of the Rocky Mountains from the top of the Porcupine Hills.

The topographic expression of the resistant sandstone marked by steep escarpments and cliffs, characteristic of the Porcupine Hills Formation, is readily visible in the Beaver Creek Valley. Especially well pronounced is a break in slope at the elevation of 4450 to 4500 feet. This break is developed at a resistant sandstone/mudstone boundary that can be traced over the entire Porcupine Hills area, and is quite visible on the Landsat image. The base of the sandstone that forms the morphological break has been arbitrarily chosen as a boundary between the lower and the upper parts of the Porcupine Hills Formation (Fig. 2).

Fire Lookout (Stop 14)

Cliffs at the top of the Fire Lookout hill are built up with a thick layer of resistant sandstone of the upper Porcupine Hills Formation. The layer consists of vertically stacked, trough crossbedded units of coarse- to medium-grained sandstone. The trough cross-stratified sets of strata are interpreted as sandy bedforms infilling a large fluvial channel, the boundaries of which are not exposed in the cliffs.

From this point at the crest of the Porcupine Hills there are spectacular views of the Laramide Foredeep from the Alberta Plains to the Front Ranges of the Rocky Mountains. They complement those seen from Lundbreck at Stop 6. Beneath our feet are subhorizontal strata of the Porcupine Hills sandstone in the core of the Alberta Syncline and immediately below us, low on the west flank of the Porcupine Hills, is the north-trending axis of the Triangle Zone. Between there and the wall of Mississippian limestone ahead of us to the west are the imbricated and topographically subdued Mesozoic rocks of the Foothills. The wall of limestone forming the Livingstone Range is the first range of the Rocky Mountains at this point. It marks the trace of the Livingstone Thrust, a major fault locally defining the interface between the Foothills and the Rocky Mountains. The fault is mapped for more than 145 km from north of the Highwood River to where it merges upwards with the Turtle Mountain Thrust in the Foothills west of Pincher Creek (Gordy et al., 1977). Beyond the Livingstone Range are glimpses of Upper Devonian and Carboniferous rocks

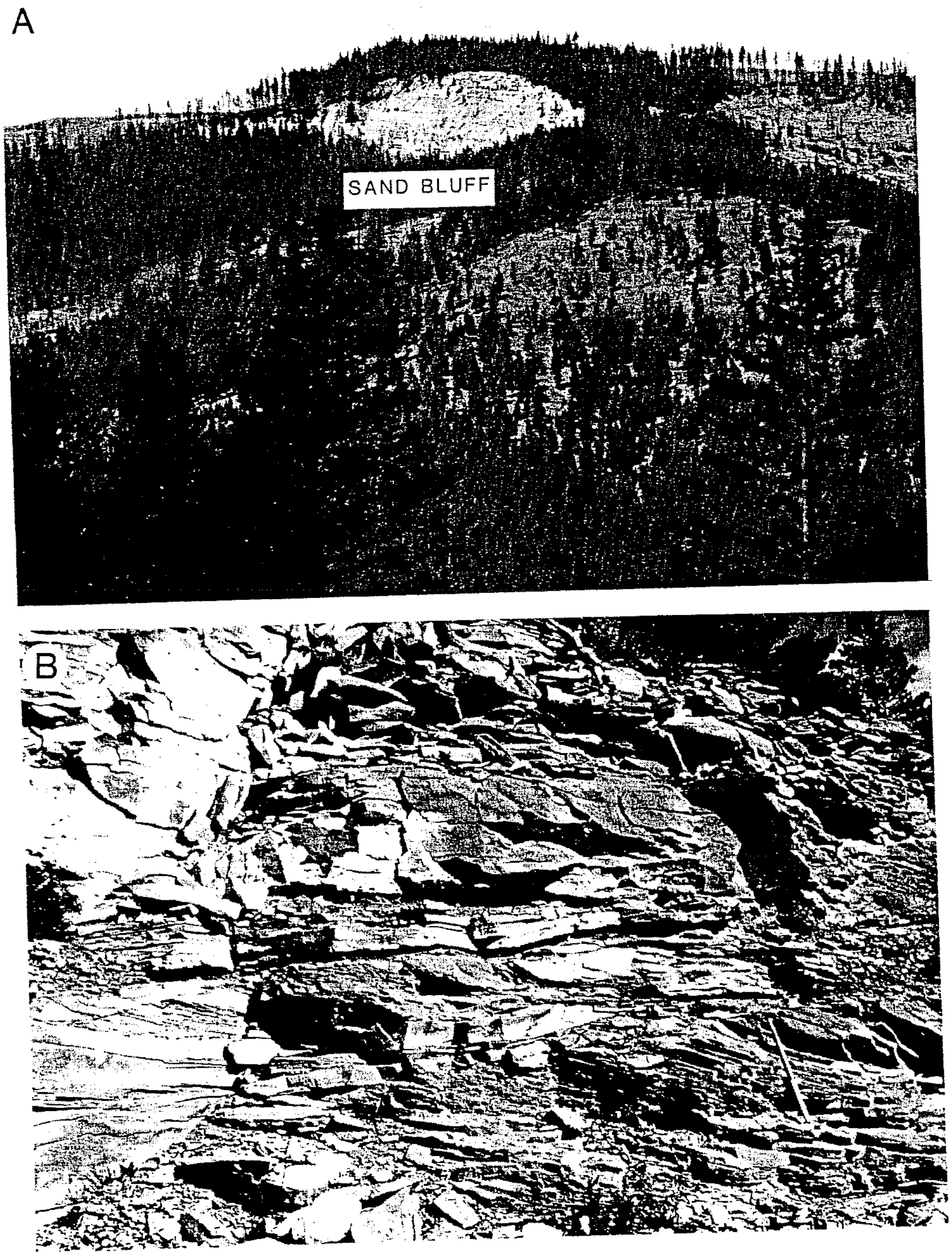


Figure 45. Upper Porcupine Hills Formation.

A. Sand Bluff outcrop near the Fire Lookout in the highest parts of the Porcupine Hills viewed from the Heath Creek road.
B. Inclined strata, erosional surfaces and trough crossbeds of a large anastomosed channel.

comprising the jagged peaks of the Highrock and Flathead ranges on the Continental Divide and forming the Lewis Thrust Plate.

Skyline Drive outcrop over Damon Creek Valley (Stop 15)

The road-cut some 6 km northwest from the Fire Lookout is one of the largest outcrops of the Porcupine Hills Formation in the area. Exposures of the channel fill, however, are fragmentary. Sets of inclined strata bounded by subhorizontal erosional surfaces are visible in a section approximately perpendicular to the axis of a main channel (Fig. 45B). Small, second order channels infilled with trough crossbedded strata are also present. Sets of inclined strata, erosional surfaces and channelized sets of trough crossbeds are interpreted as architectural elements of a large fluvial channel. From the size and geometry of these elements it is concluded that the main fluvial channel must have been of similar size and style to the anastomosed channel in the Oldman River Damsite area (Fig. 44).

Paleocurrent readings in the upper Porcupine Hills channel sandstone throughout the Porcupine Hills indicate northeasterly flow in the fluvial channels. The mean azimuth calculated from 864 readings for the entire Porcupine Hills Formation is 28° (Carrigy, 1971). Similar results were obtained by one of the authors of this Guidebook (TJ). Paleocurrent readings on trough cross-stratification (large bedforms) were grouped separately for the lower and the upper parts of the formation. Fifty readings for each part of the formation were obtained in the Porcupine Hills area. The mean azimuths were 48° for the lower, and 32° for the upper part of the formation. The 16° difference seems to be significant enough to assume that there may have been a slight change in the main direction of the flow between the early and late deposition of the formation. The style of the fluvial channels remained similar throughout the whole of the Porcupine Hills Formation. An anastomosed fluvial channel system is inferred for the Porcupine Hills in the southern segment of the foredeep. The geometry of the channels and the large amount of overbank deposits clearly indicate vertical rather than lateral accretion during the sedimentation of the Porcupine Hills Formation. Anastomosed fluvial systems are characteristic of rapidly subsiding foreland basins (Smith, 1986). The environment of the last stage of infilling of the rapidly subsiding foredeep in southern Alberta can be visualized as an anastomosing drainage system composed of channels flowing in a northeasterly direction i.e. essentially perpendicular to the mountain front.

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IV. A supplement to the Guidebook: "Evolution of the Laramide foredeep and adjacent thrust belt in southern Alberta" by T. Jerzykiewicz and D.K. Norris

Significant progress in our understanding of the stratigraphy of the "Belly River" clastic wedge has been achieved since the first edition of this guidebook because the Pakowki Formation has been positively identified within the thrust and fold belt in the vicinity of Lundbreck. It is now possible to separate the Alberta Group from the Belly River strata and to formalize the subdivision of the "Belly River". By designating the basal Belly River sandstone above the Pakowki Formation, the long standing correlation problem between the foothills and plains is resolved (Jerzykiewicz and Norris, in press). The Belly River is proposed to be raised to group status and to be subdivided into three formations, the Connelly Creek Formation (former Fluvial Member), the Lundbreck Formation (former Concretionary Member), and the Drywood Creek Formation (former Upper Member). The Transitional Member which underlies the Pakowki Formation is proposed to be subdivided into the Lees Lake and the Burmis formations. The Burmis Formation, formerly referred to as the "basal Belly River sandstone", has been correlated by Stott (1963) with the Chungo Member of the Alberta Group and included in the Belly River Formation. This practice is inconsistent with the nomenclature presented herein.

The newly proposed stratigraphic nomenclature (Figure 1S), which is the subject of this supplement, will be discussed during the field trip. It has not been published yet (Jerzykiewicz and Norris, in press).

The Pakowki Formation has been identified in two closely spaced, and tectonically repeated, railway track sections described in the guidebook as Stop 9b. A fragment of the more westernly of the two sections with the Pakowki interval marked is shown in the Figure 2S. The Pakowki Formation in this section consists of a shaly interval up to 2 m thick, underlain by about 5 m of stacked sandstone layers. Hummocky cross-stratification is the dominant sedimentary structure in both the shaly and the sandy intervals. The sandstone beds in the shaly interval are between 5 to 10 cm thick and have sharp lower and upper contacts. The soles of the sandstone beds are covered with abundant organic traces and rare scour and tool marks. The tops of some beds display straight-crested, symmetrical wave ripples and trace fossils. Sedimentary structures found in the Pakowki Formation suggest offshore deposition between storm and fairweather wave base.

A sample from the shaly interval of the Pakowki Formation "contained *Mancicorpus calvus* suggesting an upper lower to upper Campanian age for the sample. It also contained a selection of dinoflagellates indicating the depositional environment was marine." (D. Braman, written communication, 1993).

The Pakowki Formation is marked on geophysical logs (Fig. 3S) in the interval at depths between 8050 to 7925 ft (Cow Creek well), and in the interval between 6730 and 6540 ft (Alcon Peigan well). It

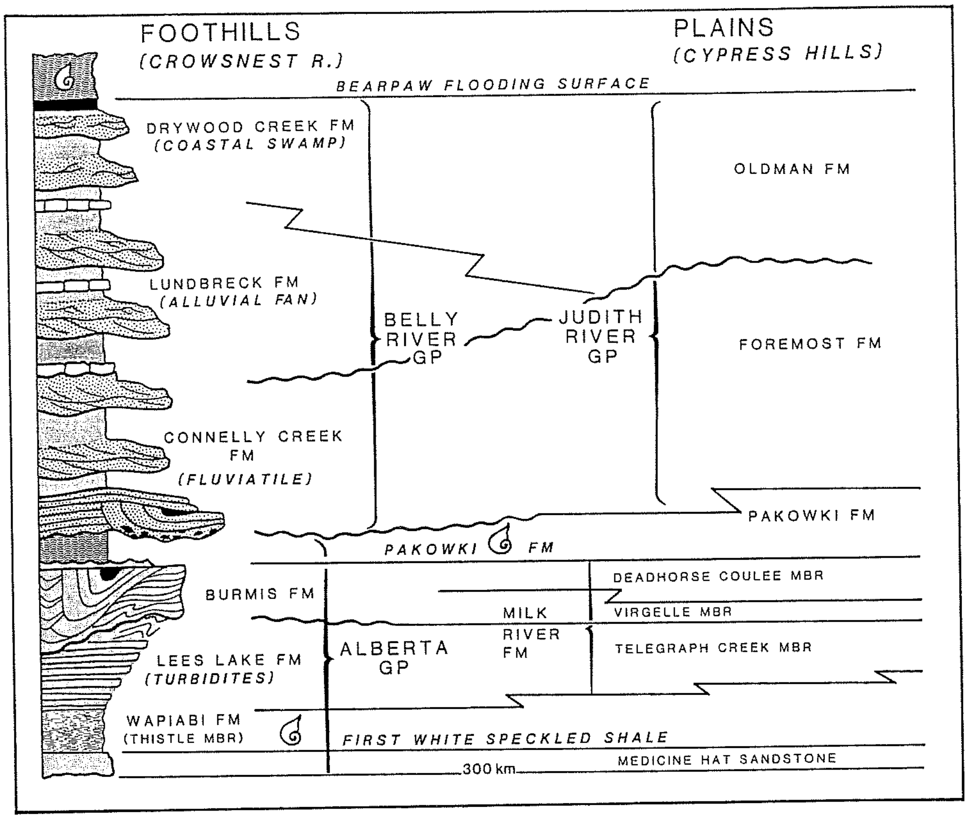


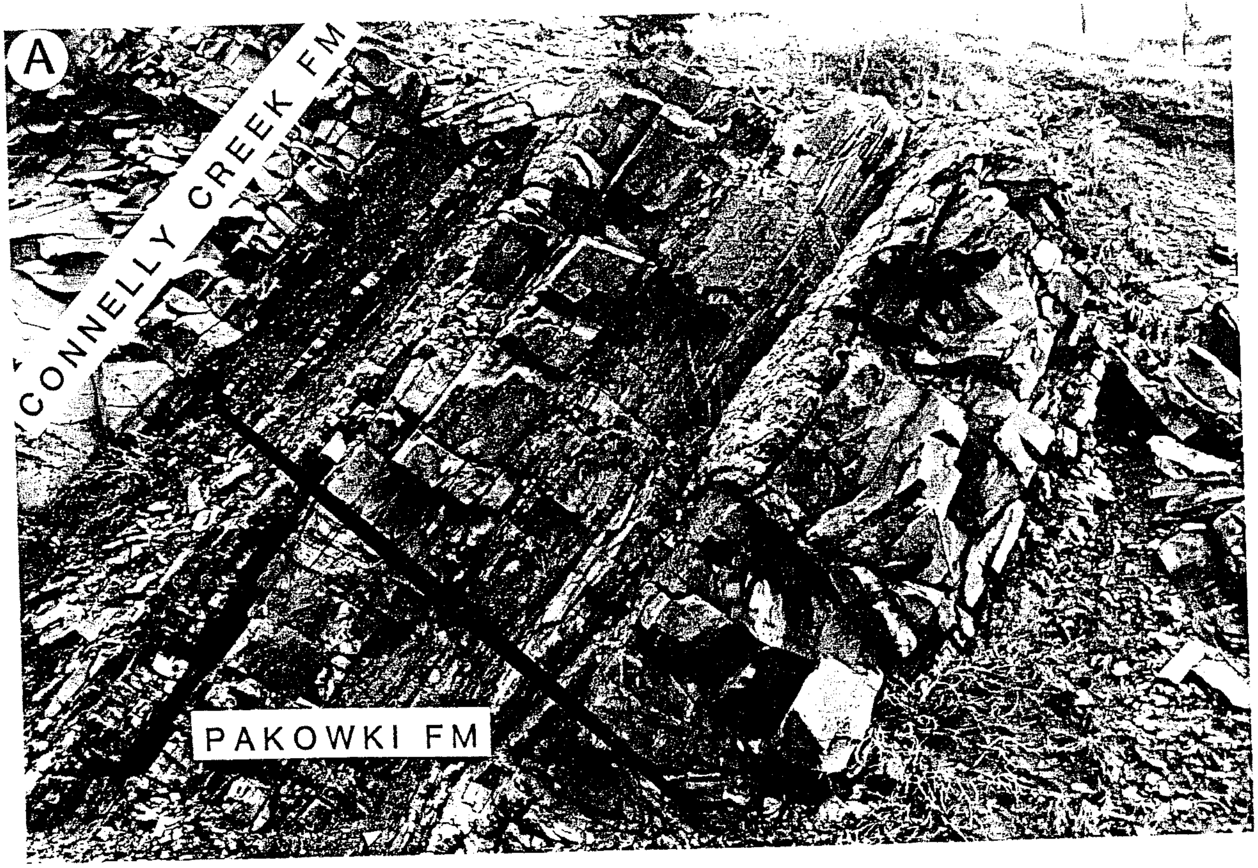
Figure 1S. Proposed stratigraphic classification of the "Belly River" clastic wedge in the southern Foothills and correlation with the southern Alberta Plains.

can be traced farther east beneath the Plains where it increases in thickness and merges with the marine shales of the type area for the Pakowki Formation. Such a correlation was recently confirmed by micropaleontological study of the California Standard Cow Creek well by J.H. Wall (unpublished GSC report no. 2–JHW–1991), who stated: "...there is a strong occurrence of *Haplophragmoides rota*, which, although present in the Bearpaw above, is also characteristic of the higher beds of the Wapiabi Fm. in the Foothills. There, the specimens tend to be large as are those in the 7940–8010 ft interval.". Foraminifera were also found in samples from the surface section of the Pakowki Formation along the railway cut (J.H. Wall, personal communications, 1992 and 1993).

Type sections and subsurface references of the newly proposed formations

Lees Lake Formation

The type section is in the Crowsnest River cutbank some 1200 m down stream from Lundbreck Falls, and is commonly referred to as the Lundbreck Falls transition section (Stop 7, Fig. 4S). The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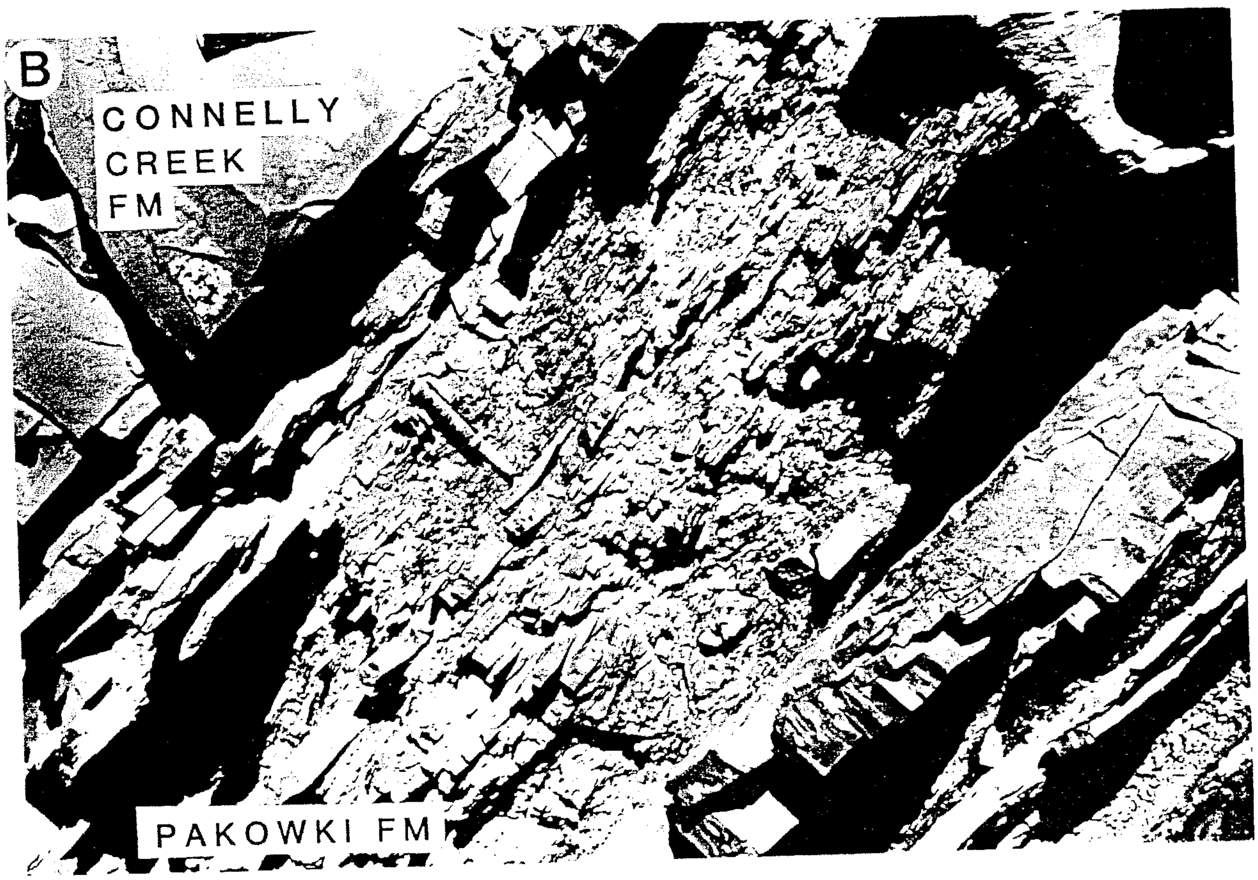
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subsurface reference section is the California Standard Company Cow Creek well (LSD 6–30–8–1W5) from depths 8580 to 8365 ft (Fig. 3S).

Burmis Formation

The type locality is at Connelly Cliffs (informal name) located near the top of a hill some 1.5 km northwest of Lundbreck Falls. The formation is named after Burmis, a hamlet located in the Crowsnest River valley along Highway 3 some 10 kilometres west of Lundbreck. The reference sections are: the Lundbreck Falls transition (Stop 7, Fig 4S) and the Lundbreck waterfall cliff. The subsurface reference is the California Standard Company Cow Creek well (LSD 6–30–8–1W5) from depths 8365 to 8050 ft (Fig. 3S). In the Petcal Company Limited Alcon Peigan well (LSD 10–27–8–28, the Burmis Formation occurs between 6985 and 6730 ft (Fig. 3S).

Connelly Creek Formation

Several good exposures of upward-fining, channelized sandstone layers and upward-coarsening sandstone beds interstratified with mudstone which belong to the Connelly Creek Formation occur in the vicinity of the Crowsnest River valley. None of these outcrops, however, provides a complete section of the formation. The entire Connelly Creek Formation, which is several hundred metres thick, has been penetrated by the California Standard Company Cow Creek well (LSD 6–30–8–1W5) between 7925 and 7357 ft (Fig. 3S). This interval is designated the type section. It is also recognizable in the Petcal Company Limited Alcon Peigan well (LSD 10–27–8–28) between 6540 and 6060 ft (Fig. 3S). The name of the formation is derived from Connelly Creek, a southeast-flowing tributary to Crowsnest River in the vicinity of Lundbreck.

Lundbreck Formation

The Lundbreck Formation is exposed in many usually small outcrops along Crowsnest River and along Highway No. 3 west of Lundbreck. The best exposure, located at the river bend some 2 km northeast of Lundbreck Falls (Stop 8), is designated the type section. All the characteristic features of these caliche-bearing, semiarid alluvial fan strata interfingering with playa sediments of the Lundbreck Formation are exposed there. The Lundbreck Formation has been indentified on electric logs of the California Standard Company Cow Creek well (LSD 6–30–8–1W5) from depths 7357 to 7045 ft, and on the electric log of the Petcal Company Limited Alcon Peigan well (LSD 10–27–8–28) from depths 6060 to 5805 ft (Fig. 3S). The name of the formation is derived from the town of

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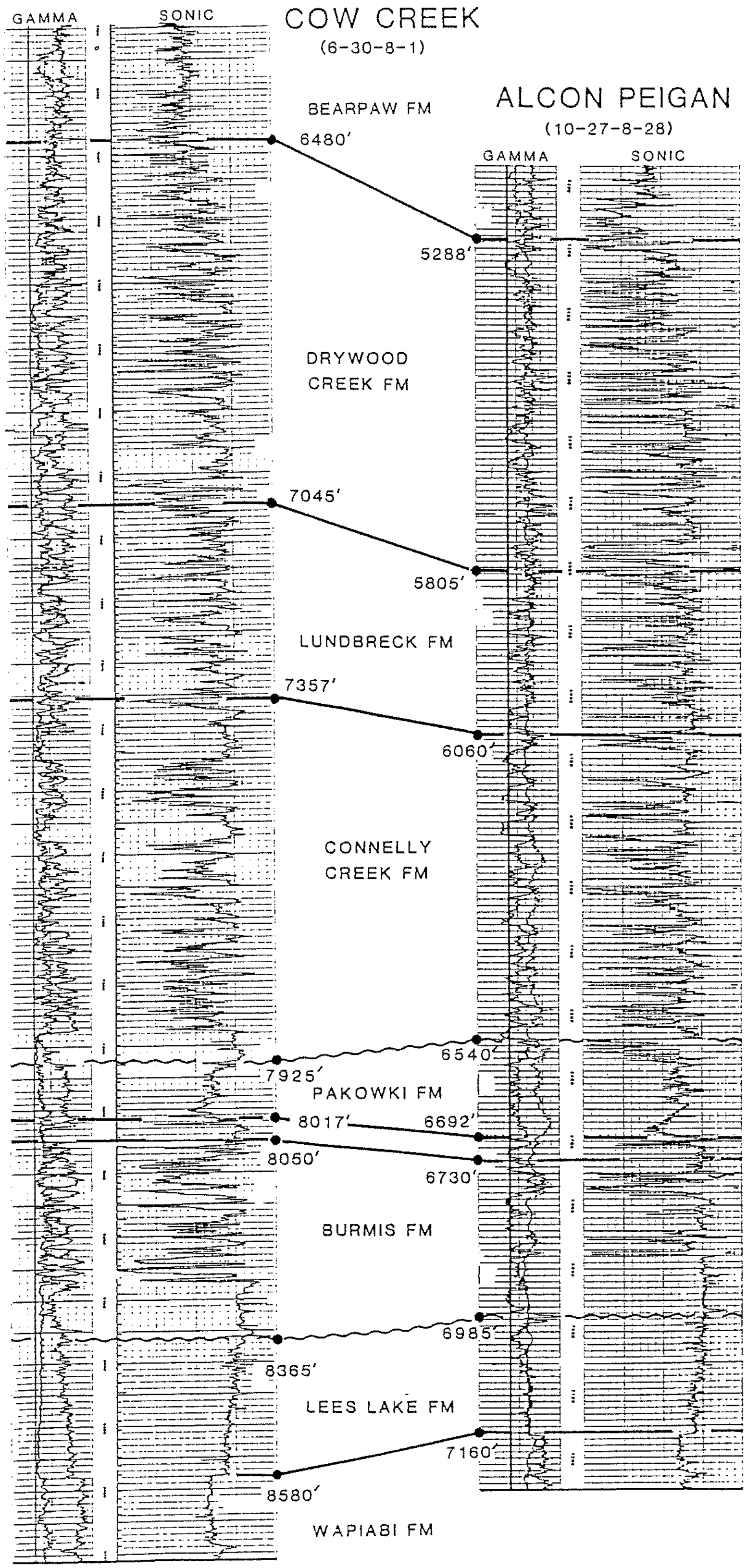
Figure 2S (left). Pakowki Formation in the railway cut some 0.5 km west of Lundbreck (Stop 9b).

A. Alternating beds of hummocky cross-stratified sandstone and shale of the Pakowki Formation overlain by the Connelly Creek Formation (now the basal Belly River sandstone).

B. Close-up view of the thin, hummocky cross-stratified sandstone/shale interval.


GAMMA
SONIC
COW CREEK
(6-30-8-1)
BEARPAW FM
ALCON PEIGAN
(10-27-8-28)
GAMMA
SONIC
6480′
5288′
DRYWOOD
CREEK FM
7045′
5805′
LUNDBRECK FM
7357′
6060′
CONNELLY
CREEK FM
6540′
7925′
PAKOWKI FM
8017′
6692′
8050′
6730′
BURMIS FM
6985′
8365′
LEES LAKE FM
7160′
8580′
WAPIABI FM

Lundbreck located some 2 km southwest of the type locality.

Drywood Creek Formation

The Drywood Creek Formation in the vicinity of the Crowsnest River occurs only as a narrow interval in the footwall of the Watson Thrust near the town of Lundbreck. It is mostly covered with Quaternary deposits. However, a continuous section of the formation is exposed on Drywood Creek some 50 km southeast of Lundbreck. This is designated the type section of the formation and its name is derived from Drywood Creek. The formation has been identified on electric logs of the California Standard Company Connelly Creek well (LSD 6–30–8–1W5) from depths of 7045 to 6480 ft, and in the Petcal Company Limited Alcon Peigan well (LSD 10–27–8–28) from depths of 5805 to 5288 ft (Fig. 3S).

Towards a sedimentary tectonic model of the "Belly River" clastic wedge

Essentials of the sedimentological interpretation included in the main body of the guidebook remain unchanged. However, recognition of the above formations allows for refinements in the interpretation of the structural evolution of the region as well as for the reconstruction of the succession of sedimentary environments in the basin presented in Figure 5S and briefly described below.

Figure 3S (left). Subsurface reference sections for the newly described post-Wapiabi formations of the southern Foothills.

During the early phase of the Laramide Orogeny the clastic debris of the Lees Lake and Burmis formations was derived from orogenic uplands well to the west and deposited in the Crowsnest Embayment of the Wapiabi Sea between the south- and southeast-trending legs of the Western Canada Miogeocline (Crowsnest Deflection, Norris, 1968). The Crowsnest Deflection formed a reentrant which focused sediment transport, acting as an inlet into the Laramide foredeep in the Late Cretaceous. It is indicated by the fan-shape of geometry of the Burmis, Connelly Creek and Lundbreck formations tapering off the Crowsnest Deflection towards the northeast, northwest and southeast.

The succession of depositional environments from distal to subproximal recorded in the Belly River clastic wedge has been interpreted in terms of a compressional, northeasterly migrating Laramide deformation front and associated foredeep. The migration was not steady. In "Belly River" time, it was interrupted by a short ingression of the Pakowki Sea which subdivided the "Belly River" clastic wedge into two shallowing-upward successions, reflecting two phases of Laramide tectonism in the source area. Another transgression occurred in Bearpaw time.

Early indication of tectonic activity in the source area are recorded by the turbidites of the Lees Lake Formation. There was a gradual increase in frequency of turbidite current influxes into an open

A

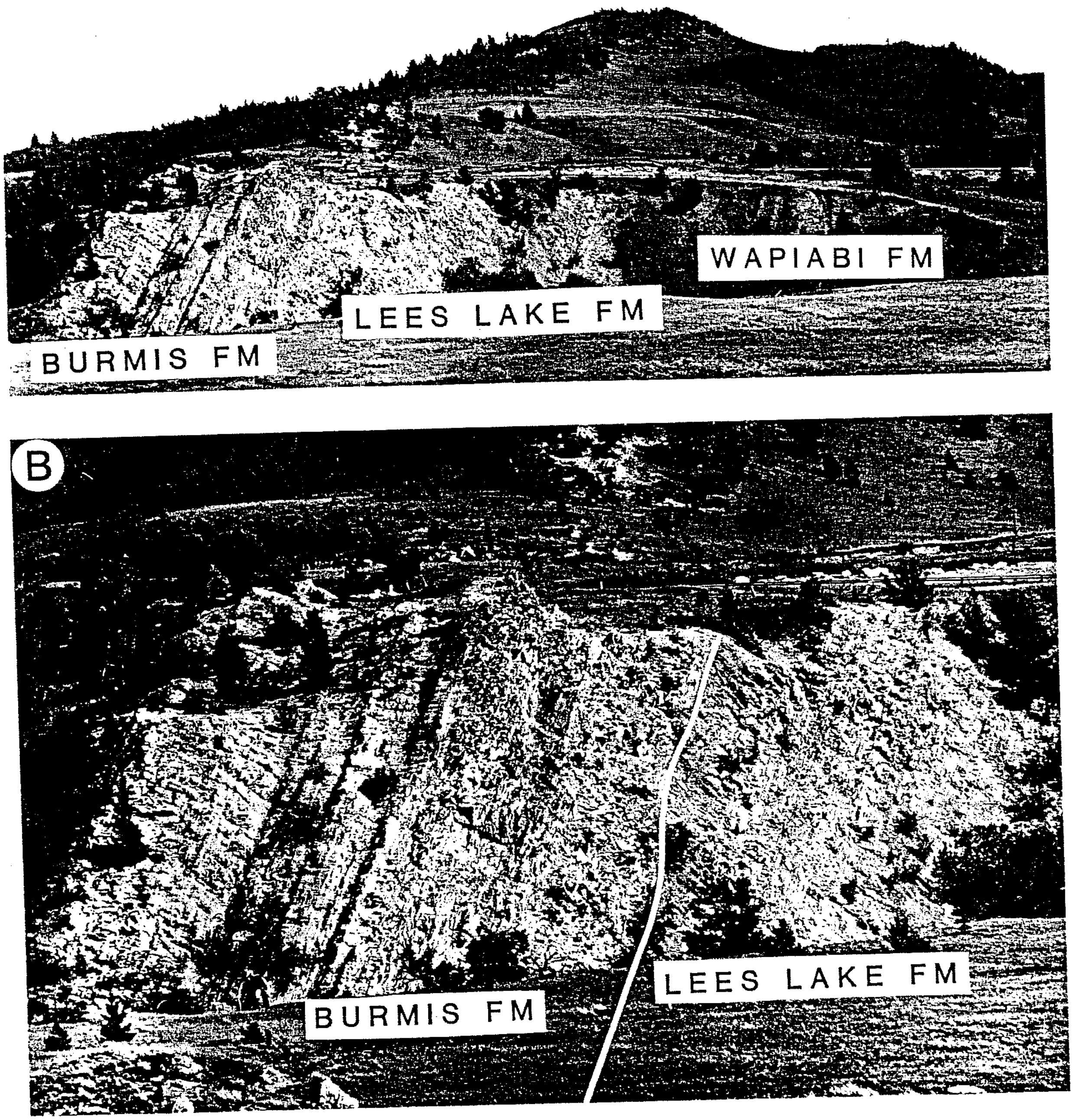


Figure 4S. Lundbreck Falls transition section in the Crowsnest River cutbank (Stop 7).

A. The Wapiabi, Lees Lake and Burmis formations on the northeast limb of the Tower Anticline.

B. Close up view of the same section. Note the white line indicating the uneven, erosional boundary between the Lees Lake and Burmis formations.

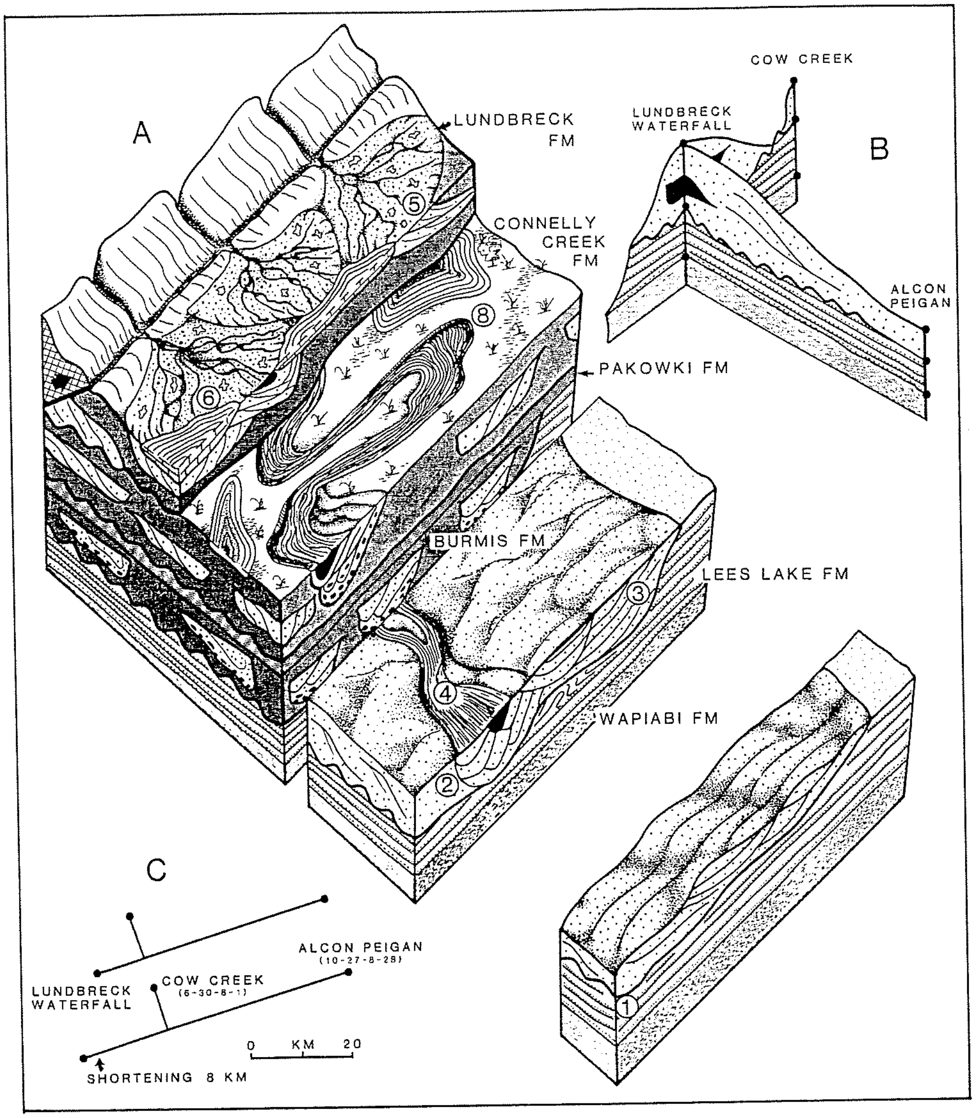


Figure 5S. Succession of depositional environments of the formations (with the exception of the Drywood Creek Formation) which built up the "Belly River" clastic wedge.

- ***A.*** *Schematic block diagram showing models of depositional environments of the Burmis, Connelly Creek and Lundbreck formations. Note the lateral facies change within the Burmis Formation.*
- ***B.*** *Schematic sections through the lower part of the "Belly River Delta" (Lees Lake–Burmis formations) perpendicular and parallel to the depositional strike. The former runs between the surface sections in the Foreland Thrust and Fold Belt near Lundbreck and the Petcal Alcon Peigan well near the core of the Alberta Syncline northeast of Brocket. The latter runs between Lundbreck and the Calstan Cow Creek well some 10 km northeast of Lundbreck. Note the Burmis Formation thickness change from over 200 m in the Lundbreck waterfall area to 0 on the northwestern limb of the Tower Anticline where the Lees Lake/Connelly Creek formations contact has been mapped (Fig. 22).*
- ***C.*** *Palinspastically restored position of the main localities utilized in the construction of the block diagram.*

Circled numbers from 1 to 8 correspond to Figure 14 in Jerzykiewicz and Norris (in press).

shelf environment. Hummocky cross-stratified sandstone marks the shelf shallowing (regression of the Wapiabi sea) when the water depth was between storm wave base and fair-weather wave base. Increase in supply of sand in the uppermost Lees Lake Formation led to the deposition of thick sandstone layers which were subsequently, syndepositionally deformed, and partly eroded by sediment-laden currents. The contact between the Lees Lake Formation and the Burmis Formation is at least partly unconformable because of submarine erosion.

The basal part of the "Belly River" clastic wedge is sedimentologically similar to regressive, upward-coarsening successions that developed at the base of other major Jurassic and Cretaceous clastic wedges in the Alberta Foreland Basin (Hamblin and Walker, 1979; Norris, 1964; Wright and Walker, 1981; Leckie and Walker, 1982). Differences appear in the upper part of the succession, however, and concern the presence or absence of a tidal and/or deltaic component. The deltaic component is well developed in the Burmis Formation and within the Connelly Creek Formation above the Pakowki shale.

The unconformity-based Burmis Formation is recognized as a sequence containing a lateral transition from distributary channel-fill, through distributary mouth-bar to shoreface facies. Documentation of such a lateral facies change within the Burmis Formation, as well as the depositional geometry of the distributary mouth-bar sandstone bodies mapped in the vicinity of Crowsnest River west of Lundbreck, led to the recognition of the lower member of the "Belly River" Delta. Fluviatile channels are interpreted as parts of the main distributary channel of the delta system, oriented approximately along the present Crowsnest River, i.e. within the structurally controlled Crowsnest reentrant. Flow directions indicate a northeasterly dipping paleoslope. The mouth of the distributary channel of the delta was located immediately northeast of the Lundbreck waterfall cliff. This can be inferred from the absence of distributary channel-fill facies in the Lundbreck transition section. Distributary mouth-bars developed along the depositional strike, laterally from the river mouth.

Distributary channel-fill, distributary mouth-bar and shoreface sandstones of the Burmis Formation make up a subordinate clastic wedge within the "Belly River wedge". A significant reduction of sandstone thickness, noticeable both perpendicular and parallel to the depositional strike within the Burmis Formation sub-wedge, gives the delta a fan-shaped appearance (Fig. 5S, B).

The next phase of the Laramide Orogeny in the Crowsnest area is recorded in the upper delta-plain to alluvial fan facies of the Connelly Creek and Lundbreck formations that form the upper part of the "Belly River" Delta. The short-lasting Pakowki ingression was quickly succeeded by upper delta-plain sedimentation in the Crowsnest Embayment.

The thickness relations between the subproximal segment of the "Belly River" clastic wedge (based on measurements in surface sections and in the Cow Creek well) and its more distal segment near the axis of the Alberta Syncline (Petcal Alcon Peigan well) clearly show a rapid tapering of the sedimentary prism both perpendicular and parallel to the depositional strike. Across the strike the easterly thinning Burmis clastic wedge is about 1700 m in the Lundbreck waterfall area, thinning to 400 m at the Petcal Alcon Peigan well. Along strike the "Belly River" clastic wedge tapers between the Lundbreck waterfall area and the Calstan Cow Creek well from 1700 m to 620 m. Unlike the deltaic members of the "Belly River" clastic wedge (from the Burmis to the Lundbreck formations), the Pakowki and the Drywood Creek formations thicken northeasterly, consistent with their marginal marine origin and position of the study area in the western periphery of the seaway.

The most dramatic and, perhaps, geologically the most significant change in the depositional geometry is seen within the Lundbreck Formation of semiarid alluvial fan and playa origin. Its thickness diminishes along the paleoslope from 600 m in the Lundbreck area to 77 m near the axis of the Alberta Syncline (Petcal Alcon Piegan well). Farther down the paleoslope it wedges out between the Connelly Creek and Drywood Creek formations (or their Plains' correlatives i.e. the Foremost and Oldman formations). From the shape of the wedge it is concluded that the total thickness of the Lundbreck Formation in the foldbelt west of Lundbreck must have been much greater.

The fan geometry and sedimentological features of the Lundbreck Formation, especially the ephemeral, high-energy channels, semiarid paleosols and playa deposits (see section on Lundbreck Formation) indicate sedimentation on a semiarid alluvial fan of the upper delta-plain environment. Rapid deposition within the ephemeral channels and deep erosion of the alluvial plain during sedimentation of the Lundbreck Formation suggest a significant syndepositional topography. The semiarid alluvial fan environment suggested for the Lundbreck Formation implies an uplifted mountain front during its formation. Basinward progradation of the Connelly Creek/Lundbreck fan-delta was caused by easterly progradation of the tectonic deformation that forced the Pakowki Sea to retreat from the Crowsnest Embayment.

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