26th Canadian Tectonics Group Workshop

25 Years

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of the Geological Association of Canada

Field Trip Guide:
The Structure of the Crowsnest Pass Transect

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EUB Alberta Energy and Utilities Board | AGS Alberta Geological Survey
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October 14-15, 2006
Crowsnest Pass, Alberta, Canada

Itinerary (Sunday 15 October)

08h00	Board bus
08h15-08h45:	**Stop 1.** Type section of the Crowsnest Volcanics
09h00-09h30:	**Stop 2.** Sub-Devonian unconformity
09h30-10h45:	**Stop 3.** Deformation of the Lewis thrust sheet
11h00-11h30:	**Stop 4.** Lower Mt. Head section at Blairmore
11h45-12h30:	**Stop 5.** Turtle Mountain Overview and conglomerate
12h30-13h30	**Lunch and Visit to Frank Slide Centre** ('In the Mountain Shadow' slide show, narrated by W.O. Mitchell, in auditorium)
13h45-14h15	**Stop 6:** Eastlimb Tower Anticline
14h15-14h45	**Stop 7:** Lundbreck Falls
17h30	Arrive at Calgary Airport

Introduction

This is a joint field trip with 5 different leaders, who all have different parts of the field trip. For this reason it may seem disjointed, but in the end it is hoped that this trip will give you a good impression of the structure of the area.

The area forms part of the area mapped and compiled by Price (1962). This map has recently been updated by Ray Price and the new version of this map will be presented at the 2006 CTG workshop, of which this field trip forms part. An overview of the geology along the Crowsnest Pass transect is presented in Figure 1, which is from the Geological Highway Map of Alberta (Canadian Society of Petroleum Geology, 2000). The stratigraphy of the area (also from the CSPG Highway Map) is shown in Figure 2. Another enjoyable introduction to the geology of the area is the traveller's guide to geological wonders in Alberta (Mussieux and Nelson, 1998), which describes 6 sites along the Crowsnest Pass transect.

Existing A series GSC geological maps in the area are Norris, 1993a (Beaver Mines, West Half) and Norris, 1993b (Blairmore, West Half). In addition, there are GSC Open File maps for the Blairmore, East Half (Stockmal and Lebel, 2003) and Beaver Mines, East Half (Lebel and Hiebert, 2001).

This field trip will illustrate some of the fold and thrust structures along the Crowsnest Pass transect.

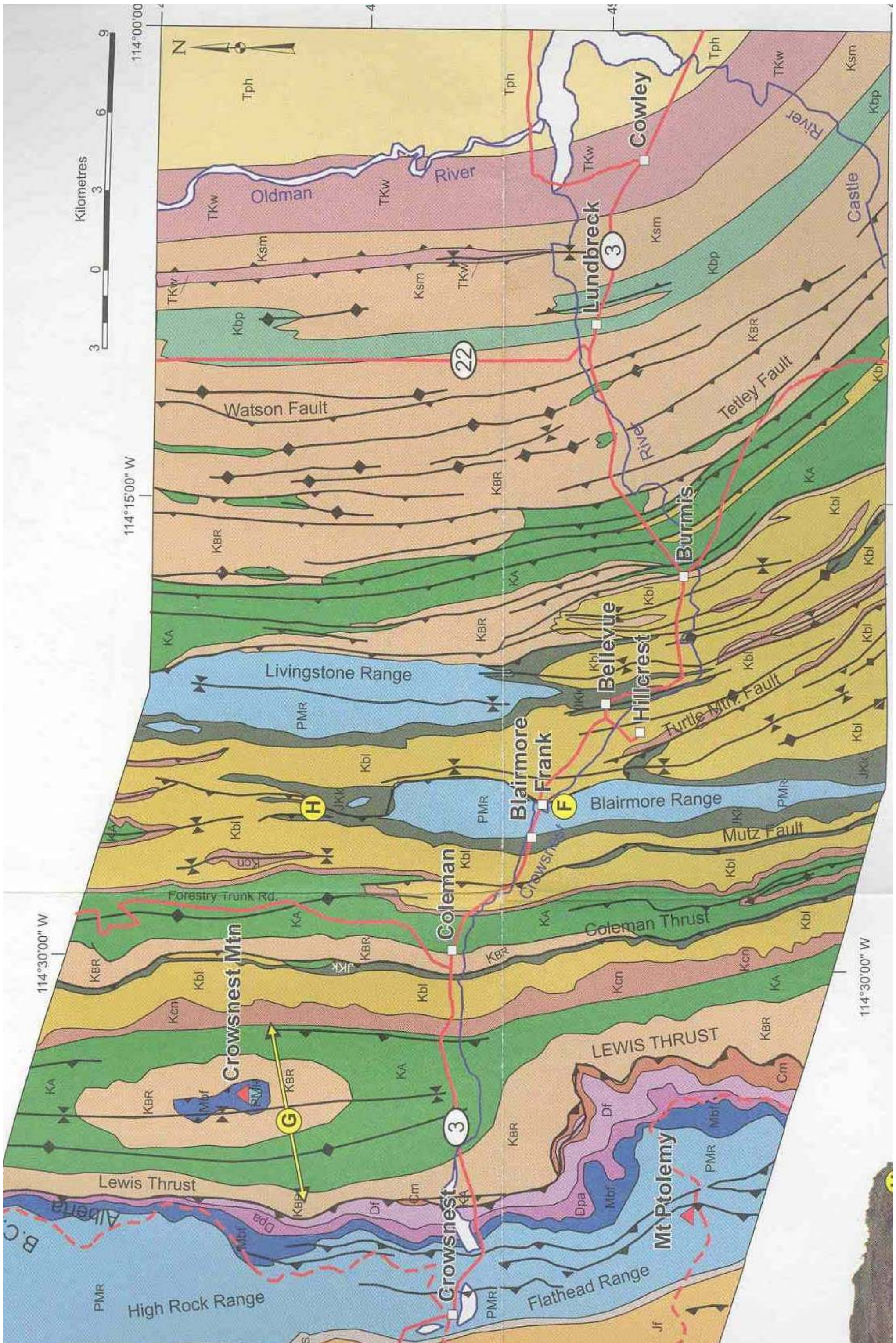


Fig. 1. Geological map of Crowsnest Pass (from the CSPG Geological Highway Map). You can complete the map by marking the field stops.

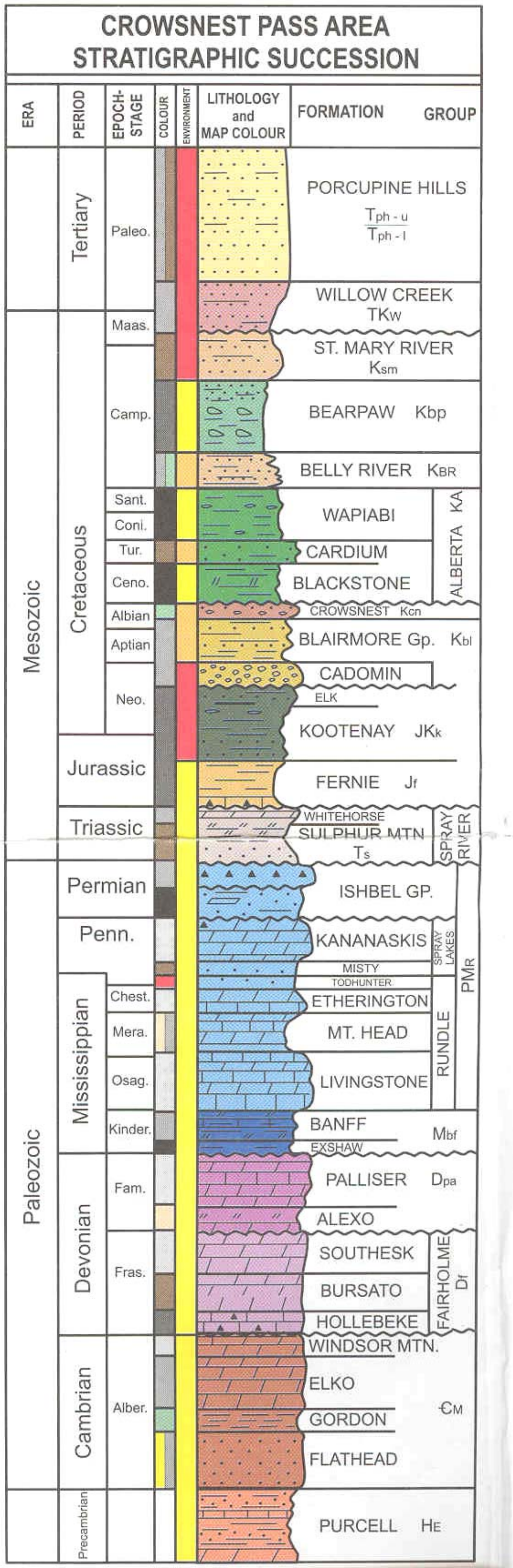


Fig.2. Crowsnest Pass stratigraphy

Locations to be visited

08h15-08h45: **Stop 1.** Type section of the Crowsnest Volcanics

The Crowsnest Formation largely consists of volcanics. The type section of the Crowsnest Formation along Highway 3 near Coleman was described by Adair and Burwash (1996). A recent U/Pb date of 103 ± .5 Ma was obtained by dating of a single sanadine crystal from these volcanics (Peterson et al., 1997), indicating the value of this unit as a time stratigraphic horizon.

The Crowsnest volcanics consist of bedded alkaline volcanic deposits containing volcanic rock fragments and crystal clasts. Evidence for fluvial processes (cross bedding) and pyroclastic flow under elevated temperatures have been reported by various authors (Adair and Burwash, 1996; Peterson et al., 1997). Lava flows are rare and domes have not been identified, although outcrops along Star Creek have been interpreted as a phonolite dome by Peterson et al. (1997). There are a great variety of rock types in the Crowsnest volcanics. One type is made up mainly of the mineral analcime and the rock is named analcimite (Peterson et al., 1997). This rock was once named blairmorite, after the town of Blairmore. Standard naming practices for igneous rocks now require names after the major mineral, instead of localities where they are found.

Things to notice:
1). This stop examines the upper member of the Crowsnest Formation, which is 228 m thick at this locality. The upper member is dominated by resistant, dark green-gray, thickly bedded breccia deposits containing abundant volcanic rock fragments (trachytes and phonolites). These deposits are distinguished from other coarse grained deposits in the lower member by their massive, locally jointed, thick depositional units and the absence of stratification. Contacts are defined by subtle colour changes, locally chilled lower contacts, and abrupt changes in grain size that reflect normal grading of the rock fragments common in many coarse grained deposits.

2). Crystal clasts of pink sanidine and black garnet (melanite) are easily recognized.

3). Charcoal (charred wood) and molds of the wood pieces, together with reaction halos in the matrix surrounding rock fragments indicate emplacement at elevated temperatures.

4). Some crude compositional zonation indicates flow processes and may include some cross bedding. These textures could indicate fluvial processes.

5). Possible fracture patterns related to thrust movements.

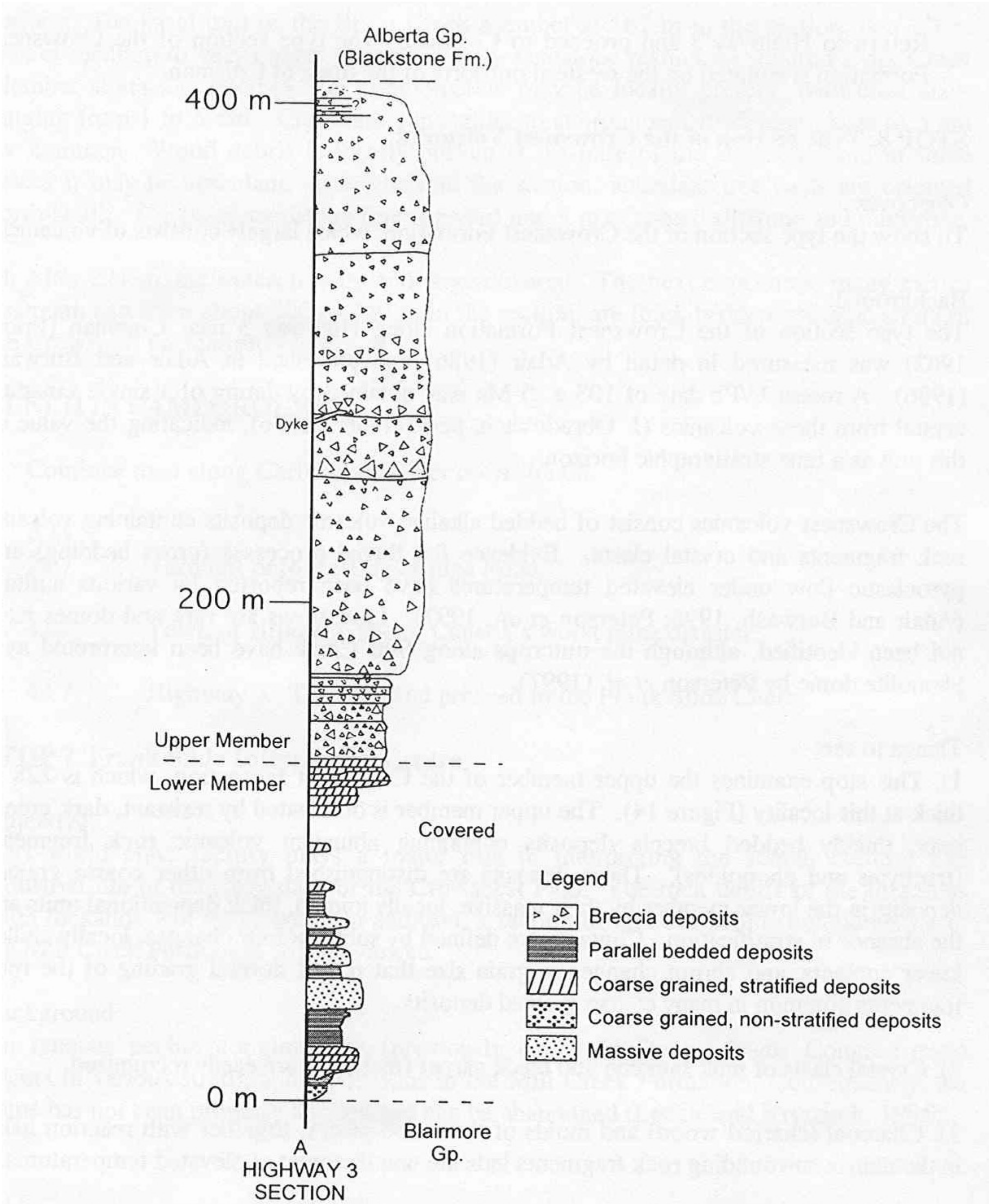


Fig. 3. Type section of the Crowsnest Formation along Highway 3 (from Adair and Burwash, 1996).

En route to Stop 2, the structural position of Crowsnest Mountain will be discussed.

Crowsnest Mountain is a classic example of a klippe, the erosional remnant of a once-continuous mass of rock.

The top of the mountain is the cliff-forming Mississippian Rundle Group limestone; the slopes below this are the slightly older shale and limestone of the Banff Formation (also Mississippian); and the massive limestone cliff just below the tree line is the Devonian Palliser Formation. Crowsnest Mountain is situated on the Crowsnest Mountain Syncline to the east of the Allison Anticline, which is situated in-between Crowsnest Mountain and the High Rock Range.

09h00-09h30: **Stop 2.** Sub-Devonian unconformity (Ray Price stop; see below).

09h30-10h45: **Stop 3.** Deformation of the Lewis thrust sheet on the north side of Sentry Mountain (Ray Price stop; see below)

Stop 2 and 3

Transect of the lower part of the Lewis thrust sheet on the north side of Sentry Mountain at Crowsnest Lake

Sub-Devonian unconformity

The regional unconformity between the Hollebeke Formation (Upper Devonian Fairholme Group) and the Elko Formation (Middle Cambrian) is exposed in new road cuts on both sides of a relocated segment of Highway #3, near of Crowsnest Lake. The unconformity is a sharp, undulating, low-relief (<2 m) surface between the thickly bedded to massive, mottled, medium crystalline dolomites of the Elko Formation and the thinly bedded silty dolomites of the lower part of the Hollebeke Formation. The Hollebeke Formation onlaps local relief on the top of the Elko Formation.

Dykes of alkaline igneous rock exposed in this road cut presumably are related to the mid-Cretaceous Crowsnest volcanics, which occur nearby to the east, between the Lower Cretaceous (Albian) Blairmore Group and the Upper Cretaceous (Cenomanian) Alberta Group, in the footwall of the Lewis thrust; and also to the mid-Cretaceous Howell Creek alkaline igneous intrusions, which occur within the Lewis thrust sheet in the Flathead area to the south.

The green shales of Middle Cambrian Gordon Formation are exposed at base of Elko Formation, but the contact with the Elko Formation is faulted.

This locality is close to the surface trace of the Lewis thrust fault. Sandstones of the Upper Cretaceous (Campanian) Belly River Group occur in nearby road cuts to the east.

Deformation of the Lewis thrust sheet on the north side of Sentry Mountain -- in road cuts along Highway #3 at Crowsnest Lake

Figure 1. View south at Sentry Mountain, Crowsnest Lake, and Highway #3. The fresh Highway #3 road cuts truncate the forested slopes of Sentry Mountain along the south side of Crowsnest Lake.

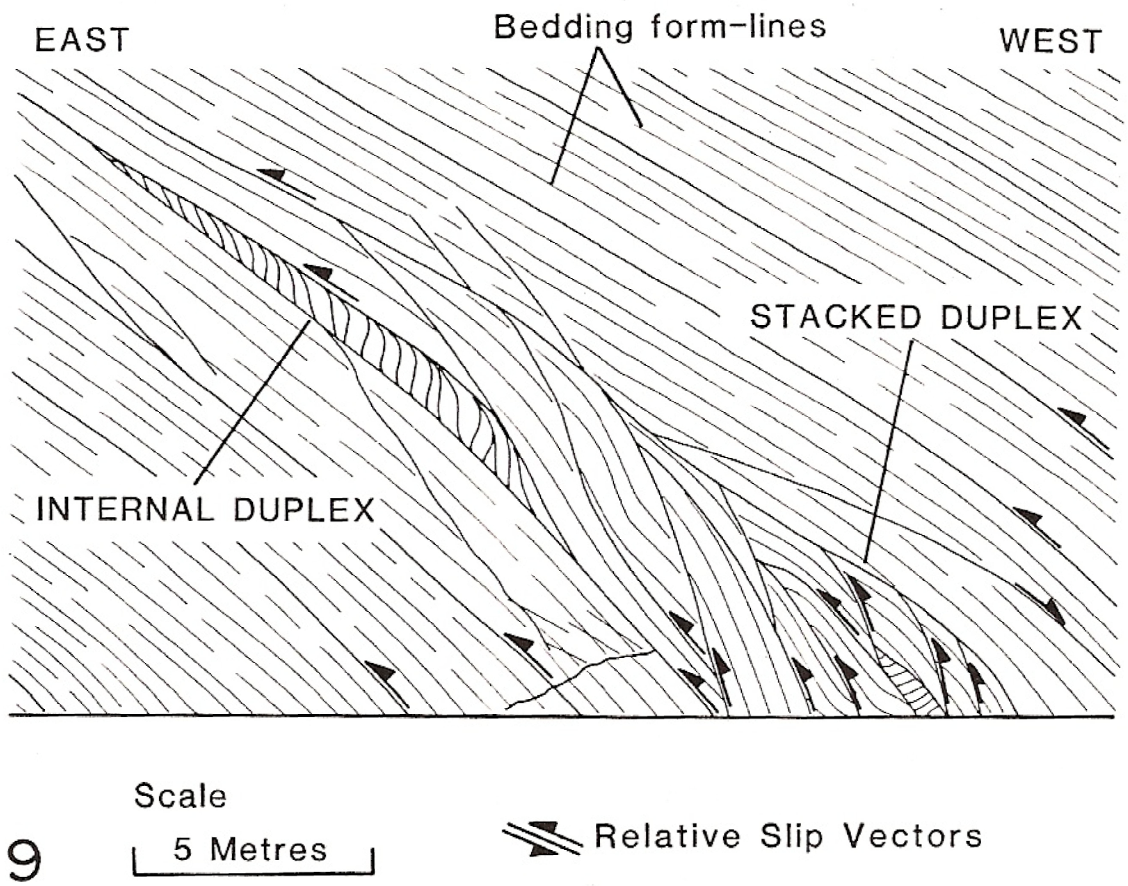
The Crowsnest Lake transect crosses the lower part of the Lewis thrust sheet within a zone in which the Lewis thrust is cutting up-section in its hanging wall from an extensive bedding detachment zone deep within Mesoproterozic rocks of the Belt-Purcell Supergroup to the south to an extensive much shallower bedding detachment zone within the Upper Devonian Palliser Formation in the region to the north. This hanging-wall lateral ramp is a region of unusually intense deformation. However, the unusual deformation may also reflect the fact that the Crowsnest Lake transect lies within the zone of transition between the dominantly northwest-striking thrust faults and folds that characterize the Lewis thrust sheet south of the Crowsnest Pass and the dominantly north-trending structures that characterize the region to the north of the pass.

Meso-scale deformation within the hanging wall of the Lewis thrust sheet on the north side of Sentry Mountain is well displayed along Highway #3 in fresh road cuts through the Upper Devonian lime mudstones of the Palliser Formation, the black shaly rocks of the Devonian-Mississippian Exshaw Formation, and the dark shales and the cherty and argillaceous limestones of the Mississippian Banff Formation (Figures 1 and 2).

Figure 2. Close-up overview, from the same location as for Figure 1, of the stratigraphic interval comprising the uppermost part of the Palliser Formation (the roadside cliff on extreme left), the Exshaw Formation (thin black shale unit immediately overlying the Palliser Formation), and Banff Formation (the remainder of the road cut).

Evidence of slip along the bedding is widespread in the road cuts, even in the normally massive lime mudstones of the Palliser Formation. The stratigraphic section has been tectonically thickened by numerous thrust faults and thrust-related folds. The thrust faults are contraction faults (they produce shortening in the plane of the bedding); they generally intersect the bedding at low angles (<30 degrees), and they commonly emerge from and merge with bedding-parallel (interstratal) shear zones (detachment zones). Thrust duplex structures of various sizes and types are common (see Figures 3 and 4 – after K.R. McClay and M.W. Insley, 1986: Duplex structures in the Lewis thrust sheet, Crowsnest Pass, Rocky Mountains, Alberta, Canada, JSG, V. 8, n. 8, p. 911-922). Most thrusts are synthetic contraction faults (they have the same sense of shear as the Lewis thrust), but some are antithetic contraction faults. Displacements on the thrusts/contraction faults range from < 1cm to many metres (?and kms?) and are generally oriented east-west. Extension faults, which produce stretching in the plane of the bedding, are also widespread, but less common than the contraction faults. They generally intersect the bedding at high angles (>60 degrees), and displacements on them are generally much lower (?<<10 m), however, these displacements also are generally oriented east-west. A third class of faults comprise transverse, generally steeply dipping, shear surfaces; some appear to be tear faults that form lateral ramps between thrust faults and/or bedding detachment faults; others are not so obviously related to the kinematics of displacement on the Lewis thrust. Calcite veins and calcite-coated fractures also are common; many are mineralized joints (extension fractures?) but some are shear surfaces and some comprise calcite fibres that have formed on fault surfaces, including bedding detachment fault surfaces.

From the tightly constrained perspective of the steep road cut along Highway #3, it is not obvious which (if any) of the numerous faults and bedding-parallel shear surfaces seen in the road cut are significant faults, at the scale of Sentry Mountain. However, the view to the north across Crowsnest Lake at the south slope of Crowsnest Ridge provides a broader perspective. In this natural section through the lower part of the Lewis thrust sheet the basic structure of the thrust sheet is clearly displayed. The sequence of stratigraphic units (Palliser, Exshaw, Banff and Livingstone Formations) is essentially homoclinal, but there is evidence of internal thickening of within formations. A comparable natural section is available in the view south toward Sentry Mountain from the microwave tower that is located north of the lake on the Crowsnest Ridge – the locality from which the photographs in Figures 1 and 2 were taken.



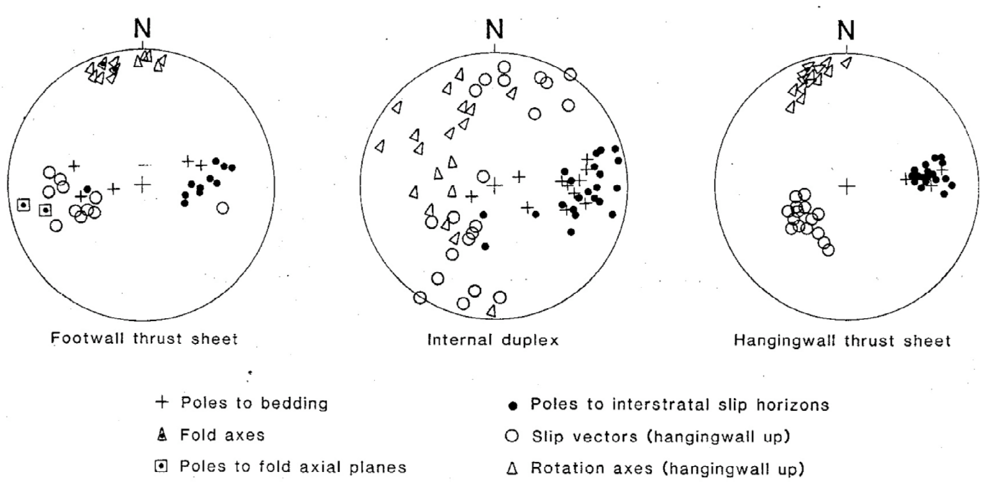
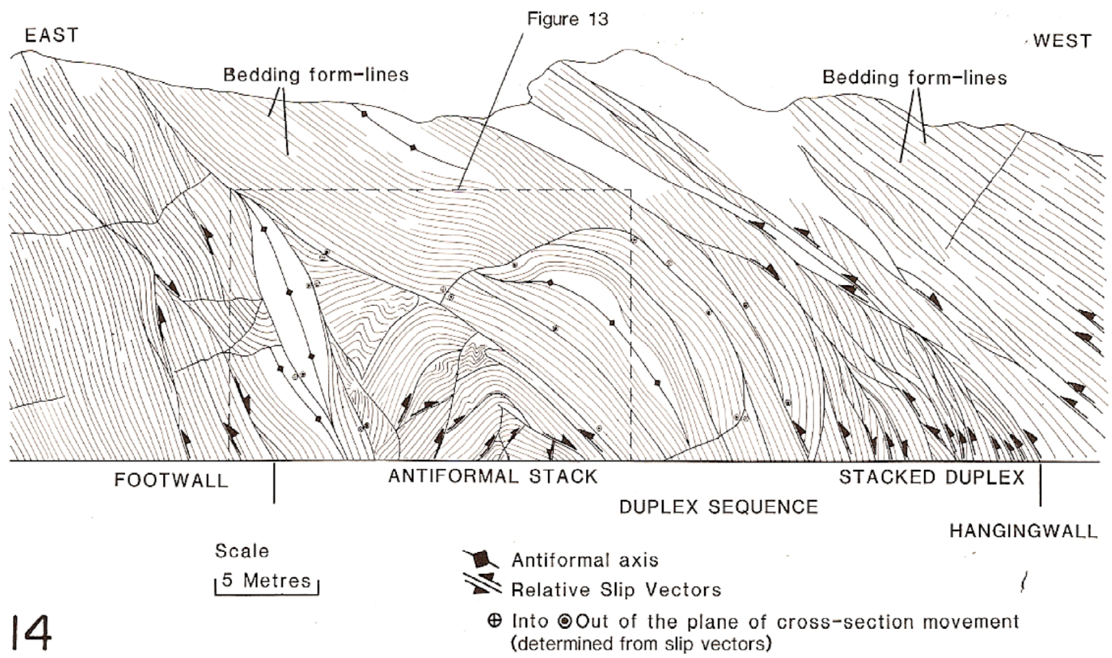


Figure 3 after McClay & Insley, 1986, JSG v.8, no. 8, Figs 9 and 10



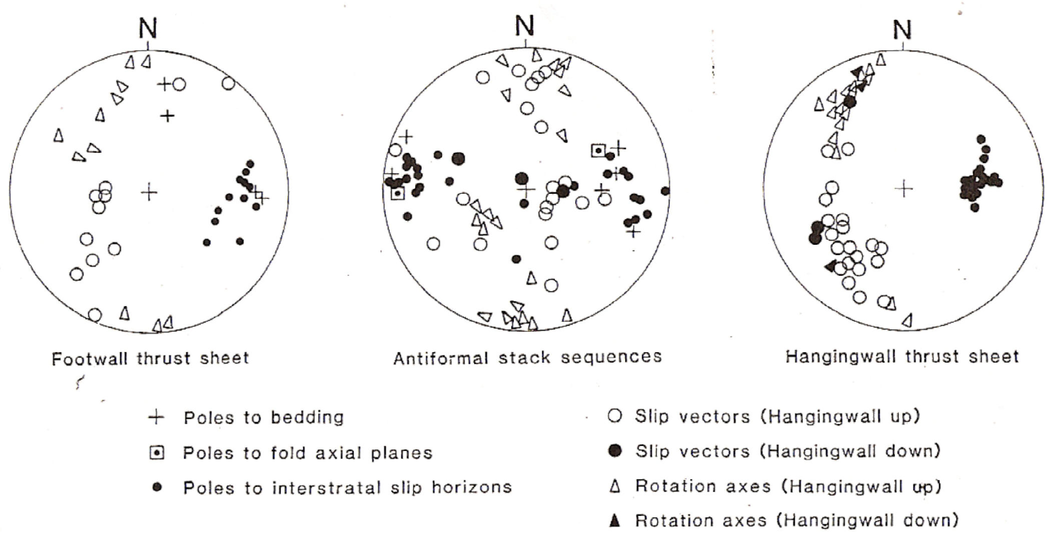


Figure 4: after McClay & Insley, 1986, JSG v.8, no. 8, Figs 14 and 15

11h00-11h30: **Stop 4.** Lower Mt. Head section at Blairmore

The west limb of the Turtle Mountain Anticline is reasonably well exposed along the Highway near Blairmore and shows an intermittent section from Banff to Fernie Formation. Covered intervals include most of the Loomis Member and an interval from the top of the Carnarvon Member till the upper part of the Etherington Formation.

A good section of the lower Mt. Head Formation will be visited, which has a thickness of 73 m. This section has been measured in detail by Barry Richards of the Geological Survey of Canada (work in progress; see also Richards et al., 1994). The seven units of this section form part of 3 mappable units on Turtle Mountain, i.e. the Livingstone Formation, the Salter/Baril/Wileman members and the Loomis Member. The stratigraphically lowest part starts by the bridge over the Crowsnest River in the uppermost part of the Livingstone Formation and continues to the thick covered interval above the lower part of the Loomis Member. Below 0 m (start of section) the rock is fractured and recessive.

1) **Livingstone Formation** 0 - 2.11 m: lime grainstone;

2) lower **Wileman** 2.11 - 5.99 m: silty dolostone; gradational contact at base. Burrows and cross bedding at 4m.

3) middle **Wileman** 5.99 - 11.55 m: skeletal lime grainstone and packstone; has a sharp erosive base (pseudo-Baril).

4) main unit of **Wileman** 11.55 - 32.11 m: dominated by brown-yellow cross-bedded silty dolostone; dolostone commonly contains lagoonal, cauliflower shaped white carbonate nodules (pseudomorphic after anhydrite).

5) **Baril** 32.11 - 34.17 m: unit is thin and poorly developed; consists of skeletal and oolitic lime grainstone and dolomitized packstone.

6) **Salter** 34.17 - 65.08 m: thick and well developed with well-developed erosion surface at base; dominated by brown-yellow silty dolostone but contains intervals of limestone showing a well developed sub-aerial, peritidal fenestral fabric (gas bubbles below algal mats; algae are now spheres in thin section; this is a typical Visean structure) and cauliflower shaped nodules (former evaporates); supratidal (often dry); algae, roots (plant remains at 58.5 m), fecal pellets, soils, coaly shale (coastal marsh); also sedimentary breccia (at 61 m).

7) **Loomis** 65.08 - 72.62 m: only the basal part of the unit is exposed; mainly oolitic skeletal lime grainstone but has dolomitized grainstone and packstone in the lower part.

Look for layer parallel stylolites and Type I and Type II fracture patterns.

11h45-12h30: **Stop 5.** Turtle Mountain Overview and outcrop of igneous pebble conglomerate

The Frank Slide Interpretive Centre, an excellent starting point for a tour of the slide, provides a superb view of Turtle Mountain, the slide scar on its eastern flank, and the immense accumulation of shattered limestone on the valley floor. This rockslide has become the classic example of mass movement because it is one of the largest slides to have eyewitness descriptions as well as numerous detailed geological reports.

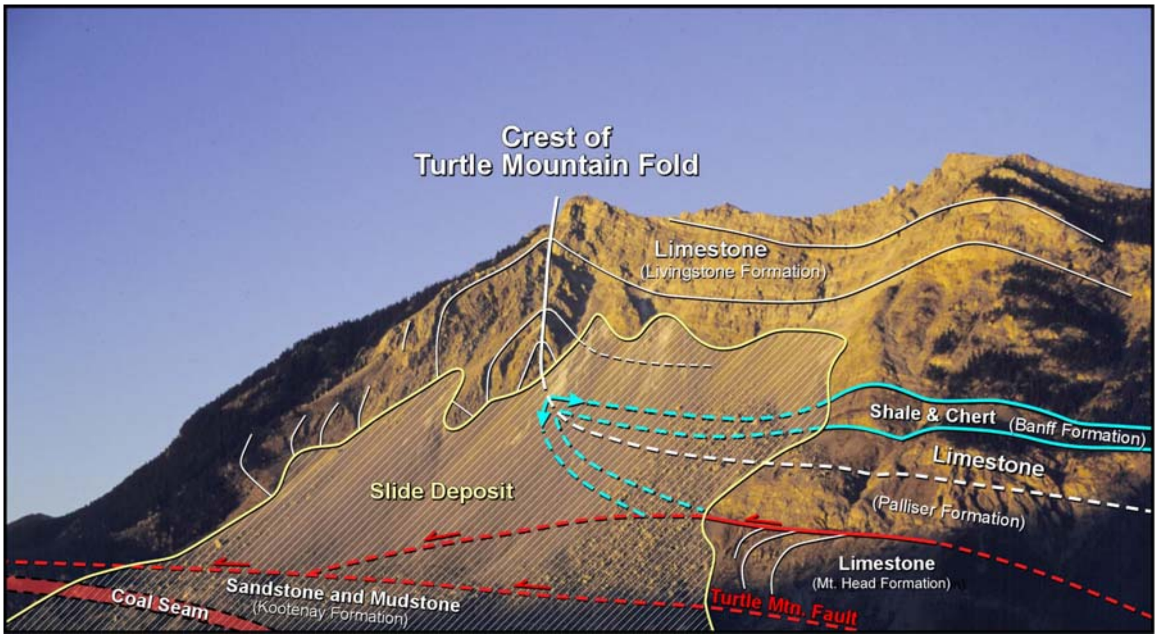


Fig. 4. Turtle Mountain with annotation of geology as seen from the Frank Slide Centre.

The geology is well exposed on Turtle Mountain (Figure 4). The rock layers of Turtle Mountain are folded into a large anticline (the Turtle Mountain Anticline) with a steeply dipping to overturned east limb that lies above a fault (see Figures 4, 5 and 6). Notice that the core of the anticline (in the so-called Hoodoo area) has been re-interpreted to contain Palliser Formation, and not Banff Formation as previously thought (for example on the map of Norris, 1993). Near South Peak the structure forms a type of box fold (see Figure 6). The Turtle Mountain Anticline is a modified fault-propagation fold and can be described as a break-thrust fold (Langenberg et al., in press). The geometry of the fold changes along its trend as shown by varying inter-limb angles (see Figure 6). It also forms a hanging-wall anticline above the Turtle Mountain Thrust. The Hillcrest Syncline is the footwall syncline and is defined by Mesozoic strata. The fold axis trend is significantly different from the trend of the Turtle Mountain Anticline; it trends west of north. This trend conforms to trends south of the Crowsnest Deflection, whereas the trend of the Turtle Mountain Anticline conforms to trends north of this deflection (see Price, 1962). Both folds are displaced by the Turtle Mountain Thrust. However, the Turtle Mountain Thrust is also folded by the Hillcrest Syncline, indicating that folding took place both before and after the thrusting.

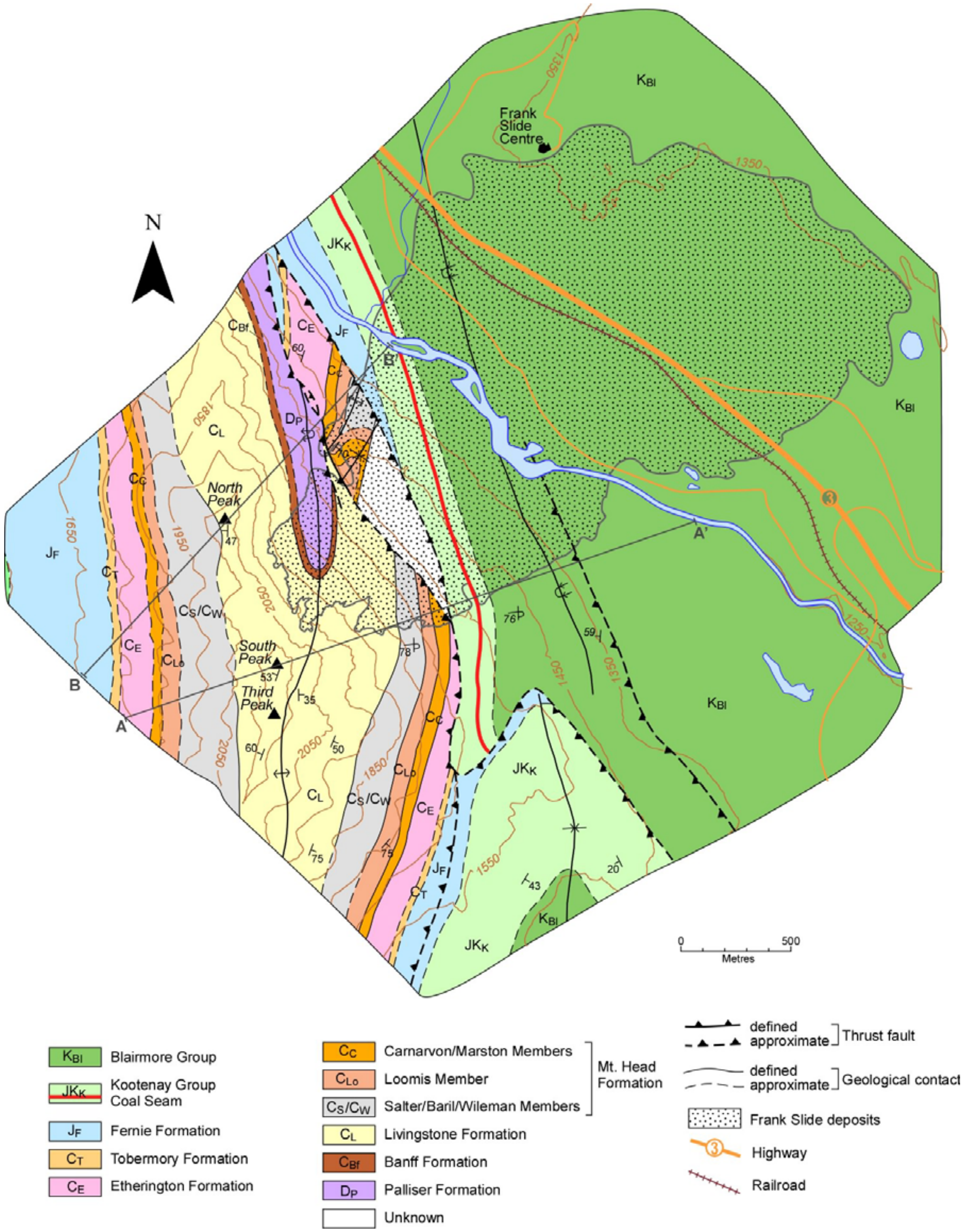


Fig. 5. The geological map of the Turtle Mountain area.

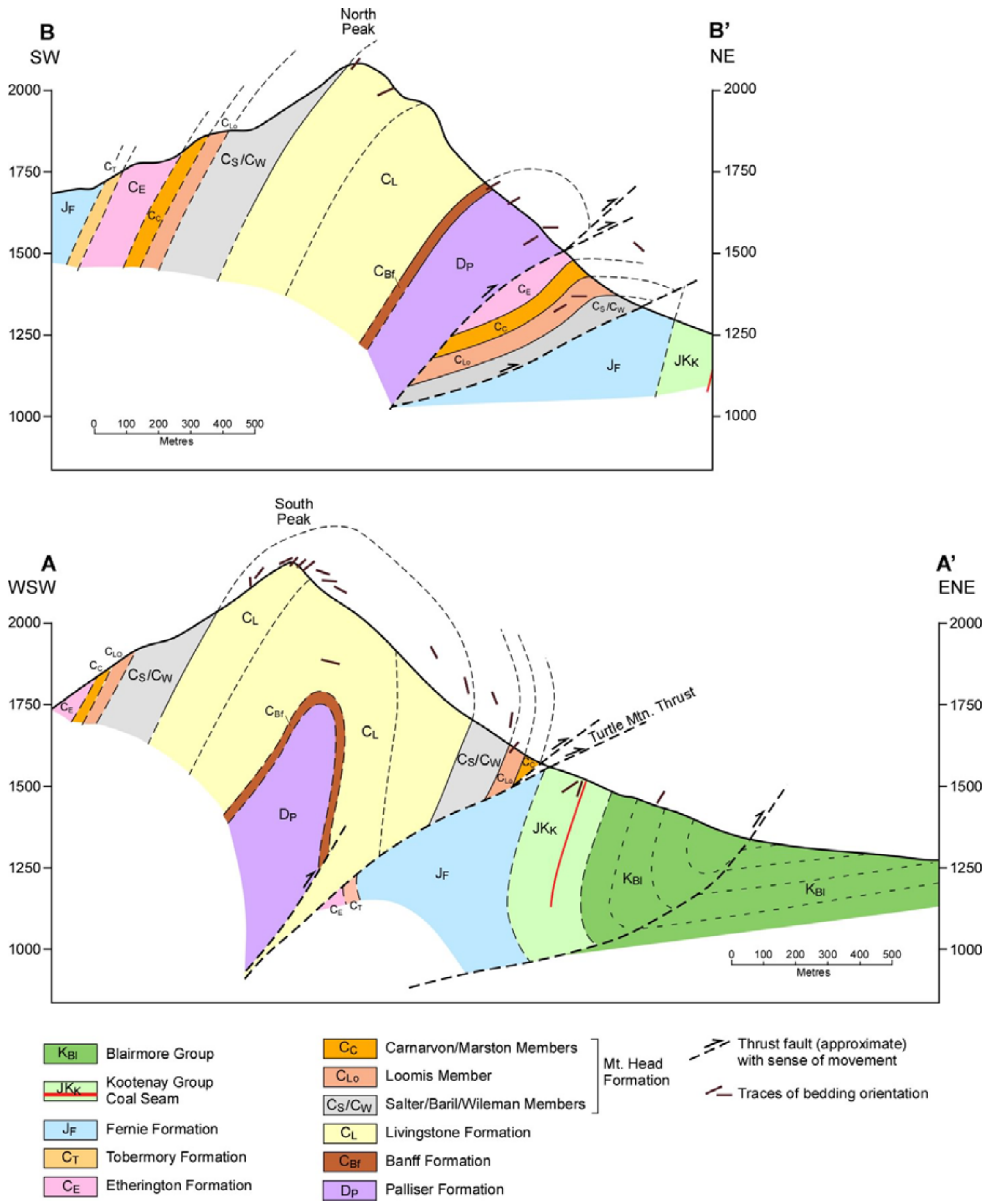


Fig. 6. Cross sections through Turtle Mountain. The lines of section are indicated on Figure 5.

TURTLE MOUNTAIN FRACTURE SYSTEMS

Deborah Spratt and Malcolm Lamb

At Turtle Mountain in the Crowsnest Pass area of southern Alberta, Mississippian limestones are exposed in an east-verging anticline with an overturned forelimb, much of which was removed by the Frank Slide on April 29, 1903. The west-dipping backlimb and the fold hinge can still be seen in the slide scarp, near the top of the talus slope on Turtle Mountain; the hinge and both limbs are visible on Hillcrest Mountain to the south (Figure 1). The entire anticline is carried on the Turtle Mountain Thrust.

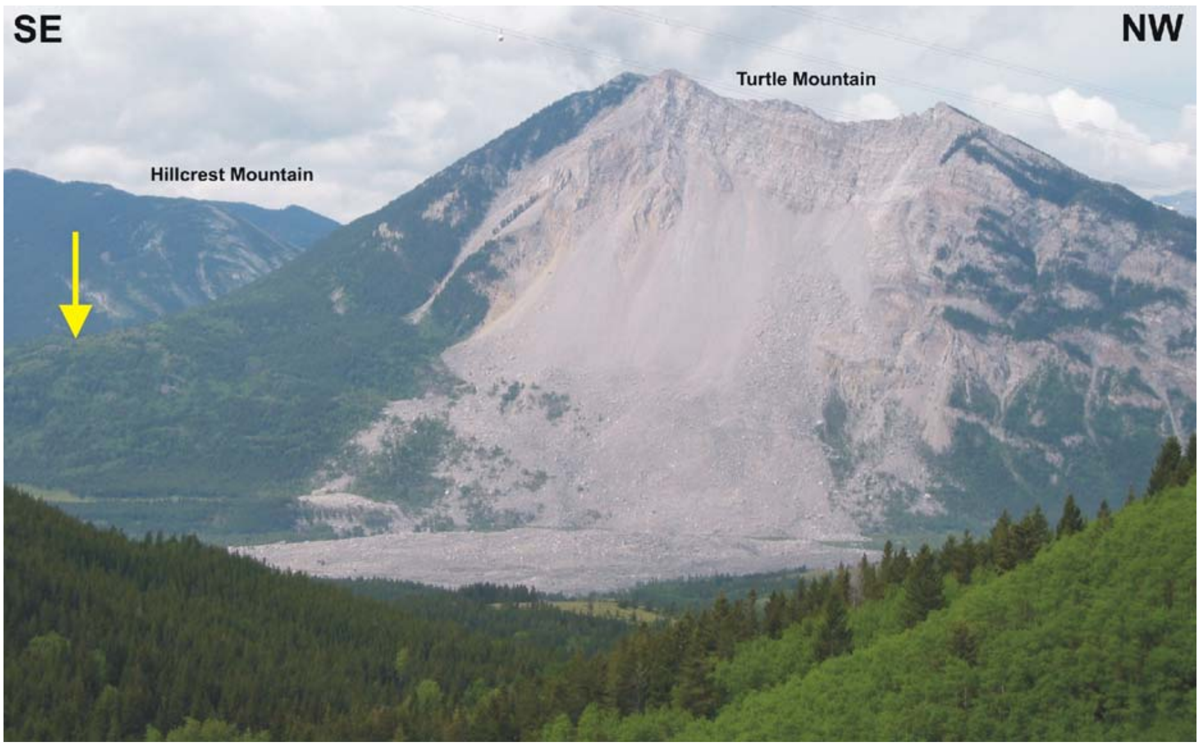


Figure 1. Turtle Mountain Anticline, visible in Turtle Mountain and Hillcrest Mountain.

As part of the Turtle Mountain Monitoring Project, a borehole was drilled with an air rotary drill on the top of Turtle Mountain, 100 m west of the Frank Slide surface, to determine the nature and orientation of discontinuities beneath the surface. The goal was to identify fractures that potentially connect to the large open cracks observed at surface and statistically analyze the fracture population to determine which orientations are most likely to be involved in future mass wasting events. In the process, it has also been possible to distinguish sets related to folding and faulting, and sets that remain open due to gravitational effects or situ stresses.

TURTLE MOUNTAIN BOREHOLE IMAGE LOGS

The borehole was drilled to a depth of 61.3 m and 40.5 m of image logs were acquired with an Advanced Logic Technology (ALT) Obi40 digital optical televiewer from below the surface casing to the bottom of the hole. The image is first oriented relative to magnetic north, and then sliced down the north side of the borehole and unrolled to produce a two dimensional image. The direct RGB images are shown in the second track (grey image). The RGB image is converted into a histogram image on which features such as bedding and fracture planes can be identified. Sinusoids on the converted image represent planar surfaces and are interpreted as bed boundaries (green), fractures (blue) and major open fractures (light blue) that have apertures of >1 cm in this study. Because of the nature of the rock (relatively homogeneous carbonate), the bedding is difficult to pick out, but it is best seen on the RGB image where gradational light-dark bands, some with vugs, are present and have sinusoidal contacts. Open cracks and planar features that are not parallel to bedding are interpreted to be fractures (Figures 2 and 3).

ORIENTATIONS OF SUBSURFACE DISCONTINUITIES

Bedding was consistently oriented over the logged interval, with a mean dip direction and dip of 294°/37° (strike and dip: 204°,37°W), indicating that the borehole intersected only the west-dipping limb of the Turtle Mountain Anticline.

Several large open fractures, labeled as “major fractures”, were encountered in the borehole. Each has an aperture of more than 1 cm, as seen in the 1:5 scale image logs. Theoretical and field studies indicate that large aperture fractures are typically much longer than small aperture fractures, with 1 mm wide natural fractures being on the order of 1 m long and 1 cm wide fractures being on the order of 100 m long (Vermilye and Scholz, 1995; Olson, 2003). So the major fractures (> 1 cm aperture) on Turtle Mountain are the ones most likely to connect to fractures observed at the surface. Data (Figure 4) are shown in SpheriStat 2.1 displays. The most frequent dip directions of the major fractures are to the northeast and east (toward the Frank Slide surface and toward the town of Hillcrest), and most of the dips are steeper than 60°. One major fracture dips WNW, subparallel to bedding; another dips south along the ridge.

151 other fracture surfaces, with apertures <1 cm (commonly ≤1 mm), were also identified and measured in the image logs. Their orientations are more variable, but the larger sample size provides more statistically valid results. The three most frequently encountered orientations dip WNW (subparallel to bedding), ESE and ENE. Adding the 16 major fracture orientations to the dataset yeilds the distributions seen in Figure 5.

Since the 40.5 m long borehole logs sampled only a limited portion of Turtle Mountain, it is useful to compare these results to surface data near the borehole to determine if they are representative of a wider area and how far we can extrapolate information from the borehole. Geologic maps based on surface mapping and air photographs tend to emphasize the steeply dipping fractures, whereas the sub-vertical borehole is able to detect potentially dangerous planes of weakness that were not obvious during field mapping. Together these datasets provide a complete picture of all the discontinuities that could contribute to slope instability.

ORIENTATIONS OF FRACTURES AT THE SURFACE

Several members of the Turtle Mountain Monitoring Project have contributed fracture orientation data that have been analyzed in the same manner as the borehole data. Figure 6 shows all surface data measured for the Project. Five main trends are seen. Here the dominant set dips ~30°SE and the next most frequent is the steeply-NE dipping set. NW-dipping bedding-parallel and steeper than bedding fractures are also common, as is the S-dipping set.

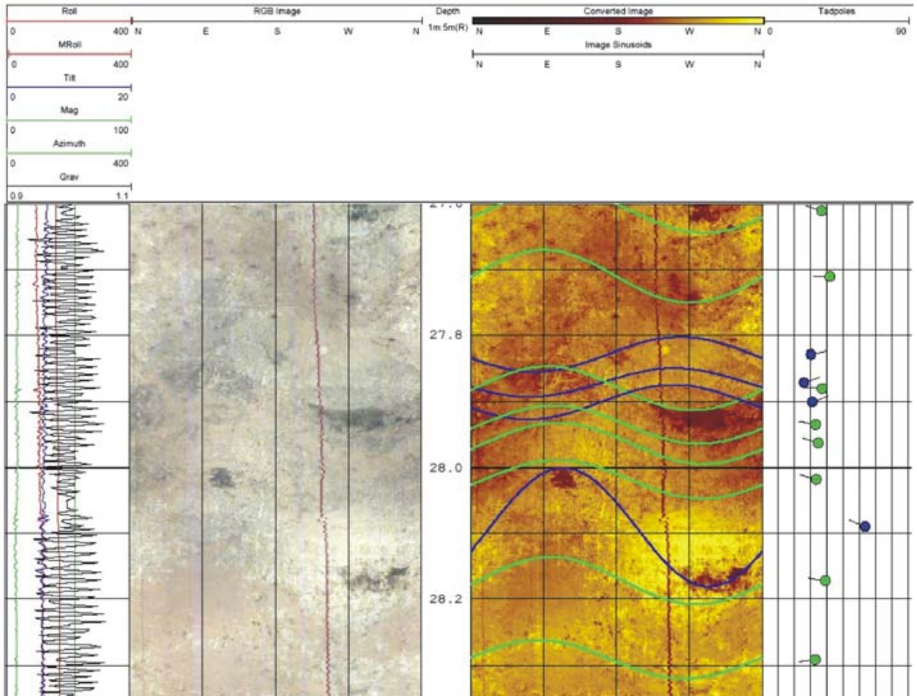


Figure 2. Example of Turtle Mountain RGB and Converted image logs and tadpole plot. Green sinusoids parallel bedding, blue sinusoids parallel fractures. Note vugs aligned with bedding. Heads of tadpoles give dip, tails show dip directions.

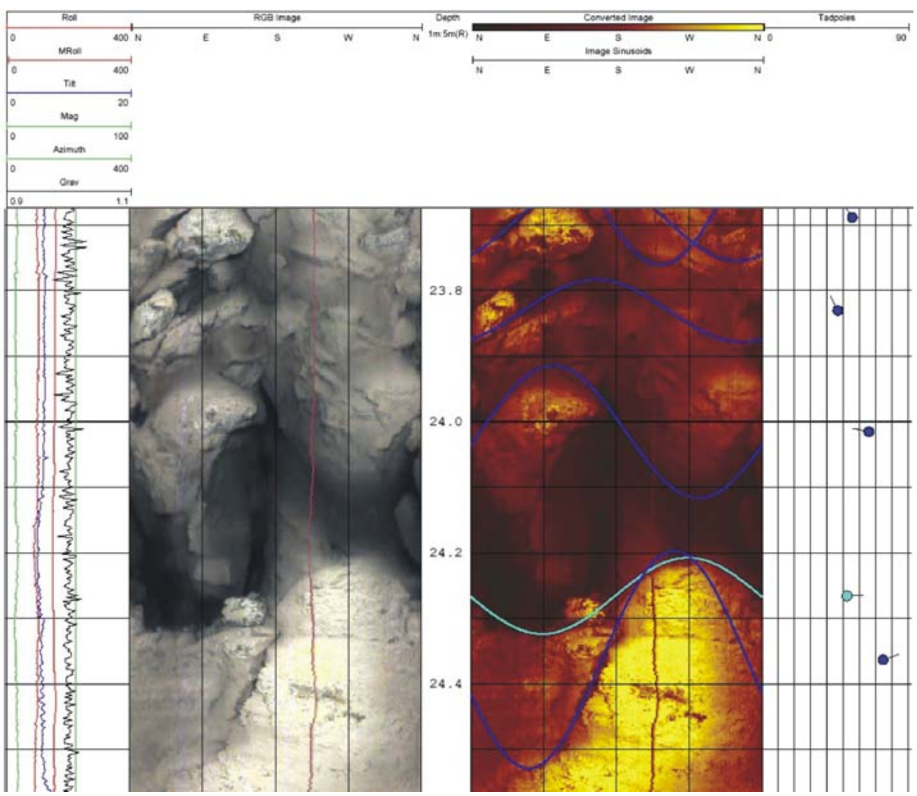


Figure 3. Example of a wide open "major fracture" (light blue) and other fractures (dark blue) imaged in a portion of the Turtle Mountain borehole.

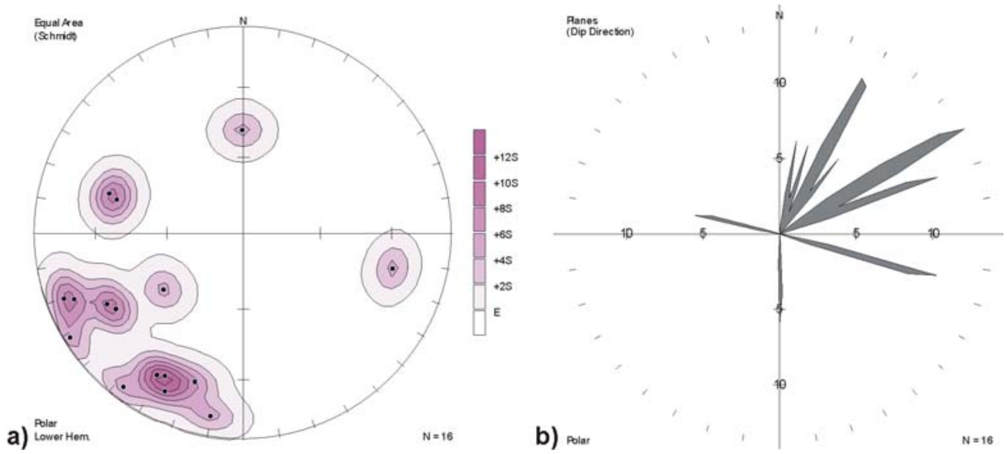


Figure 4 a) Stereoplot of contoured poles to major fractures (aperture >1 cm) in the borehole. **b)** Rose diagram of these fractures, with azimuth = dip direction, radius = frequency, class interval = 5°.

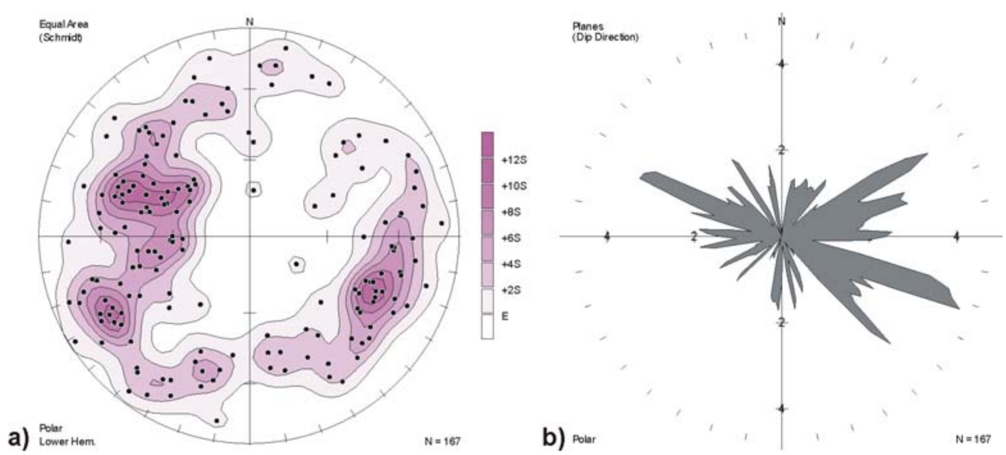


Figure 5 a) Stereoplot of contoured poles to all fractures and major fractures in the borehole. **b)** Rose diagram of these fractures with azimuth = dip direction, radius = frequency, class interval = 5°.

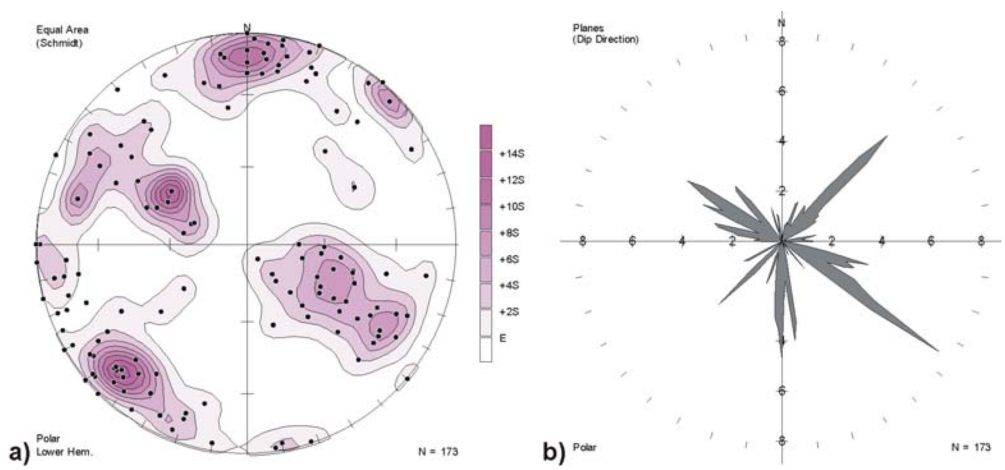


Figure 6 a) Stereoplot of contoured poles to all fractures and cracks measured at the surface. **b)** Rose diagram of these fractures, with azimuth = dip direction, radius = frequency, class interval = 5°.

Comparing the surface data (Figure 6) to the borehole data (Figure 5) we see that the three most frequent orientations in both datasets are the NW-dipping steeper-than-bedding set, the set dipping steeply NE toward the Frank Slide surface, and the set that dips ~30°SE toward Hillcrest. The two main differences between the plots are the lack of vertical beds measured in the borehole due to the low probability of intersecting surfaces sub-parallel to the borehole. The fewer azimuths represented in the surface data may be due to human bias - the tendancy to look for patterns and sets rather than measuring every orientation in outcrop, as is done with borehole data.

If all of the fractures developed during folding of the beds in the Turtle Mountain Anticline, Stearns' (1967) simple sets of Type 1 and Type 2 extension and shear fractures would be expected (Figure 7).

Fractures and cracks measured in outcrops on Turtle Mountain include Stearns' (1967) Type 1 and Type 2 extension and shear fractures, but several additional sets are observed (Figure 8). The compression direction at the time of thrusting was deduced from the hundreds of measurements of slickenside orientations made in the region by Don Norris (pers. comm., 1995) of the Geological Survey of Canada. Note that they are oblique to both the local fold axis orientation and the bedding strike in the vicinity of the borehole. This is not surprising considering that Turtle Mountain lies in the middle of the Crowsnest Deflection, where structures trend N-S to the north of the deflection and NW-SE to the south of the deflection. Type 1 dextral shears and Type 2 extension fractures associated with the regional compression direction are the most abundant, and there are significant numbers of fractures perpendicular to the local fold axis orientation (*ac* fractures) and others sub-parallel to local bedding.

Even more fracture orientations are encountered in the borehole (Figure 9); this is probably because the orientations of all obvious fractures in the borehole were measured, but there is a tendancy to visually filter out less common orientations when measuring fracture sets at the surfaces.

To compare the borehole data to the interpreted surfaces in the GPR Line B data collected by Theune et al. (2004), we first determined that the borehole plunges 84° toward 049° and that, near the borehole, the GPR line trends 057° relative to True North. Then, the apparent dips of mean bedding (red) and of all the major fractures in the borehole were plotted on the interpretation of the GPR line (Figure 10). Fractures that have apparent dips to the SW in the line of section are coloured blue and green and are consistent with the bedding-parallel and steeper than bedding fractures seen at the surface. These orientations are also interpreted in the GPR data. There are several sets of fractures with apparent dips to the NE that are coloured black. Most are not imaged in the GPR data because they are nearly perpendicular to the ground along the chosen line of acquisition. These large fractures have the most dangerous orientations because they dip toward the Frank Slide surface and the town of Hillcrest. GPR lines down the northeast slope of South Peak may be better able to image these orientations.

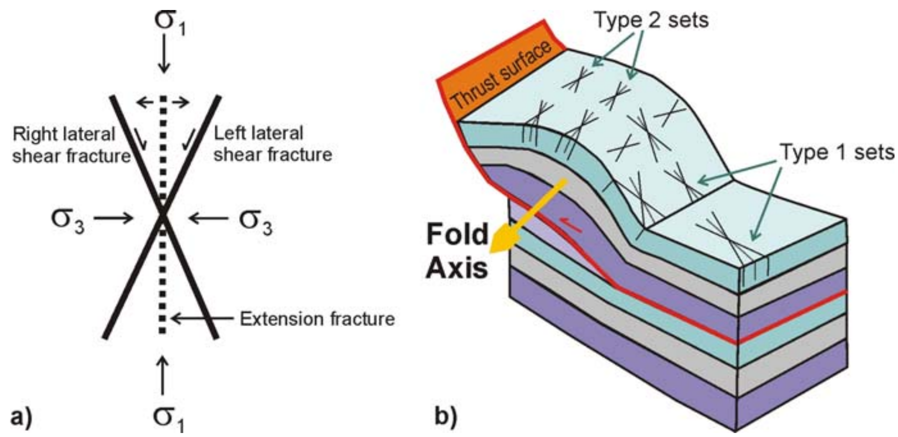


Figure 7 a) Orientations of extension and shear fractures relative to the maximum (σ_1) and minimum (σ_3) compressional stresses. **b)** Diagram of these fracture sets relative to the fold axis and thrust fault orientations in fold and thrust belts (after Stearns, 1967).

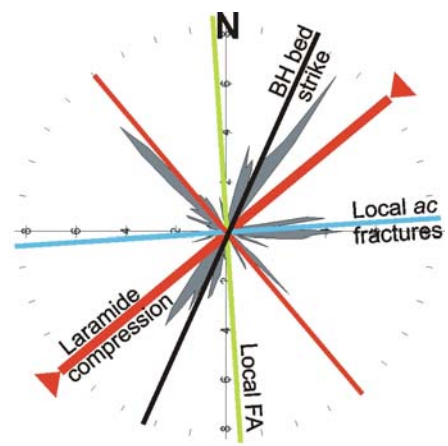


Figure 8. Rose diagram of all fractures and cracks measured at the surface. Here the azimuth = STRIKE, radius = frequency, class interval = 5°.

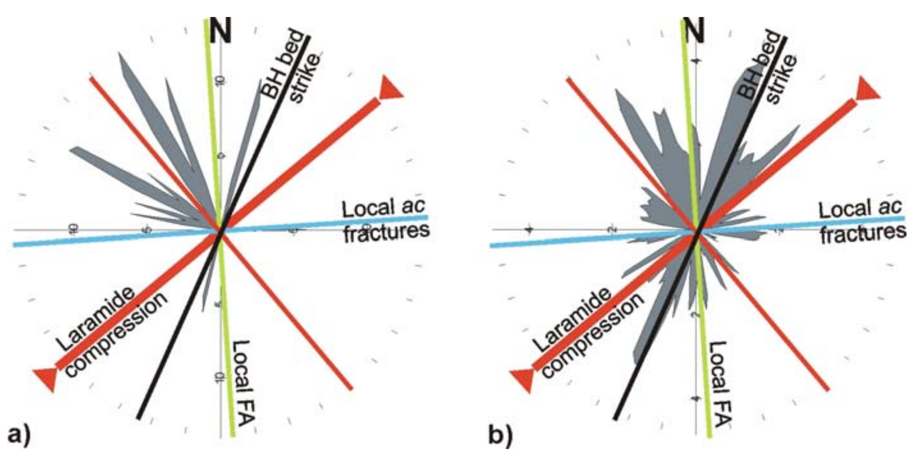


Figure 9. Orientations of extension and shear fractures relative to the Laramide compression direction, local fold axis trend, and local bedding strike for **a)** the major open fractures (aperture >1 cm) encountered in the borehole, and **b)** all major and minor fractures in the borehole. Azimuth = STRIKE, radius = frequency, class interval = 5°.

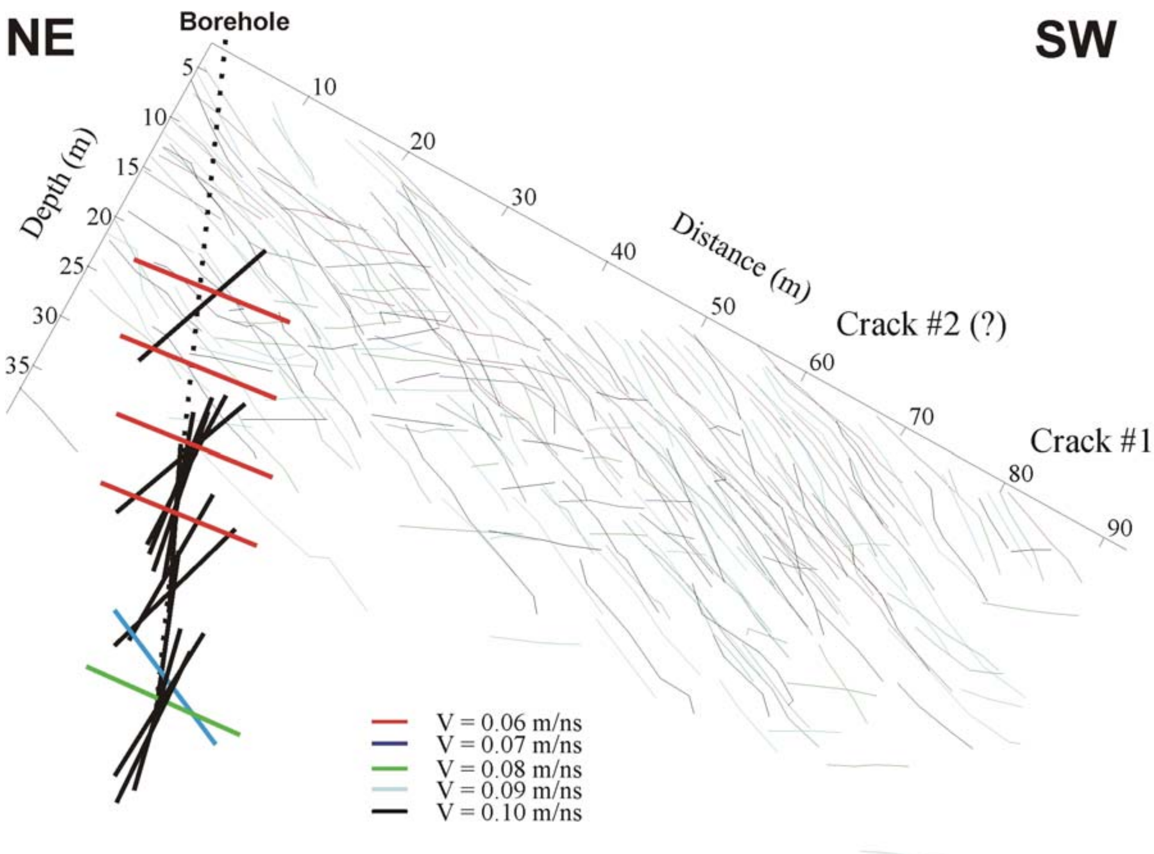


Figure 10. Borehole superimposed on the GPR data interpretation (thin lines) of Theune et al., 2004. Dotted line is the borehole trajectory, thick red lines are bedding, green and blue lines are major fracture sets parallel to and steeper than bedding. Black lines are major fractures most likely to contribute to slope instability.

Looking back at Figure 1 after completing the fracture analysis, it is clear that the dominant NE-dipping fractures in Figures 5 and 6 are related to the Frank Slide and the topographic slope marked by the yellow arrow appears to represent a post-glacial paleoslide related to the dominant SE-dipping fractures. Either fracture set could fail again, but the previous slide deposits may help to limit the lateral extent of future slide deposits.

REFERENCES

Olson, J.E., 2003. Sublinear scaling of fracture aperture versus length: An exception or the rule? Journal of Geophysical Research, v. 108, n. B9, p. 2413-2424.

Stearns, D.W., 1967. Certain aspects of fracture in naturally deformed rocks. *In:* Rieker, R.E. (ed.) National Science Foundation Advanced Science Seminar in Rock Mechanics: Special Report. Air Force Cambridge Research Lab, Bedford, Massachusetts, p. 97-118.

Theune, U., deGroot, M., Rokosh, C.D., Sacchi, M.D., Schmitt, D.R., Welz, M., and Holzhauer, J. (2004 manuscript). Looking inside Turtle Mounatin: Mapping fractures with GPR.

Vermilye, J.M., and Scholz, C.H., 1995. Relation between vein length and aperture. Journal of Structural Geology, v. 17, n. 3, p. 423-434.

Stop 5 continued

An igneous pebble conglomerate (previously called McDougal-Segur Conglomerate) is exposed in various places around the Frank Slide Centre and indicates braided river deposition. The conglomerate occurs in various stratigraphic positions in the Blairmore Group (Mill Creek Formation) and consequently, the McDougal-Segur name has not been properly applied and can be abandoned (Leckie and Krystinik, 1995; Leckie and Burden, 2001). The source of the igneous pebbles is a long distance away and is somewhere in BC.

A good exposure of the igneous pebble conglomerate north of the parking lot of the Centre will be visited.

12h30-13h30	**Lunch and Visit to Frank Slide Centre** ('In the Mountain Shadow' slide show, narrated by W.O. Mitchell, in auditorium)
13h45-14h15	**Stop 6:** Eastlimb Tower Anticline (from Osadetz et al., 2005, see below)
14h15-14h45	**Stop 7:** Lundbreck Falls (from Osadetz et al., 2005, see below)
17h30	Drop off at Calgary Airport

Stop 6 and 7

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

24.40 km Road cut through Virgelle Formation; belt of outcrop continues across the Crowsnest River to Stop 6

24.70 km T-junction with Highway 3; view to south of Wapiabi and Milk River group outcrop on south side of the Crowsnest River; **TURN WEST (RIGHT) ONTO HIGHWAY 3**

24.90 km Virgelle Formation outcrop

25.20 km Lundbreck Formation outcrop, Belly River Group

26.50 km Belly River Group outcrop

26.80 km Junction with Highway 3A, to Lundbreck Falls Recreation Area, **TURN SOUTH (LEFT) ONTO HIGHWAY 3A**

27.30 km Virgelle Formation outcrop

28.00 km Parking lot at Lundbreck Falls viewpoint; spectacular outcrop of Virgelle Formation

28.05 km Crowsnest River Bridge

28.10 km Access to parking lot on south side of Crowsnest River. **TURN RIGHT** and park near picnic shelter. **Stop 1-6a**; walk southeast toward high point on outcrop adjacent to the railroad cut.

Stop 1-6a: Virgelle Formation outcrop on east edge of an interpreted "pop-up" structure, at Lundbreck Falls Recreation Area, on Highway 3A, east of west junction of Highways 3 and 3A.

Distance: 28.10 km from turnout off Highway 22 leading to Stop 1-5a.

Access: From Highway 3, take the west access onto Highway 3A to Lundbreck Falls Recreation Area. Drive 1.3 km, passing the falls and crossing the bridge to turn right onto access road.

Theme: Triangle zone structure and stratigraphic succession of the Foreland Basin.

Purpose: Observation and discussion of structures interpreted as a “pop-up” feature associated with the triangle zone.

Geology: We will discuss the stratigraphy of the Milk River and Belly River groups in more detail at Stop 1-6b, located 1.2 km to the east (Figure 1-6-1). At this location, however, we have a good view of a series of structures that have been interpreted as a pop-up feature (Stockmal, 2004).

We are standing on the Virgelle Formation of the Milk River Group, in the immediate hanging wall of an east-directed thrust, labeled TF1 (thrust fault 1) in Figure 1-6-1. The Milk River Group comprises three formations, the middle of which is the Virgelle Formation (Figure 1-6-2), a thick (~40 m) and erosionally resistant shoreface sandstone. At this locality, bedding is anomalously flat lying, in comparison to moderate to steep dips generally seen across the Foothills belt. This attitude is clearly seen in front of us, on the map (Figure 1-6-1), and on air photos (Figure 1-6-3). The course of the Crowsnest River transects this flat-lying structure, forming spectacular Lundbreck Falls. The river lies near the trough of an open east-west trending, spoon-shaped fold delineated by the resistant top of the Virgelle Formation (Figure 1-6-4).

Figure 1-6-4 is an annotated panoramic view to the north. To the west, behind the house on the north bank of the river, are a number of outcrops of Virgelle Formation. The most distant is separated from the others by a foreland-directed thrust fault, labeled TF2. The trace of this fault appears on the hill to the north, where it separates a slightly east-facing anticline in its hanging wall from a slightly west-facing anticline in its footwall. Both these folds are easily seen in air photos (Figure 1-6-3, top and lower right). The juxtaposition of these two oppositely facing anticlines involving the Virgelle Formation, across foreland-directed TF2, is an unusual structural situation. As discussed below, this juxtaposition, coupled with the atypical flat-lying geometry of the structure through Lundbreck Falls, is the basis for the interpretation of a cryptic backthrust (BT2) and the pop-up structure.

The long, shallowly east-dipping east limb of the eastern fold is easily seen on the hill to the north, outlined by the resistant shoreface sandstones of the Virgelle Formation and the basal Belly River Group (Figure 1-6-4). The Virgelle Formation on this limb is structurally continuous with the rocks beneath our feet. The Milk River and Belly River units are truncated to the east by the thrust fault (TF1 in Figure 1-6-4) that lies immediately east of us and is associated with the small rollover anticline seen in the railroad cut behind us. Farther to the east (right in Figure 1-6-4) we see another ridge underlain by the resistant Virgelle Formation. However, at that locality the Virgelle is moderately east dipping and the ridge is carried on a west-directed backthrust (BT1 in Figure 1-6-4). This backthrust will be more apparent at Stop 1-6b.

Figure 1-6-5 shows two panoramic views, from points shown in Figure 1-6-1. The panoramic view to the north (Figure 1-6-5, top) shows the following main features, from east to west: (1) the Milk River Group and the basal Belly River sandstone in the hanging wall of backthrust BT1, which cuts off the trace of the Tower Anticline to the north; (2) the continuous panel of west-dipping Belly River strata in the footwall of backthrust BT1, that also underlies the viewpoint location; (3) the foreland-directed thrust, TF1, that places Milk River Group on Belly River Group; (4) the shallowly east-dipping panel of Milk River Group strata in the hanging wall of thrust TF1; and (5) the next foreland-directed thrust to the west, TF2, across which the two anticlines noted above face each other.

The panoramic view to the south (Figure 1-6-5, bottom) shows the following main features, from east to west: (1) Milk River Group strata folded across the Tower Anticline, into the core of which backthrust BT1 dies out; (2) the continuous panel of west-dipping Belly River strata on the west limb of the anticline (and to the north, in the footwall of backthrust BT1) that underlies the viewpoint location for the north-facing panorama; (3) foreland-directed thrust TF1 that places Milk River Group on Belly River Group (fault TF1 bifurcates south of the Crowsnest River); (4) the sub-horizontal panel of Milk River Group strata in the hanging wall of thrust TF1, which tilts progressively more westward as the structure is followed to the south; and (5) the next foreland-directed thrust to the west, TF2.

Overall, these two views show along-strike structural variation. The panel of rocks on which we are standing, sub-horizontal in attitude adjacent to the Crowsnest River, is shallowly east-dipping to the north (Figure 1-6-5, top), but shallowly west-dipping to the south (Figure 1-6-5, bottom), indicating an along-strike clockwise sense of rotation. Backthrust 1 (BT1), well-developed north of the Crowsnest River (Figure 1-6-5, top), dies out to the south where is it replaced by a fold (the Tower Anticline; Figure 1-6-5, bottom). At the Crowsnest River, this fold is well exposed in the immediate hanging wall of BT1 (visible from Stop 1-6b).

Line-length-balanced cross-sections across this structure are shown in Figure 1-6-6 (locations shown in Figure 1-6-1). Although not constrained here by seismic data, a nearby well (Cow Creek 6-30-8-1W5)

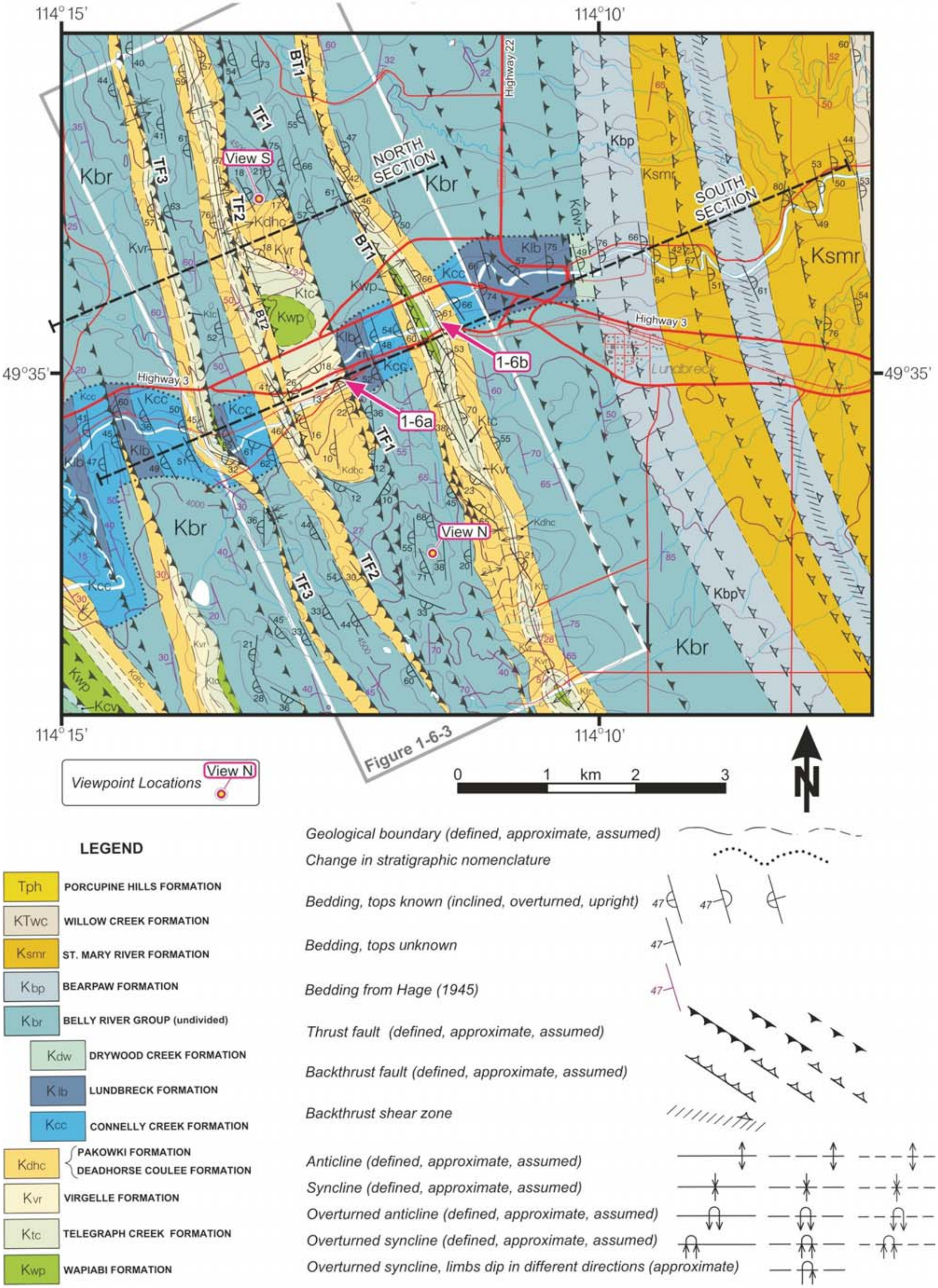
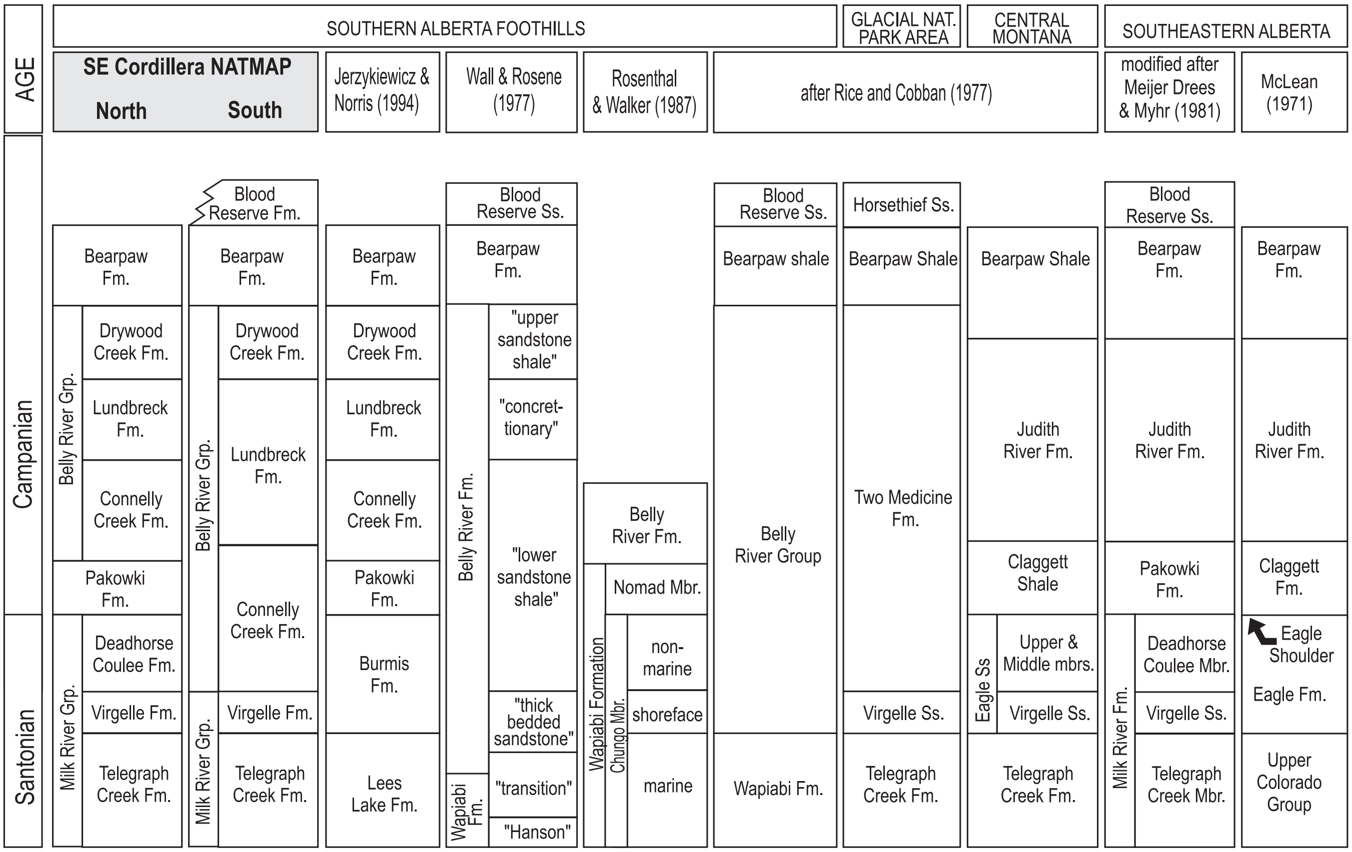


Figure 1-6-1. Detail of GSC Open File #1653, map of Blairmore (east half) (Stockmal and Lebel, 2003), showing locations of Stops 1-6a and 1-6b, and associated figures, viewpoints, and cross-section locations.



Lithostratigraphic units applied to Santonian-Campanian strata in southern Alberta and adjacent Montana.

Figure 1-6-2. Lithostratigraphic nomenclature applied to Santonian-Campanian strata in southern Alberta and Montana, based on unpublished figure by A.R. Sweet (GSC-Calgary). The units mapped in the area discussed on the field trip are in the columns with shaded headings.

and published seismic data 5 km to the south (Bégin et al., 1996) support the interpretation of a triangle zone structure at depth. The south section shows the locations of Stop 1-6a, at Lundbreck Falls, and Stop 1-6b, at the “Lundbreck transition outcrop”. The enlargement of the north section shows the juxtaposition of oppositely facing anticlines, with little stratigraphic offset across TF2. To both the south and north, stratigraphic offset across TF2 increases (Figure 1-6-1). Footwall synclines are very common in thrust-and-fold belts, but footwall anticlines are rare.

A reasonable explanation for this structure involves a cryptic backthrust, as shown in both cross sections (labeled BT2) and most previous figures for this stop. In this interpretation, the anticline in the footwall of foreland-directed thrust TF2 also lies in the hanging wall of backthrust BT2, and the facing direction of the anticline is then consistent with the sense of shear on the backthrust (as shown in Figure 1-6-7). The existence of backthrust BT1 documented 1.5 km to the east lends additional support to this interpretation, in the sense that if mechanical conditions existed that were conducive to creating one backthrust, then a second becomes more plausible. The possible deformation paths of a pop-up structure, and the resultant structure assuming transport up a ramp and onto a flat, are shown schematically in Figure 1-6-7. Out-of-sequence development of a thrust fault branching off the top of the ramp, and subsequent back-rotation of the entire structure as the triangle zone develops results in a configuration very similar to that shown in Figure 1-6-6.

The restored cross sections further suggest a linkage between backthrust BT1 documented west of the Lundbreck transition outcrop and the interpreted, cryptic backthrust BT2. Both these backthrusts are associated with foreland-directed faults, forming pop-up structure geometries in restoration (Figure 1-6-6).

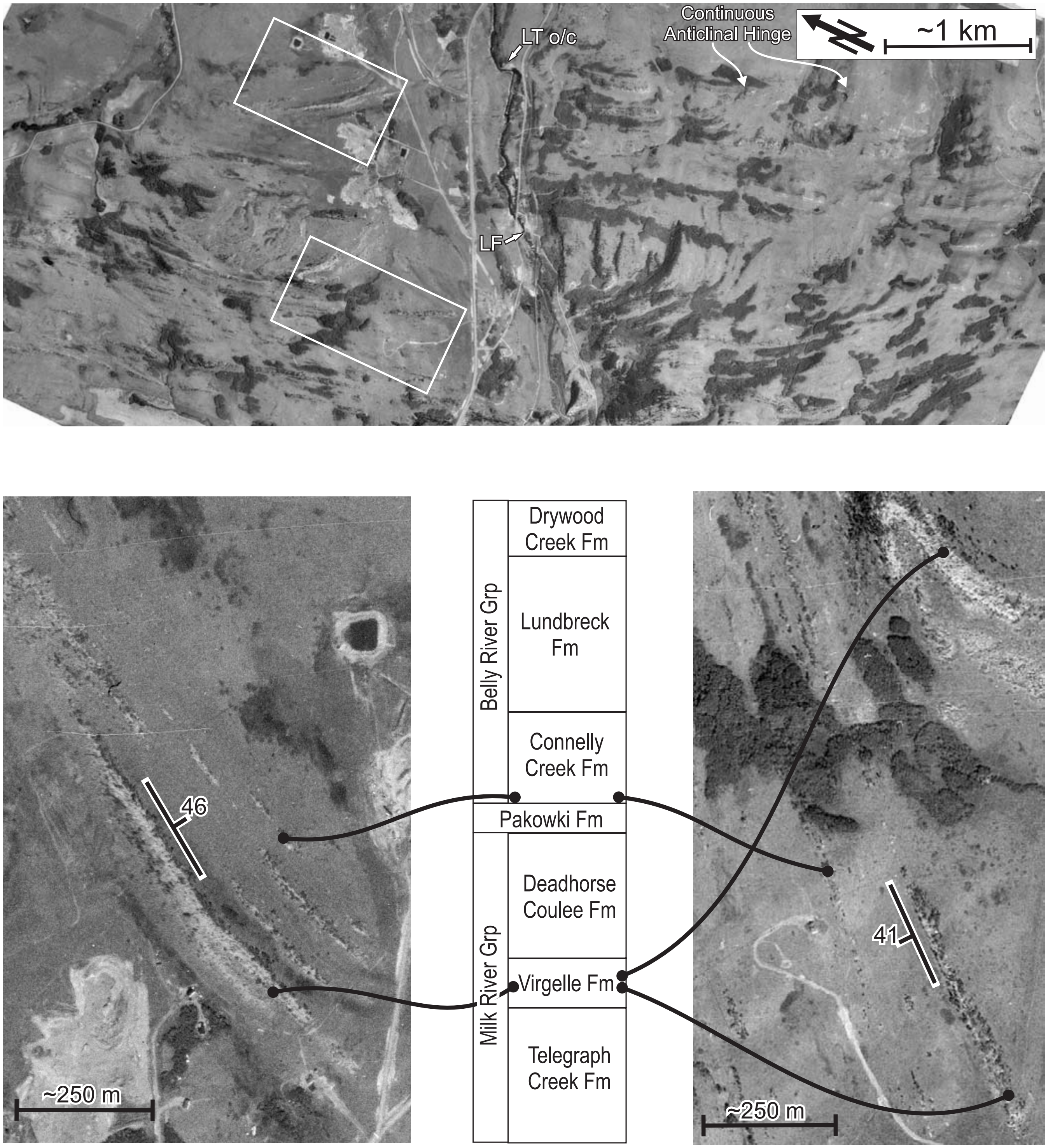


Figure 1-6-3. Examples of air photo expressions of structure. Top figure is area outlined in Figure 1-6-1, and shows outlines of areas enlarged in bottom figures. West-facing anticline in footwall of backthrust BT1 is seen at top of lower right image.

The position of the inferred foreland-directed thrust at depth, east of the Lundbreck transition outcrop in restoration, is constrained simply by assuming that the uppermost fault of the inferred antiformal stack filling the triangle zone is detached at about the same stratigraphic level as implied for the west-dipping thrust sheets (somewhere in the Wapiabi Formation marine shales, indicated in the restored cross sections as a broad cross-hatched zone).

Panoramic View North From Stop 1-6a (Lundbreck Falls)

Figure 1-6-4. Panoramic view north from Stop 1-6a at Lundbreck Falls. Near the skyline, middle, are oppositely facing anticlines well-outlined by the resistant Virgelle Fm, separated by a known east-directed thrust fault (TF2) and an inferred west-directed backthrust (BT2). The viewpoint lies next to the trace of another thrust (TF1), on an anomalously broad and sub-horizontal structure interpreted as a pop-up.

A speculative association between pop-up structures and the triangle zone is illustrated schematically in Figure 1-6-8. Figure 1-6-8a shows an idealized triangle zone (shaded), bounded by (1) a foreland-directed lower detachment, (2) a hinterland-directed upper detachment, and (3) the first foreland-directed thrust fault that crops out in the footwall of the upper detachment. Typically, triangle zones are filled by a duplex structure where displacement on individual foreland-directed thrusts is transferred to hinterland-directed motion on the upper detachment (e.g., see MacKay et al., 1996). Shown beneath and in front of the triangle zone in Figure 1-6-8a are two nascent duplex horses, labelled A and B. Assuming an in-sequence development of the wedge, horse A would be incorporated into the triangle zone prior to incorporation of horse B. The frontal ramps of these horses are shown with low to moderate dips of 10°-20°, consistent with observed values for southern and central Alberta compiled by Spratt and Lawton (1996).

An alternative configuration for nascent duplex horses involves the incorporation of pop-up structures initiated in front of the triangle zone, as illustrated in Figure 1-6-8b, where the foreland-directed thrusts bounding the pop-ups are utilized as in option (3) in Figure 1-6-7. These thrusts form ramps with steeper dips of perhaps 30°-35° (Figure 1-6-8b), resulting in relatively large hanging wall cutoff angles, as observed for thrust TF1 (Figures 1-6-1 and 1-6-6). The nascent horses labeled A and B in Figure 1-6-8b are subsequently incorporated into the advancing triangle zone, where they are structurally elevated and back-rotated through accretion of additional duplex horses as shown in Figure 1-6-8c.

Thrust fault TF2 is interpreted here as a relatively late feature, that overrode the pop-up structure following motion on backthrust BT2 (Figure 1-6-8c). This is a plausible explanation for the spacing of foreland-directed thrusts seen in the restored sections (Figure 1-6-6), where faults TF1 and TF2 are much more closely spaced than the other documented faults. Fault TF2 may have branched upward from near the top of the thrust ramp of fault TF1 that must exist at depth (Figures 1-6-6 and 1-6-8c), similar to the evolution of an idealized pop-up structure illustrated in Figures 1-6-7c and 1-6-7d.

Road Log:

Return on the access road to Highway 3A, near the east end of the bridge.

Reset odometer to ZERO, and turn east (right).

0.00 km At Stop sign on access road.

1.20 km **Stop 1-6b**; Milk River Group outcrop to north at crest of hill; park on shoulder.

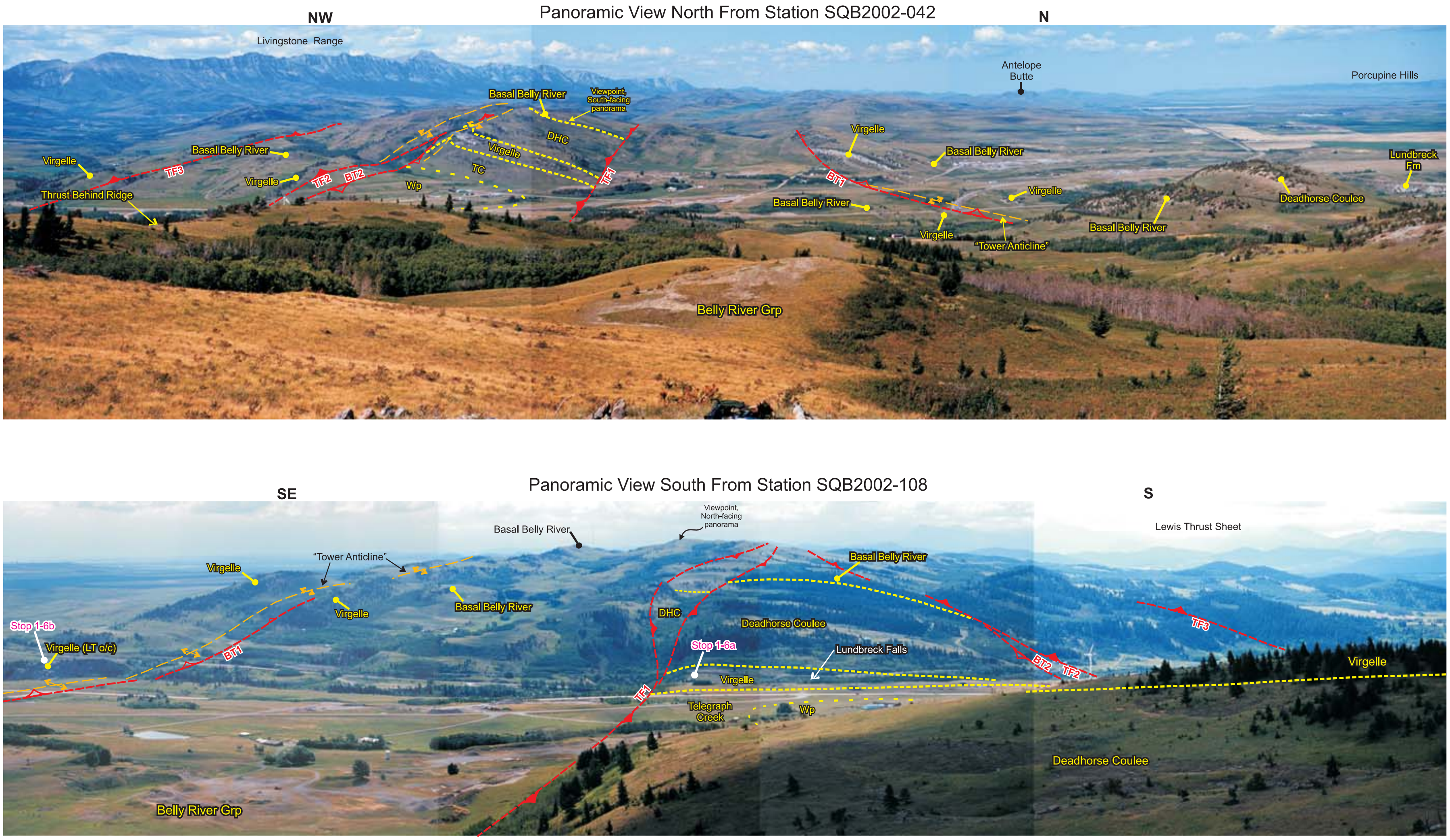


Figure 1-6-5. Panoramic views of the pop-up structure from viewpoints indicated in Figure 1-6-1 (labeled "View N" and "View S"). Stop locations 1-6a and 1-6b are indicated in the bottom panorama.

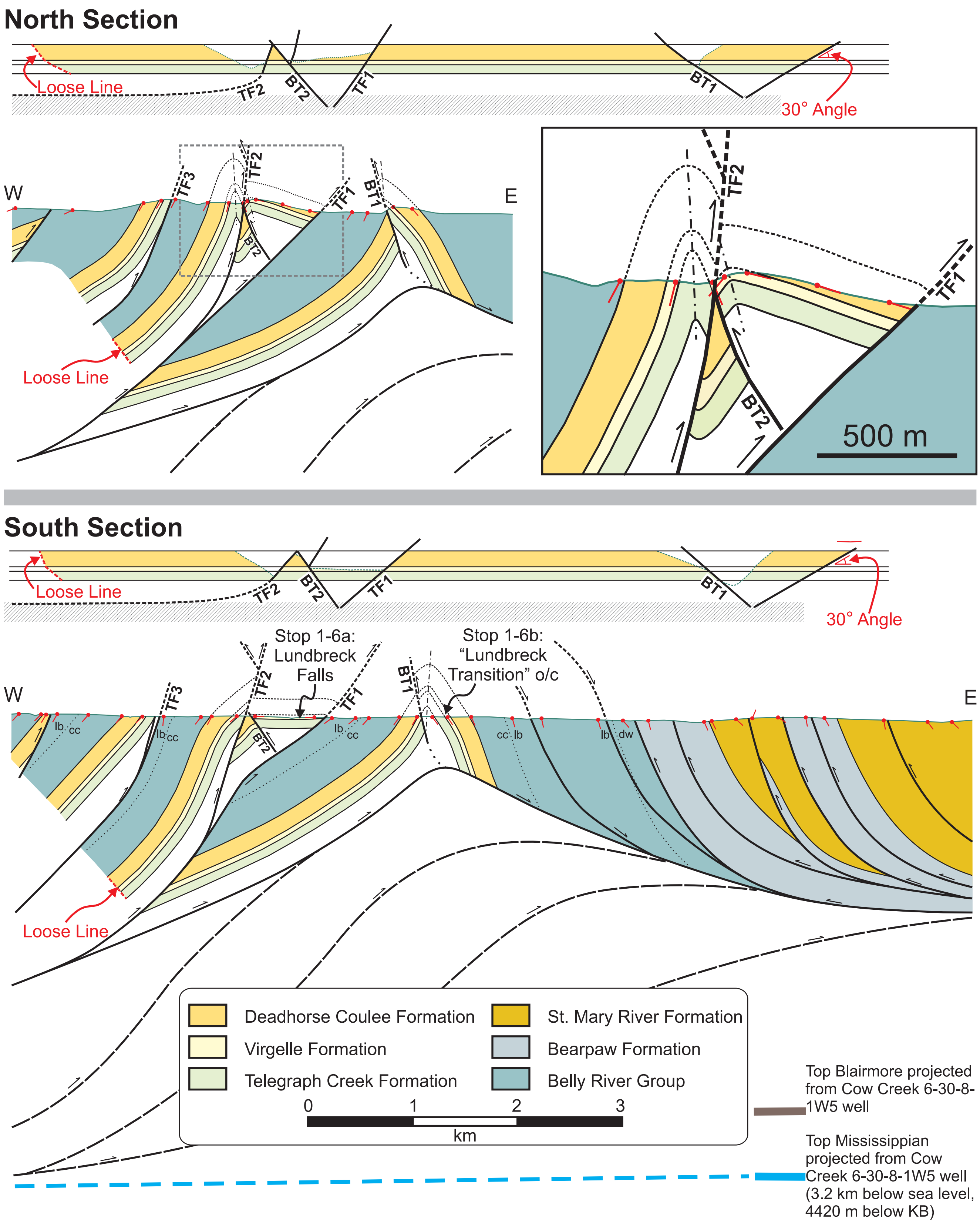


Figure 1-6-6. Structural cross-sections and palinspastic restorations (bed-length balanced). Lines of section are shown in Figure 1-6-1. Enlargement of folds in north section shown in inset.

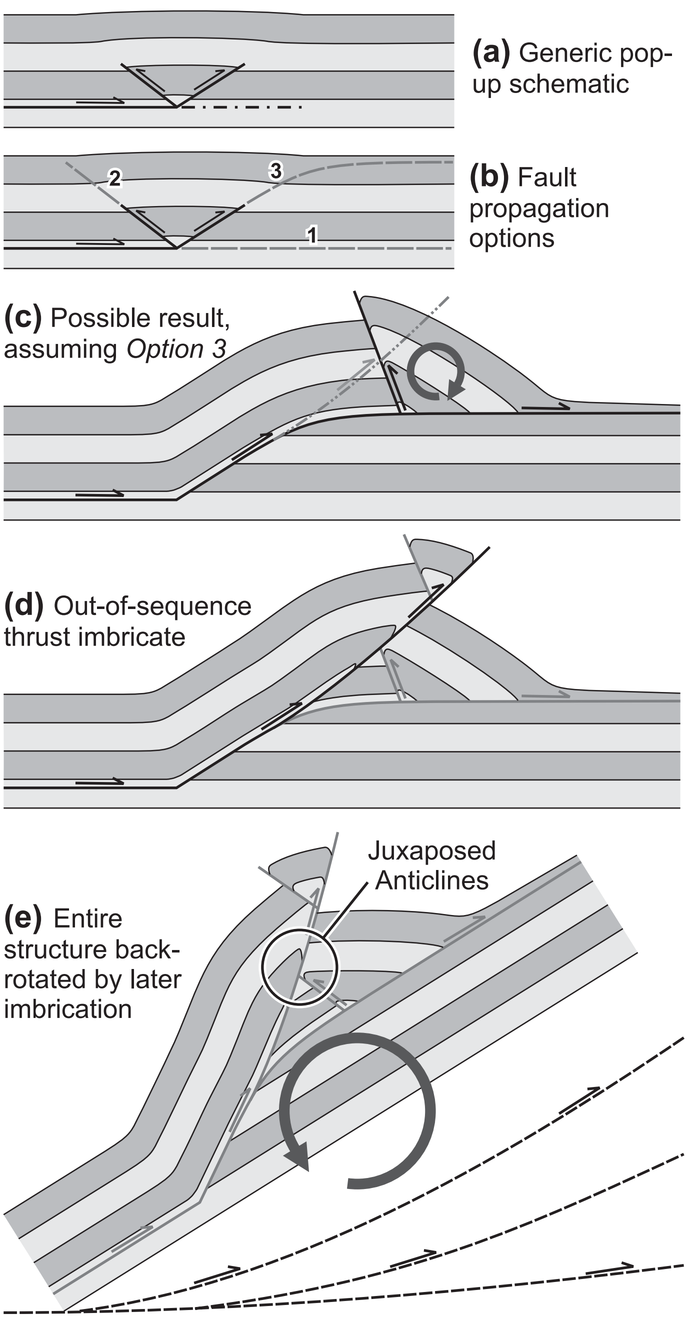


Figure 1-6-7. Definition and possible kinematic deformation paths of a pop-up structure. The sub-horizontal configuration and opposing anticlines seen at Lundbreck Falls are interpreted as structures associated with a transported, cross-cut, and back-rotated pop-up.

Stop 1-6b: Milk River Group outcrop, downstream of Lundbreck Falls Provincial Recreation Area, on Highway 3A.

Distance: 1.20 km from access road to Stop 1-6a.

Access: From Stop 1-6a, drive 1.2 km east on Highway 3A to the crest of a hill. Park at the side of the road opposite the flat top of a prominent, large outcrop of east-dipping cliff-forming sandstones. Carefully cross the barbed-wire fence to a viewpoint near the cliff edge (caution!).

Theme: Stratigraphic succession of the Foreland Basin

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

Geology: This is the frequently visited “Lundbreck transition” outcrop on the Crowsnest River west of Lundbreck (Figure 1-6-1). This unit has also been known as the Chungo Member of the former Belly River Formation, that is now mapped as part of the Milk River Group (Stockmal, 1995, 1996, 2004). The Milk River Group consists of the Telegraph Creek, Virgelle, and Deadhorse Coulee formations (Figure 1-6-8). It is underlain by the Wapiabi Formation and overlain by the Pakowki Formation (formerly Nomad Member), both marine shales. The Pakowki is overlain in turn by the Belly River Group, mappable locally at the formation level.

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

Figure 1-6-10 is an annotated view facing north from the viewpoint on top of the Virgelle outcrop. These Milk River, Pakowki, and Belly River units are mappable across the grassy hills. Note how the thick Virgelle sandstone can crop out as discrete, narrower bands,

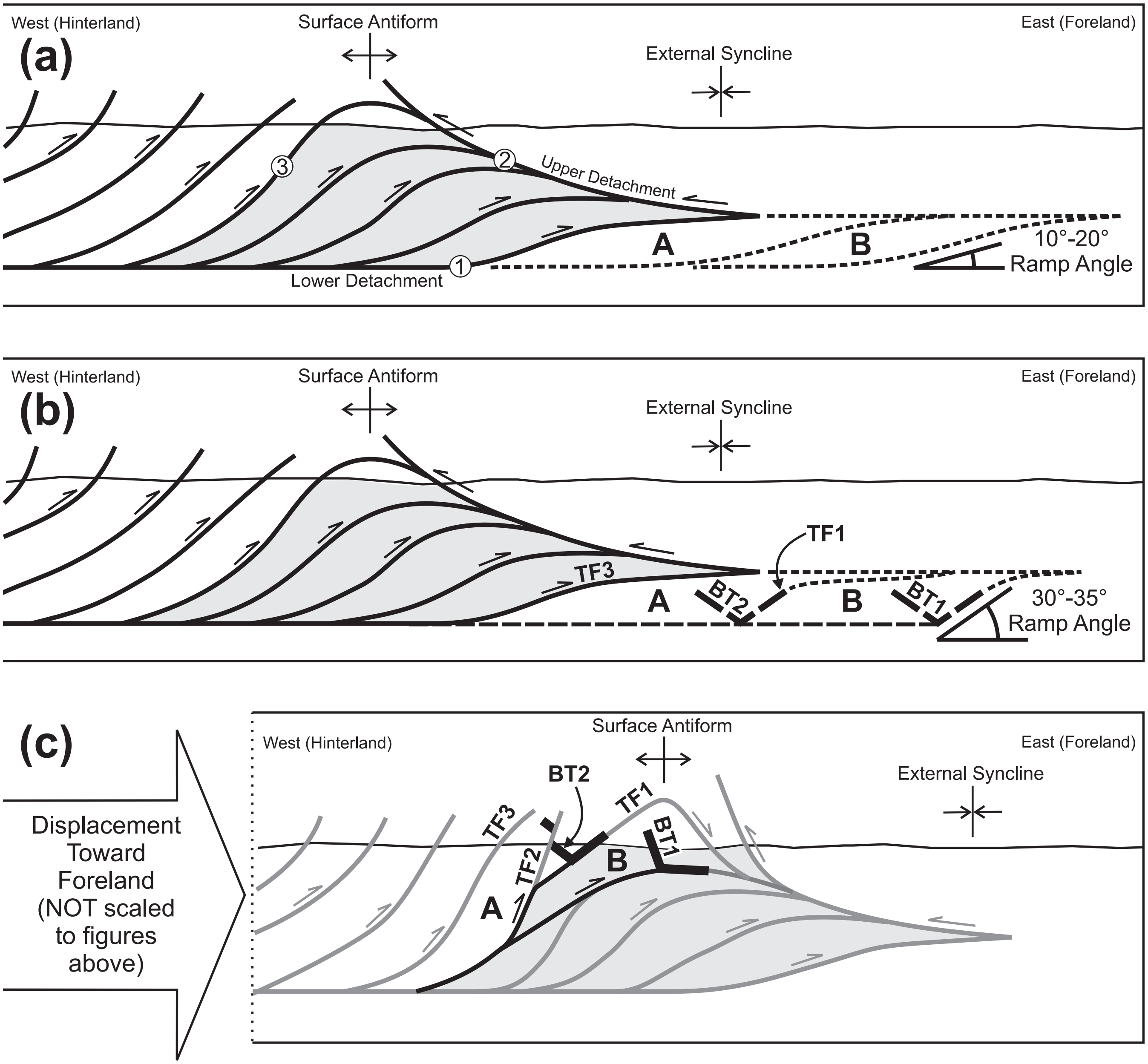


Figure 1-6-8. Schematic triangle zone configurations and possible relationships to pop-up structures. **(a)** Idealized configuration showing the three sides (numbered) bounding the triangle zone (shaded). Short-dashed lines indicate nascent thrusts with relatively low frontal ramp angles bounding horses labelled A and B. **(b)** Similar to configuration in (a) except relatively steep frontal ramps of nascent horses A and B coincide with foreland-directed thrusts bounding pop-up structures (thick-dashed lines). Note possible correspondence to mapped faults BT1, BT2, TF1, and TF3. **(c)** Possible configuration of (b) following triangle zone advance and incorporation of horses A, B, and others. Compare geometries of labelled faults with those in Figure 1-6-6. Thick, solid, black lines are faults bounding the pop-up structures; thin, solid, black lines are detachments corresponding to thin, long-dashed, black lines in (b).

rather than as a single unit, complicating correlation especially on aerial photographs. Figure 1-6-11 is an annotated view of the outcrop from the north, facing south, from Highway 3. The approximate locations of the formation boundaries are marked, including the location of the Pakowki Formation marine shale, and the overlying prominent shoreface sandstone at the base of the Belly River Group (Connelly Creek Formation).

Structurally, we are on the east limb of the Tower Anticline (Figures 1-6-1, 1-6-5, and 1-6-6), in the hanging wall of the small-displacement, west-directed Backthrust 1 (Stockmal, 2004). Backthrust 1 is interpreted as a splay off the top of the antiformal stack that probably fills the core of the triangle zone (Figure 1-6-6). The interpreted upper detachment of the triangle zone is ~3 km to the east. Two belts of deformed Bearpaw Formation strata are exposed on

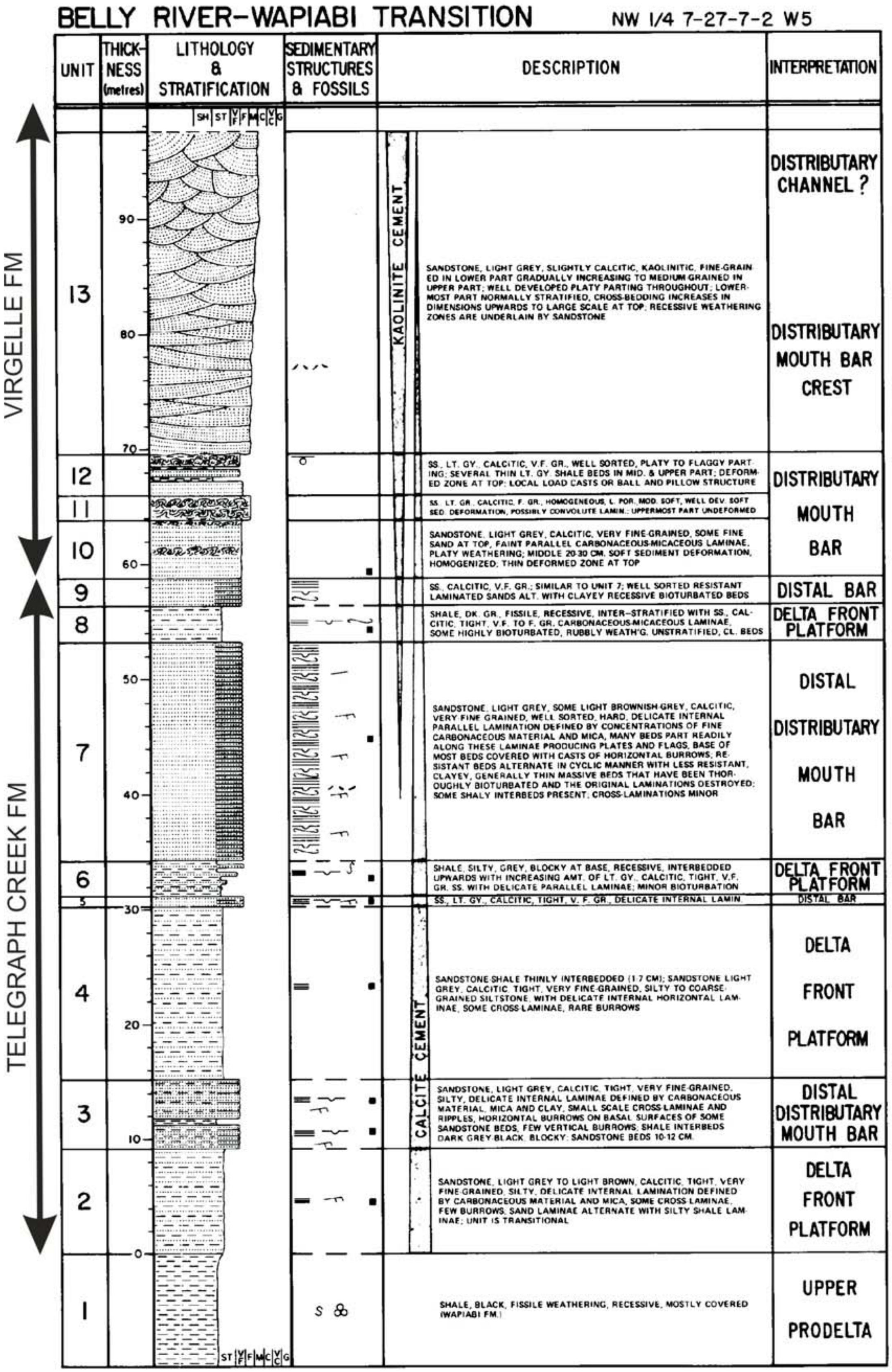


Figure 1-6-9. Measured section, Crowsnest River (from Lerand and Oliver, 1975). The extents of the Telegraph Creek and Virgelle formations, in comparison to the numbered units of Lerand and Oliver (1975) are indicated.

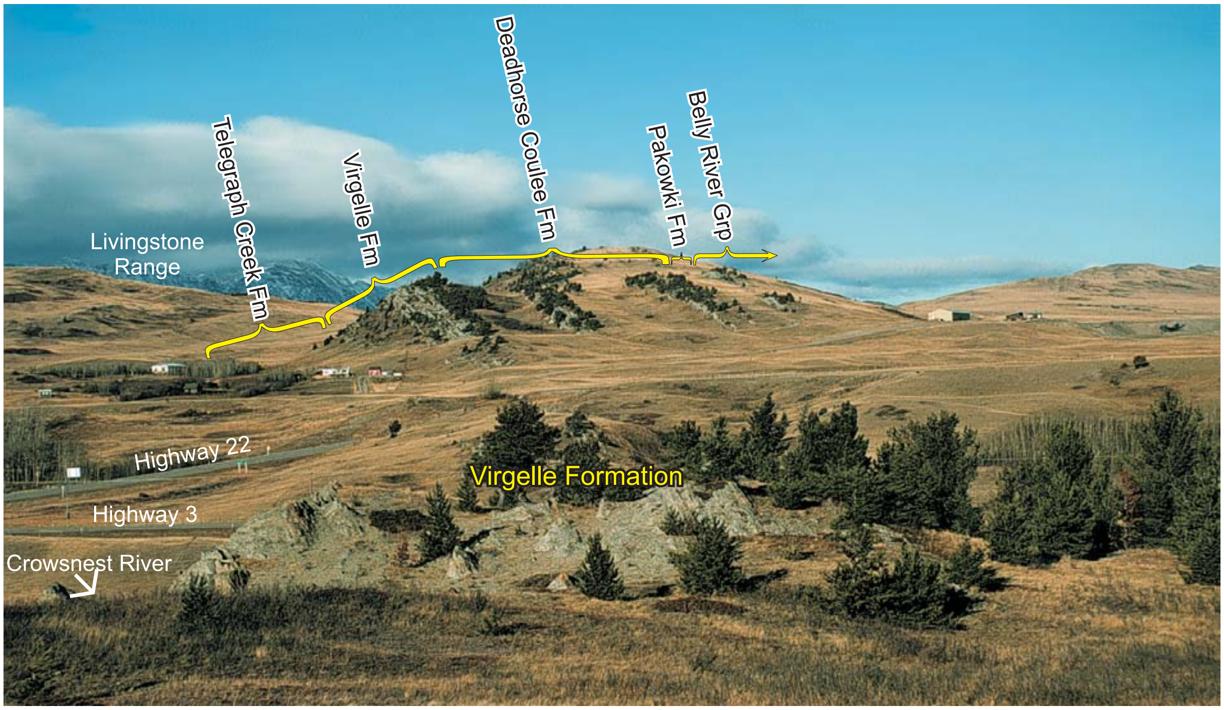


Figure 1-6-10. Annotated view north from top of Virgelle Formation outcrop at Stop1-6b, south side of Crowsnest River. Units along strike on distant ridge are labeled. Mississippian carbonates exposed in the Livingstone Range in far distance.

Figure 1-6-11. Panoramic view facing south, of Milk River Group outcrop at Stop 1-6b, viewed from Highway 3, north side of Crowsnest River. This east-dipping section is complete from the uppermost Wapiabi Formation (marine shale), the Telegraph Creek (lower shoreface), Virgelle (upper shoreface), and Deadhorse Coulee (non-marine) formations of the Milk River Group, the marine Pakowki Formation shale, through to the Connelly Creek Formation of the Belly River Group, the basal unit of which is a prominent shoreface sandstone similar to but thinner than the Virgelle.

the Crowsnest River (Figure 1-6-1), suggesting a more complicated structural history for the upper detachment here than to the north. To the south, the deformation front swings markedly to the southeast (Price, 1962). The triangle zone is known to continue at least as far south as the Waterton River (township 4), where it was interpreted by Shell Oil Company geologists (as reported in Gordy et al., 1977, where the term “triangle zone” was first used in publication). However, the triangle zone is not clearly expressed at the surface farther to the south in the Cardston map sheet (Lebel, 1994), although Bearpaw Formation, Blood Reserve Formation, and lower St. Mary River Formation strata occur within the imbricate slices of Foothills sheets, suggesting that the upper detachment migrates to a higher stratigraphic level to the south.

Road Log:

29.30 km From Stop 1-6b, continue south on Highway 3A

30.20 km Junction with Highway 3

Reset odometer to ZERO, and turn east (right)

References

Adair, R.N. and Burwash, R.A., 1996, Evidence for pyroclastic emplacement of the Crowsnest Formation, Alberta. Canadian Journal of Earth Sciences, v.33, pp.715-728.

Canadian Society of Petroleum Geology, 2000, Geological Highway Map of Alberta, Edited by M. Cooper.

Langenberg, C.W., Pana, D., Richards, B.C., Spratt, D.A. and Lamb, M.A., (in press), Structural geology of the Turtle Mountain area near Frank, Alberta, Alberta Energy and Utilities Board, EUB/AGS Earth Sciences Report.

Lebel, D. and Hiebert, S.N., 2001, Geology, Beaver Mines (NTS 82G/8 – East Half), Geological Survey of Canada, Open File 4024, scale 1:50,000.

Leckie, D.A. and Burden, E.T., 2001, Stratigraphy, sedimentology and palynology of the Cretaceous (Albian) Beaver Mines, Mill Creek and Crowsnest Formations (Blairmore Group) of southwestern Alberta. Geological Survey of Canada, Bulletin 563, 103 pages.

Leckie, D.A., and Krystinik, L.F., 1995, Cretaceous igneous-clast conglomerate in the Blairmore Group, Rocky Mountain Foothills and adjacent subsurface (Bow Island Formation), Alberta, Canada. Bulletin of Canadian Petroleum Geology, v.43, pp. 320-342.

McClay, K.R. and Insley, M.W., 1986, Duplex structures in the Lewis thrust sheet, Crowsnest Pass, Rocky Mountains, Alberta, Canada. Journal of Structural Geology, v.8, pp.911-922.

Mussieux, R. and Nelson, M., 1998, Geological Wonders in Alberta, The Provincial Museum of Alberta, 254 pages.

Norris, D.K., 1993a, Geology and structure cross-sections, Beaver Mines (West Half-82G/8W), Survey of Canada, Map 1829A, scale 1:50,000.

Norris, D.K., 1993b, Geology and structure cross-sections, Blairmore (West Half-82G/9W), Geological Survey of Canada, Map 1829A, scale 1:50,000.

Osadetz, K.G., Stockmal, G.S., and Kisilevsky, D.K., 2005. Structure and hydrocarbon occurrence, Rocky Mountain Foothills and Front Ranges, Turner Valley to Waterton Lakes. Guidebook, Field Trip #12, 2005 American Association of Petroleum Geologists Annual Convention, Calgary, Alberta, 166 p.

Peterson, T.D., Currie, K.L., Ghent, E.D., Begin, N.J., and Beiersdorfer, R.E., 1997, Petrology and economic geology of the Crowsnest volcanics, Alberta. Geological Survey, Bulletin 500, pp.163-184.

Price, R.A., 1962, Fernie map-area, east half, Alberta and British Columbia. Geological Survey of Canada, Map 35-1961.

Richards, B.C., Barclay, J.E., Bryan, D., Hartling, A., Henderson, C.M., Hinds, R.C. (1994): Chapter 14 - Carboniferous Strata of the Western Canada Sedimentary Basin. In: Geological Atlas of the Western Canada Sedimentary Basin. G.D. Mossop and I Shetson (compilers), Canadian Society of Petroleum Geologists and Alberta Research Council, pp. 221-250.

Stockmal, G.S. and Lebel, D., 2003, Geology, Blairmore (82G/9E – East Half), Geological Survey of Canada, Open File 1653, scale 1:50,000.