

# GEOLOGY OF THE TOAD RIVER AREA (NTS 094N), NORTHEAST BRITISH COLUMBIA

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## ABSTRACT

Regional mapping within the Toad River map area (NTS 094N) during the summer of 2011 will be incorporated with published and unpublished geological studies, including the unpublished detailed mapping along the Liard River corridor for BC Hydro, to update the geological database of this map area. More than 8000 m of strata spanning the Mesoproterozoic to Upper Cretaceous occur in the area. Abrupt changes in thickness and facies, and the local absence of specific stratigraphic intervals indicate that block faulting was active during the Middle Cambrian, Ordovician to Silurian, Mississippian to Permian, and Jurassic to Early Cretaceous (pre-Albian). These early faults were commonly reactivated during Cretaceous shortening and controlled the trend and position of younger structures. Thrust faulting is the dominant form of shortening within the competent Mesoproterozoic to Paleozoic successions, whereas detachment folding is the prevailing mechanism within the interlayered competent and incompetent Upper Devonian to Cretaceous successions. Principal detachment horizons include Upper Devonian to Mississippian shale of the Besa River Formation, Triassic shale and siltstone of the Toad/Grayling formations and shale of the Lower Cretaceous Buckingham and Garbutt formations. Shortening at the top of the Triassic in the eastern part of the Rocky Mountain Foothills near the Toad River is estimated to be approximately 5–6 km. Shortening at the top of the Triassic across the eastern part of the Liard Fold and Thrust Belt is even less. Hydrocarbon resources occur within large, structural culminations of the Beaver River and Crow River gas fields. In addition, the Paleozoic and Mesozoic successions contain several organic-rich horizons (Besa River Formation, Toad/Grayling formations and Garbutt Formation) that are stratigraphically equivalent to sequences being developed for shale gas resources elsewhere within the Western Canada Sedimentary Basin.

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**Key Words:** Toad River map area, Liard River, Rocky Mountains, Rocky Mountain Foothills, Mackenzie Mountains, Liard Fold and Thrust Belt, Bedrock geology, GIS-enabled maps, stratigraphy, structure, Tuchodi Formation, Neoproterozoic, Cambrian, Quartzite, Mount Roosevelt Formation, Kechika Group, Nonda Formation, Muncho-McConnell Formation, Wokkash Formation, Stone Formation, Dunedin Formation, Besa River Formation, Mattson Formation, Kindle Formation, Tika formation, Fantasque Formation, Grayling Formation, Toad Formation, Liard Formation, Luddington Formation, Baldonnel Formation, Pardonet Formation, Chinkeh Formation, Garbutt Formation, Scatter Formation, Lepine Formation, Buckingham Formation, Sikanni Formation, Sulley Formation, Dunvegan Formation, Kotaneelee Formation, pre-Cordilleran structure, Detachment folding, Forcier fault, Sulphur Creek fault, Larsen fault

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## INTRODUCTION

The Toad River map area (NTS 094N) forms the western edge of the Liard Basin (Fig. 1), a sub-basin of the Western Canada Sedimentary Basin, with up to 5000 m of Upper Devonian to Cretaceous sedimentary fill, located west of the Bovie fault and adjacent to the portion of the Horn River Basin undergoing development for shale gas (Wright et al., 1994; Walsh et al., 2005). Three organic-rich horizons with shale gas potential (Besa River, Grayling and

Garbutt formations; e.g., Ferri et al., 2011a, b) occur in the Liard Basin and have been deformed and brought near or to the surface in and around this structural depression in the Toad River map area. In addition, significant gas reserves that occur in Middle Devonian carbonate rocks are involved in structures north of the Liard River (Beaver River gas field;  $7.1 \times 10^9 \text{ m}^3$  ( $250 \times 10^9 \text{ ft}^3$ ). In 2011, the Geological Survey of Canada (GSC) and the British Columbia Ministry of Energy and Mines (MEM) undertook fieldwork in the Toad River area as part of the GSC's ongoing Geomapping

for Energy and Minerals (GEM), Yukon Sedimentary Basins project, to update the bedrock geological database, constrain the maturation history and provide a geological synthesis of the area. In 2010, this program focused on the examination of Devonian and Cretaceous shale gas sequences (Ferri et al., 2011a, b) and the mapping of surficial geology deposits that will assist with operational aspects of resource development in the eastern Liard Basin (Huntley and Sidwell, 2010; Huntley et al., 2011).

The Toad River map area contains one of the few regions in the eastern Canadian Cordillera (Foreland Belt) where a pronounced change in the structural trend occurs. Near Liard River, the orientation of regional structures swings from the northwest in the south, to north and northeast in the north (Fig. 1). The area contains the northern end of the Rocky Mountains and the Rocky Mountain Foothills

structural subprovinces and the southern end of the Mackenzie Mountains structural subprovince, the Liard Fold and Thrust Belt and the Liard syncline (Fig. 2). Similar to other parts of the Foreland Belt, the topography in the area reflects the underlying geology. Paleozoic and Triassic carbonate strata hold up mountain ranges in the western part of the area. In the eastern Rocky Mountain Foothills and Liard Fold and Thrust Belt, ridges are underlain by anticlines of folded Mississippian and Triassic sandstone units and valleys have formed above synclines. High tree-topped mesas that formed above gently dipping Cretaceous sandstone or conglomerate characterize the Liard syncline.

The Liard Fold and Thrust Belt is known to hold important gas reserves in Middle Devonian structural plays of the Beaver River and Crow River gas fields (Fig. 2). Several gas shows have been found in Mississippian through

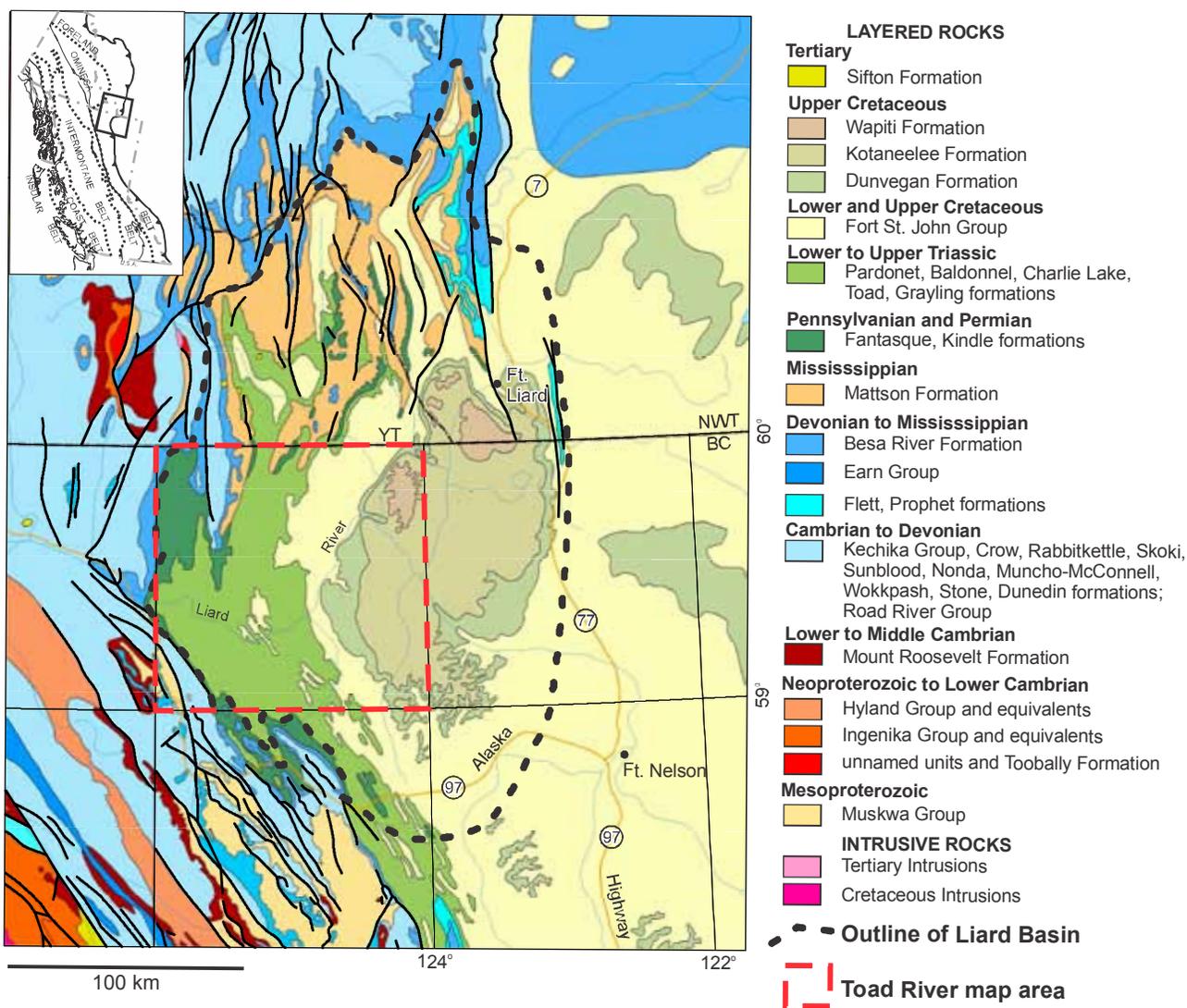


Figure 1. Geology of the Liard Basin and adjacent areas. The red box outlines the Toad River map area. Geology is from Wheeler and McFeely (1991).

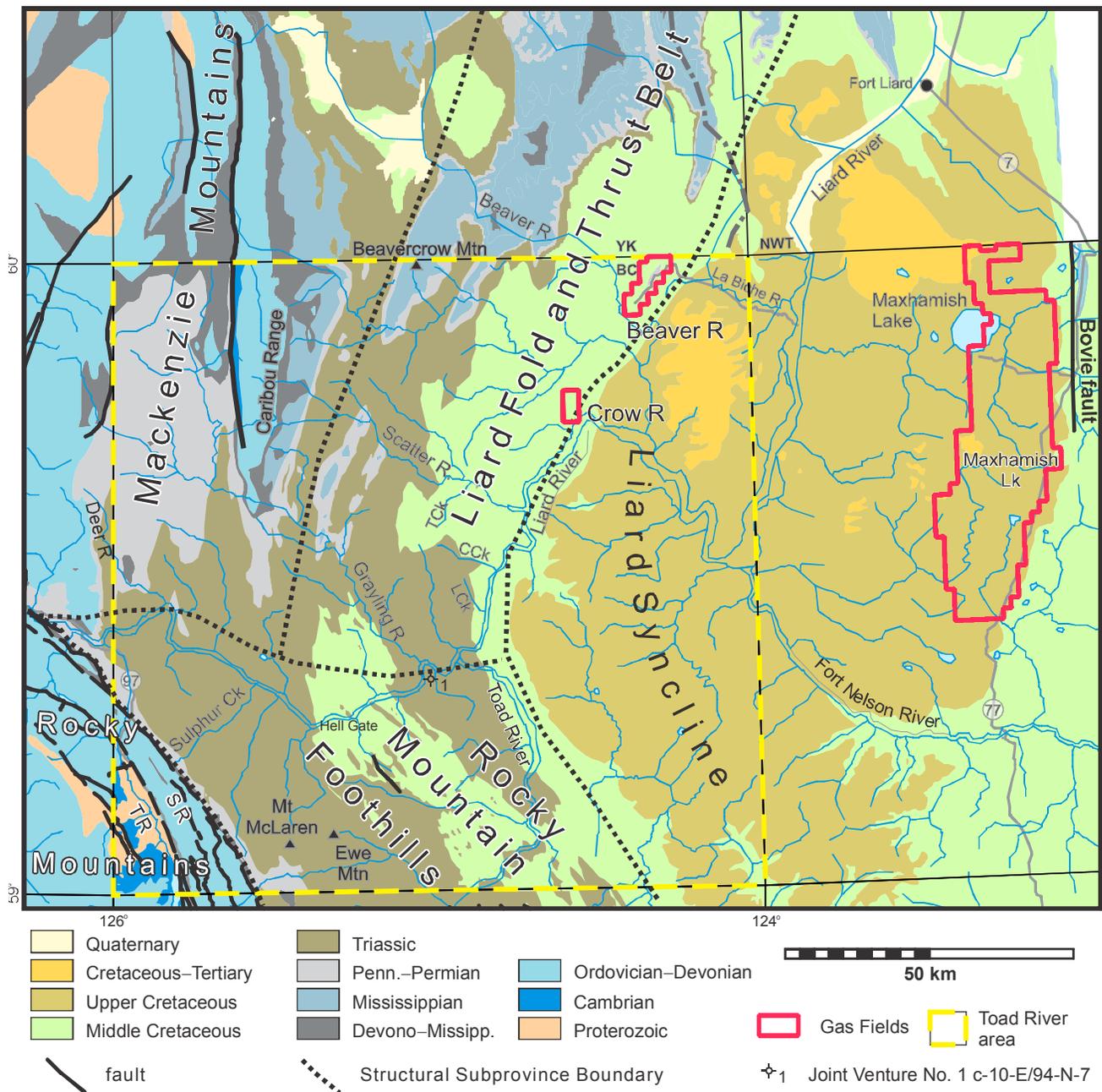


Figure 2. Geological subprovinces in the Toad River area. Abbreviations: CCK, Chimney Creek; LCk, Lepine Creek; SR, Sentinel Range; TCk, Toreva Creek; TR, Terminal Range. Modified from Ferri et al. (2011a). Geology is from MapPlace.ca (BC Geological Survey, 2012) and based on published maps by the Geological Survey of Canada (cf. Taylor and Stott, 1980; Stott and Taylor, 1968; Douglas, 1976; Douglas and Norris, 1976). Structural subprovinces are modified after Gabrielse and Yorath (1991).

Permian intervals (Walsh et al., 2005) and some shale gas production from Devonian and Mississippian sequences in the Beaver River gas field has occurred (Oil and Gas Journal, 2008). Petroleum exploration in the area began with the Joint Venture No. 1 c-10-E/94-N-7 well drilled on the Toad anticline near Liard River in 1953. In 1958, Amoco Canada Petroleum Company Limited made the first discovery at the Beaver River gas field (Snowdon, 1977). Further drilling delineated that pool and discovered the Crow River gas field. Limited drilling has occurred away from those two

fields with only ten exploration wells drilled as of 2011.

Early geological work in the Toad River map area occurred along the Liard and Fort Nelson rivers (McConnell, 1890; Williams, 1923; Kindle, 1944; McLearn, 1945) and then adjacent to the Alaska Highway (Hage, 1944; Laudon and Chronic, 1949). More widespread stratigraphic and mapping studies began with the advent of helicopters in the 1950s. Pelletier (1961), Bamber et al. (1968), Stott (1968, 1982), Taylor and MacKenzie (1970) and Post and Long (2008) have published on Triassic, Cretaceous, Devonian

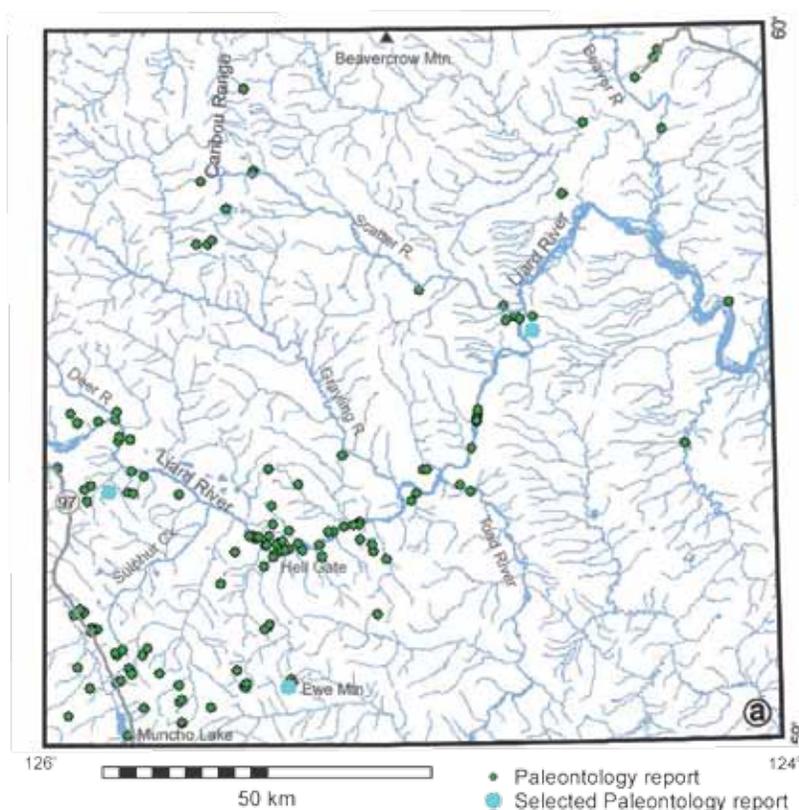
and Cambrian stratigraphy, respectively. The first complete geological map of the Toad River map area was published without an accompanying report in 1980 by Taylor and Stott. The unrevised map was republished in colour in 1999 (Taylor and Stott, 1999). Detailed, unpublished 1:10 000 scale mapping was conducted along most of the Liard River in the 1980s as part of a BC Hydro dam site investigation (Geotex Consultants, 1984).

The current study builds on published and unpublished geological studies, including the detailed mapping along the Liard River prepared for BC Hydro (Geotex Consultants, 1984). New GIS-enabled bedrock geological maps will be produced for the Toad River map area. Each map will include baseline mapping data (location, lithological, structural observations) and baseline data for measured sections (location, observer) together with datasets related to sample acquisition (paleontology reports, Rock Eval™, geochronology and vitrinite reflectance) collected from this

project and from historical sources (Fig. 3a, b). This report provides the first summary report on the stratigraphy and structure of the Toad River map area since McLearn and Kindle's summary report (1950) on the geology of north-eastern British Columbia.

## STRATIGRAPHY

Approximately 8 km of Mesoproterozoic to Upper Cretaceous strata are exposed in the Toad River map area. The oldest strata occur in the southwest part of the Rocky Mountains and the youngest in the northeast part of the Liard syncline (Fig. 2). In general terms, the succession consists of 1) a Mesoproterozoic, clastic-dominated succession deposited in shelf environments after Mesoproterozoic rifting; 2) unconformably overlying clastic-dominated and rift-related uppermost Neoproterozoic–Cambrian strata; 3)



Selected Attributes of LHA09\_ED.PaleoReports94N selection

OBJECTID*	REPORT_NO	YEAR	C_NUM	COLLECTOR	LAT	LONG_	MAP_ID	IDENTIFIER	AUTHOR_ID	Shape
168	AS-13-1982	1982	C-099631	J.F.Psutka	59.575062	-124.658355	094N/10	ARS	ARS	Point
222	Tr1-1982-ETT	1982	C-090882	J.T.Fyles	59.352598	-125.82377	094N/05	ETT	ETT	Point
205	Tr1-1982-ETT	1982	C-090865	P.B.Read	59.078425	-125.334863	094N/03	ETT	ETT	Point

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Figure 3. a) Map showing location of paleontology samples identified in paleontology reports in the Toad River map area; b) ArcMap attribute table summarizing data for the three paleontology samples selected in Figure 3a.

an unconformably overlying carbonate-dominated, shelf-platform succession that persisted through the Middle Devonian; 4) a clastic-dominated upper Paleozoic succession that records local block faulting and extension; 5) easterly derived Triassic clastic and younger carbonate strata that indicate renewed subsidence in the southern part of the area and 6) unconformably overlying Lower and Upper Cretaceous shale-dominated foreland basin strata. Important changes in preservation, thickness and/or facies occur across the area in Cambrian, Devonian, Mississippian, Permian and Triassic units. Some of these changes indicate the presence of older (pre-Cordilleran deformation) faults. Brief descriptions of the 34 stratigraphic units recognized in the study are given below.

## *Mesoproterozoic*

### **TUCHODI FORMATION, MUSKWA GROUP**

Sandstone, siltstone, argillite and dolostone of the Tuchodi Formation (Bell, 1968) are the oldest rocks exposed in the Toad River area. The sandstones are generally grey, very fine to medium-grained, very thin to thick-bedded and vary from grey weathering and siliceous to orange-brown weathering and dolomitic. The sandstones are commonly separated by argillite or siltstone interbeds and partings and are locally mud-cracked and rippled. Resistant sections dominated by siliceous quartzite are up to 50 m thick (Fig. 4a). Intervals of green-grey and grey siltstone with argillite laminae or argillite with siltstone laminae are common. Dolostone is silty or sandy, very thin to medium-bedded, orange-brown weathering and locally has mud-cracked varicoloured argillite interlaminae to very thin interbeds. Several dark, chloritized mafic dikes 10–30 m wide cut Tuchodi strata at a high angle. Both the Tuchodi Formation and the dikes are unconformably overlain by either the unnamed uppermost Neoproterozoic–Cambrian quartzite unit or the Middle Cambrian Mount Roosevelt Formation in the Terminal Range and the Silurian Nonda Formation in the Sentinel Range. More than 500 m of Tuchodi strata are exposed in the Terminal Range.

## *Proterozoic*

### **UNNAMED SILTSTONE-SANDSTONE UNIT**

Locally in the southern Caribou Range, approximately 100 m of dark grey to grey, grey or rusty weathering, very thin to medium-bedded, quartzose siltstone to fine-grained sandstone was recognized beneath the overlying unnamed quartzite unit (Fig. 4b). Finer-grained strata appear slaty and the siltstone-sandstone is locally rippled. The age of this unit is poorly defined. It may correlate with either the

Mesoproterozoic Muskwa Group or the Neoproterozoic Windermere Supergroup.

## *Uppermost Neoproterozoic–Lower Cambrian*

### **UNNAMED QUARTZITE UNIT**

Orthoquartzite forms a resistant unnamed unit in the Terminal and Caribou ranges. This rock is pale grey, white or maroon weathering, fine- to coarse-grained, medium- to thick-bedded, massive to laminated and locally burrowed. A reddish cobble conglomerate to breccia several metres thick with a dark grey quartz sandstone matrix and clasts of quartzite occurs at the base of the unit in the Caribou Range. The quartzite unit is unconformably overlain by Silurian dolostone of the Nonda Formation in the Caribou Range and disconformably overlain by brightly coloured, Middle Cambrian sandstone and dolostone of the Mount Roosevelt Formation (Fig. 4c) in the Terminal Range. Estimated thickness ranges from up to approximately 300 m in the Terminal Range to more than 400 m in the Caribou Range. The unit is not preserved beneath the Silurian Nonda Formation in the Sentinel Range.

## *Middle Cambrian*

### **MOUNT ROOSEVELT FORMATION**

The Mount Roosevelt Formation (Post and Long, 2008) is only preserved in the Terminal Range, where it consists of three members. The heterogenic lower member forms a distinctive bright weathering unit consisting of sandstone, siltstone and carbonate. Clastic units include red weathering, planar bedded, pebbly siltstone and muddy sandstone with discontinuous interbeds of white, laminated to thin-bedded, massive carbonate; red-brown weathering, medium-bedded to massive, planar-bedded pebbly sandstone and pebble conglomerate associated with red, hematitic pebbly medium-grained sandstone; and medium grey, dull red weathering, very fine grained, thin- to thick-bedded, locally crossbedded and rippled, variably dolomitic sandstone. Carbonates include pink weathering, fine crystalline locally pebbly and sandy dolostone; buff weathering, grey, medium- to thick-bedded, laminated to massive limestone; and minor pedogenic limestone. The middle and upper members (Post and Long, 2008) consist of red-brown weathering, poorly sorted, cobble to boulder, polymict conglomerate with local discontinuous interbeds of massive pebbly medium-grained sandstone (Fig. 4d). Conglomerates are noncalcareous in the middle member and mainly calcareous in the upper member. Intervals of buff weathering, light grey, massive to crudely bedded, fine to medium crystalline dolostone occur in the upper member. Maximum

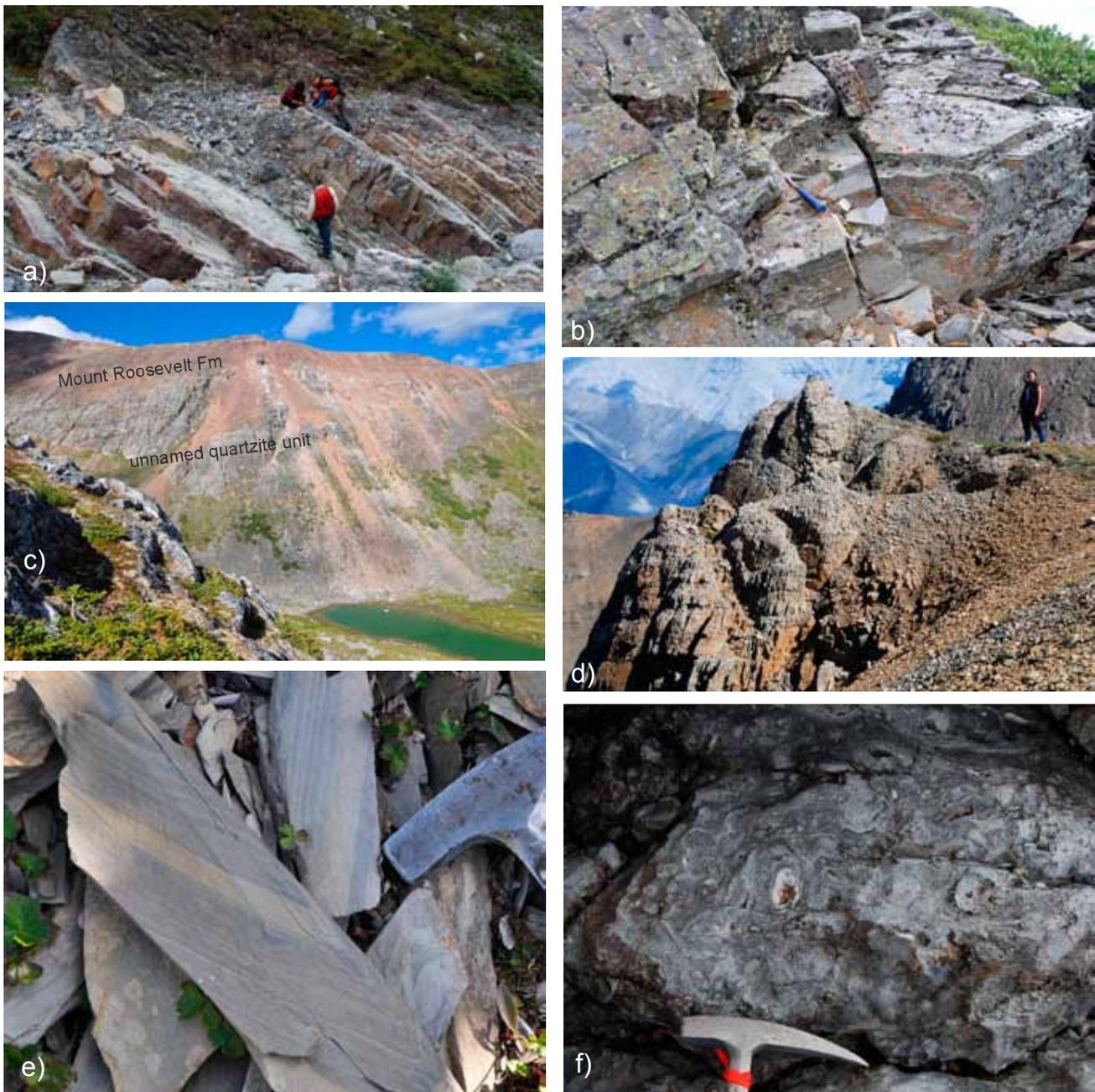


Figure 4. a) Quartzite-dominated interval in the Tuchodi Formation, Sentinel Range; b) unnamed Proterozoic fine-grained sandstone to siltstone locally exposed beneath Neoproterozoic–Lower Cambrian quartzite in the Caribou Range; c) bright weathering siltstone, sandstone and carbonate of the lower member of the Mount Roosevelt Formation disconformably overlying the resistant unnamed Neoproterozoic–Lower Cambrian quartzite unit, Terminal Range; d) crudely bedded, matrix-supported conglomerate of the middle member of the Mount Roosevelt Formation, Terminal Range; e) parallel-laminated, cleaved, silty limestone of the Kechika Group, Terminal Range; f) stromatopoid dolostone in the Nonda Formation, Sentinel Range.

thickness of the lower member is approximately 135 m and estimated thickness of the middle and upper members is 1800 m (Post and Long, 2008).

### *Upper Cambrian–Ordovician*

#### **KECHIKA GROUP**

The Kechika Group (Gabrielse, 1963) is only preserved beneath the sub-Nonda Formation unconformity in the Terminal Range. At the base of the Kechika Group, Bell (unpublished GSC field notes, 1963) reported 8 m of

medium grey, olive brown weathering, cleaved, very calcareous siltstone with some sandstone interbeds overlain by 64 m of medium grey, grey-brown weathering, thick-bedded, slightly calcareous siltstone with brown weathering more calcareous bands. Most of the Kechika Group exposed in the Toad River map area consists of brown-grey weathering, medium grey, thin- to thick-bedded argillaceous and silty limestone that was locally parallel laminated (Fig. 4e). A few hundred metres of Kechika strata are exposed in the southwestern corner of the map area.

## ***Silurian***

### **NONDA FORMATION**

The Nonda Formation (Norford et al., 1966) forms a distinctive, resistant, dark weathering, poorly bedded dolostone unit. Minor white, brown-grey weathering, medium- to thick-bedded, fine- to coarse-grained quartz sandstone that is locally cross-laminated occurs at the base. The main part of the formation consists of dark grey, dark grey weathering, thick-bedded to massive dolostone. Stromatoporoids (Fig. 4f) and corals are common fossils and some beds are biostromal. Vuggy porosity and calcite-filled vugs are common and chert nodules occur locally. Intervals of medium grey, light grey weathering, medium- to thick-bedded, commonly laminated dolostone up to 5 m thick occur mainly in the upper part of the formation. Minor local medium grey, tan weathering, medium- to thick-bedded, silty dolostone is overlain by a few centimetres of dark grey weathering black shale. The Nonda Formation is approximately 290 m thick in the Caribou Range and approximately 300 m in the Sentinel Range (Norford et al., 1966)

## ***Upper Silurian–Lower Devonian***

### **MUNCHO-MCCONNELL FORMATION**

The Nonda Formation is disconformably overlain by much lighter grey weathering, resistant, well-bedded dolostone of the Muncho-McConnell Formation (Fig. 5a; Taylor and Mackenzie, 1970). Light to dark grey, light to medium grey weathering, thin- to thick-bedded dolostone with common laminae characterize the Muncho-McConnell Formation. Light grey dolostone is predominant especially in the lower part of the formation, and in most exposures, there is a thin unit of medium grey, tan weathering, argillaceous dolostone at the base. The formation is 246 m thick in the Caribou Range and 349 m in the Sentinel Range (Taylor and Mackenzie, 1970).

## ***Lower Devonian***

### **WOKKPASH FORMATION**

The Wokkpash Formation (Taylor and Mackenzie, 1970) forms a distinctive tan to yellow- brown weathering unit in the lower Paleozoic succession. In most of the Sentinel Range, the main part of the formation consists of light grey, bright yellow-orange weathering solution collapse breccia with a few interbeds of red and green argillaceous dolostone and grey medium-bedded dolostone (Fig. 5b). Light grey to white, tan to white weathering, very fine to fine-grained, locally burrowed, dolomitic and nondolomitic quartz arenite overlies the breccia. In the Caribou Range and locally in the southern Sentinel Range, dolostone and dolomitic sandstone form the dominant rock types. The Wokkpash is 113 m thick in the Caribou Range and 109 m in the Sentinel Range (Taylor and Mackenzie, 1970).

## ***Lower–Middle Devonian***

### **STONE FORMATION**

The Stone Formation (Taylor and Mackenzie, 1970) forms a thick resistant dolostone unit in the Caribou and Sentinel ranges. The Stone Formation is characterized by light and medium grey, light and medium grey weathering, medium- to very thick-bedded, massive or less commonly laminated dolostone. In the Sentinel Range, the lower part of the formation shows lighter weathering than the upper part (Fig. 5c). Barite cobbles occur locally at the base of the formation in the northern Sentinel Range and indicate the presence of a disconformity (Taylor and Mackenzie, 1970). Zones of brecciated dolostone in a cement of white calcite occur sporadically. The Stone Formation is 473 m thick in the Caribou Range and 586 m in the Sentinel Range (Taylor and Mackenzie, 1970).

## ***Middle Devonian***

### **DUNEDIN FORMATION**

The Dunedin Formation (Taylor and Mackenzie, 1970) caps the Paleozoic carbonate succession. In the Toad River area, the exposed Dunedin Formation consists mainly of medium to dark grey, medium and light grey weathering, thin- to very thick bedded limestone (Fig. 5d). The limestone occurs as cycles of thick wackestone beds grading up to thin packstone and grainstone beds separated by thick sequences of wackestone (Morrow, 1978). Crinoids, brachiopods, corals and ostracods are common fossil fragments. Black chert nodules are common near the top of the

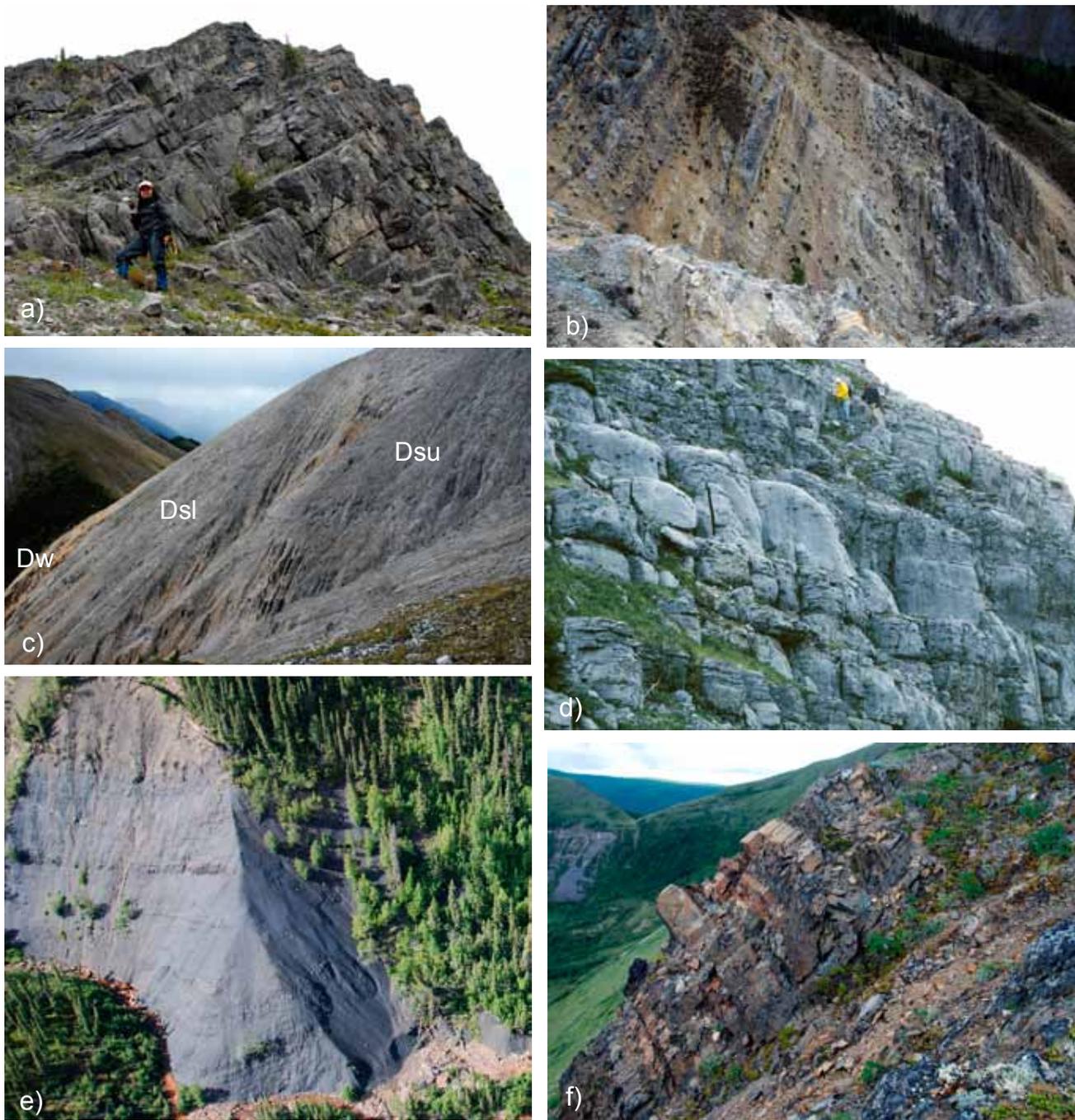


Figure 5. a) Well-bedded dolostone of Muncho-McConnell Formation, Sentinel Range; b) interlayered solution collapse breccia, dolostone and argillaceous dolostone of the bright weathering Wokkash Formation, Sentinel Range; c) well-bedded dolostone of the Stone Formation stratigraphically overlying the bright weathering Wokkash Formation (Dw), Sentinel Range. The lower Stone Formation (Dsl) is lighter weathering than the upper Stone Formation (Dsu); d) chert nodule-rich, bedded limestone near the top of the Dunedin Formation, Caribou Range; photography by K.M. Fallas; e) blue-grey weathering shale of the Besa River Formation, east of the Caribou Range; f) graded and interbedded fine-grained sandstone to siltstone from the lower part of the Mattson Formation, southwest of the Caribou Range (north Deer River).

Dunedin in the Caribou Range. Limestone in the basal part of the formation is dolomitic and argillaceous with common shaly partings. Interbeds of grey, yellow-grey weathering, thin-bedded dolostone with common interclasts and algal laminae occur locally. The upper part of the Dunedin

changes facies into dark shale of the Besa River Formation near 60°N (Taylor and Stott, 1980). The Dunedin Formation is 288 m thick in the Caribou Range south of the facies change into the Besa River Formation and 340 m in the Sentinel Range immediately south of the Toad River map area (Morrow, 1978).

## *Middle Devonian–Mississippian*

### **BESA RIVER FORMATION**

The Besa River Formation (Kidd, 1962) forms a thick, recessive weathering interval dominated by dark shale and siltstone (Fig. 5e). Shale is dark grey to black, rusty to dark grey to blue-grey weathering, commonly carbonaceous and silty, and locally laminated. Pyrite and orange weathering nodules are common near the top. Siltstone is light to dark grey, tan to orange-brown to rusty weathering, thin-bedded with common shaly partings and local laminations. Light grey to black, rusty to grey weathering, laminated or bedded siliceous shale with laminae of nonsiliceous shale form a 50 m thick subunit in the middle part of the Besa River Formation east of the Caribou Mountains (Ferri et al., 2011a). A few interbeds of quartz arenite occur beneath a gradational contact with the Mattson Formation in the northern half of the area. South of Liard River, the Mattson Formation changed facies into the Kindle Formation and the upper contact of the Besa River is marked by a change from pyritic shale to siltstone interbedded with nonpyritic shale (Bamber et al., 1968; Chung, 1993). The Besa River Formation is approximately 330 m thick east of the Caribou Range and more than 500 m thick in the subsurface east of Liard River. For a detailed description of the Besa River Formation in the east Caribou Mountain area, its geochemistry and correlation with important shale gas formations in the Horn River Basin, see Ferri et al. (2011a).

## *Mississippian and Pennsylvanian*

### **MATTSON FORMATION**

The Mattson Formation (Harker, 1961) comprises three informal members in the north-central part of the map area. The following descriptions are based largely on MacNaughton and Pigage (2003) and Fallas and Evenchick (2006), who examined the Mattson Formation immediately north of the Toad River area. In the Caribou Range and to the east, the lower member consists of light grey or buff, grey to orange weathering, thin- to medium-bedded, well-indurated, fine- to very fine grained quartz arenite with crossbeds, crosslaminations, trace fossils and ripples. Sandstone is interbedded with intervals of dark grey siltstone and shale that typically form coarsening-upward sequences. Minor orange weathering, massive dolostone occurs in eastern exposures. West and south of the Caribou Range, the lower part of the formation dominantly consists of medium to dark grey, dark grey or rusty weathering siltstone and blue-grey and brown-grey weathering, thin- to thick-bedded, graded, laminated, fine-grained sandstone to siltstone (Fig. 5f). Interbeds and lenses of sandy limestone are common in the Deer River area. The middle member

consists mainly of white to medium grey to buff, light grey to buff to orange-brown weathering, thin- to very thick bedded, massive to crossbedded to rippled locally calcareous sandstone that is very fine to medium grained (Fig. 6a) with minor interbeds of medium to dark grey, medium grey weathering siltstone and shale. The upper member is characterized by the presence of carbonate or sandy carbonate. It consists of light to medium grey, light grey weathering, thin- to thick-bedded, fine- to coarse-grained, commonly crossbedded, locally calcareous or dolomitic sandstone interbedded with minor grey, medium- to thick-bedded, typically fossiliferous, locally sandy limestone; brown to orange weathering, grey dolostone and dark grey siltstone and shale. The upper member is not recognized in the west and southwest of the Caribou Range. The Mattson Formation is approximately 650 m thick in the Crow River gas field (B.C. Richards, pers comm, 2011) and is not developed south of Liard River.

## *Mississippian, Pennsylvanian*

### **KINDLE FORMATION**

In this report, the name ‘Kindle Formation’ (Laudon and Chronic, 1949; restricted by Chung, 1993) is used for the siltstone-dominated succession above either the sandstone of the Mattson Formation or the dark shale of the Besa River Formation and below the chert and siliceous strata of the Fantasque Formation. South of the Liard River, the lower part of the (restricted) Kindle Formation consists of dark grey, dark grey weathering shale with a few intervals of dark grey, dark grey weathering, argillaceous, calcareous siltstone overlain by dark grey, dark grey weathering, thick-bedded, argillaceous siltstone interbedded with dark grey, silty shale. These are in turn overlain by medium grey, medium grey weathering, very thin to medium-bedded, slightly dolomitic siltstone showing laminations and burrows. South of the Liard River, the upper part of the (restricted) Kindle Formation forms a parallel-bedded unit with distinctive orange weathering stripes. This upper unit consists of medium to dark grey, light brown-grey weathering, medium-bedded, locally laminated, graded or pyritic siltstone with lesser interbeds of dark grey, dark grey weathering, very silty shale and medium grey, orange weathering, calcareous siltstone that is medium to thick bedded. North of the Liard River, a nearly identical striped weathering unit comprises the entire Kindle Formation. The underlying sandstone, siltstone and limestone succession has been included in the Mattson Formation (Fig. 6b). The (restricted) Kindle Formation at its type section is Mississippian and Pennsylvanian and correlative with the Mattson, Stoddart and Taylor Flat intervals (Chung, 1993). The (restricted) Kindle Formation is 80 m thick at its type section near the hamlet of Toad River on the Alaska Highway (Chung,



Figure 6. a) Large-scale crossbedding in the middle member of the Mattson Formation, Beavercrow Mountain; b) Besa River to Fantasque section exposed southwest of the Caribou Range (Deer River); black carbonaceous shale of Besa River Formation (DMbr) at base is overlain by the sandstone-dominated Mattson Formation (Mm), which is overlain by parallel-bedded, striped weathering strata assigned to the Kindle Formation (Pk); the section is capped by siliceous mudstone and siltstone assigned to the Fantasque Formation (Pf); c) well-bedded chert of the Fantasque Formation, east side of the Caribou Range; d) light grey weathering, dark grey shale of the Grayling Formation with several more resistant sandstone interbeds, on the south fork of the Scatter River; e) dark siltstone with common sandstone interbeds of the upper Toad Formation (TrT) conformably overlain by the sandstone-dominated Liard Formation (TrL), Rocky Mountain Foothills; f) large-scale crossbedding in calcareous sandstones of the Liard Formation, eastern Rocky Mountain Foothills.

1993), 79 m on the ridge immediately south of the study area and approximately 30 m thick in the Deer River area (Bamber, unpublished GSC field notes, 1965).

## ***Permian***

Two disconformity-bounded Permian units, the Tika formation (informal) and Fantasque Formation, occur in the northern part of the area. Elsewhere, only the Fantasque is thought to be present.

### **TIKA FORMATION**

The Tika formation (informal; Currie et al., 2000) is a mixed carbonate and clastic unit. In the northeastern part of the study area, it consists of medium to dark brown, buff weathering, medium-bedded, massive to cross-laminated, silty or sandy limestone and dolostone with rare brachiopod and trace fossils, rhythmically interbedded with lesser dark brown or grey calcareous siltstone and sandstone. Grey weathering, crossbedded, glauconitic sandstone occurs at the base (Fallas and Evenchick, 2006; B.C. Richards, pers comm, 2011). At the Liard River, the Tika formation consists of a lower unit of dark grey, dark grey weathering, calcareous siltstone with worm tracks and pyrite, interbedded with lesser dark grey, medium to dark grey weathering, calcareous, argillaceous siltstone and lenses to beds of medium grey, grey weathering, silty or sandy limestone (Bamber, unpublished GSC field notes, 1965). This is overlain by dark grey, medium grey to rusty weathering, medium-bedded pyritic siltstone commonly grading to dark silty shale with a few interbeds of medium grey, orange weathering, thin- to thick-bedded calcareous siltstone and rare lenses of silty limestone. Interbedded dark pyritic siltstone and dark grey siliceous siltstone occur at the top (Bamber, unpublished field notes, 1965). P.B. Read (unpublished field notes, 1982) reported medium grey weathering, fine-grained sandstone in this same area. Tika strata along the Liard River were previously included in the Kindle Formation by Bamber et al. (1968). The strata are well dated as Lower Permian age by conodonts (Orchard, unpublished paleontology report prepared for Geotex Consultants). The Tika formation is more than 60 m thick on the Liard River (Bamber, unpublished GSC field notes, 1965) and approximately 150 m in the Crow River gas field (B.C. Richards, pers comm, 2011).

### **FANTASQUE FORMATION**

The Fantasque Formation (Harker, 1961) forms a very resistant weathering unit in the northernmost and southernmost parts of the map area. In the north (Fig. 6c), it consists of dark to medium grey, rusty brown weathering, medium- to very thick bedded, spiculitic chert interbedded with minor dark grey to dark brown siliceous siltstone. On the

Liard River, the Fantasque consists of 20 m of dark grey to black, dark grey weathering, very thin to medium-bedded chert, overlain by 22 m of dark grey, dark grey weathering siltstone with two brown weathering, medium grey, medium-bedded, fine-grained sandstone beds (Bamber, unpublished field notes, 1965). Immediately south of the map area, the Fantasque consists of 41 m of dark to medium grey, grey to brown weathering, thin- to medium-bedded chert or siliceous mudstone with silty shale partings, overlain by 20 m of dark grey, light to medium grey weathering, medium- to very thick bedded siltstone, argillaceous siltstone and siliceous siltstone (Bamber, unpublished field notes, 1965). The Fantasque is more than 40 m at its type section immediately north of the study area (Bamber et al., 1968), 41 m on the Liard River and 61 m immediately south of the study area (Bamber, unpublished field notes, 1965). Abrupt changes in thickness are mapped across small faults at 60°N (Fallas et al., 2004; Fallas and Evenchick, 2006).

## ***Triassic***

In the Toad River map area, the Triassic thins markedly from west to east and northward from the Liard River to 60°N. Thinning is due to increased erosion beneath the sub-Cretaceous unconformity and, to a lesser extent, depositional thinning. Six formations are recognized. The older formations are clastic units that change up-section from shale dominated (Grayling Formation), to interlayered siltstone, shale and sandstone dominated (Toad Formation), to sandstone dominated (Liard Formation). The younger formations are mixed clastic and carbonate (Luddington, Pardonet) and carbonate (Baldonnel) units, and are only preserved in the western Rocky Mountain Foothills. To a large extent, the Grayling and Toad formations are facies equivalents and are mapped together as the Toad/Grayling formations in much of the area. The Liard Formation changes facies westward into the Luddington and Toad formations (Taylor and Stott, 1973).

### **GRAYLING FORMATION**

The Grayling Formation (Kindle, 1944) consists of medium grey, light grey weathering, flaky, laminated, noncalcareous shale with minor interbedded brown-grey weathering, medium grey, very thin to thin-bedded, fine-grained sandstone and medium grey, laminated dolomitic shale (Fig. 6d). A brown-grey weathering, medium grey, irregularly bedded sandstone approximately 10 m thick marks the base of the formation along the Liard River (Bamber, unpublished GSC field notes, 1965). Ripple laminations, ripple marks and sole marks are common in the sandstone. Pelletier (1961) reported that more than 400 m of the Grayling Formation occurred along the Liard River upstream of its confluence with the Grayling River.

## TOAD FORMATION

The Toad Formation (Kindle, 1944, 1946) forms a dark weathering siltstone-dominated unit. Dark grey, dark grey to brown weathering, thin- to thick-bedded, commonly laminated calcareous siltstone and grey to brown weathering, dark grey, platy, calcareous siltstone and shale, and minor dark grey or brown weathering, dark grey to black shale comprise most of the Toad Formation. Intervals and interbeds of dark grey, brown-grey weathering, thin- to thick-bedded, very fine to fine-grained calcareous sandstone are more common in the middle and upper part (Fig. 6e). Sandstones are commonly laminated and sharp based. Crossbeds and sole marks occur locally. The Toad Formation is approximately 365 m thick at its type section near the junction of the Toad and Liard rivers and is more than 886 m thick on Ewe Mountain (Pelletier, 1961).

## LIARD FORMATION

The Liard Formation (Kindle, 1946) comprises sandstone and subordinate limestone. Limestone is common in the type exposures on the island by Hell Gate on the Liard River but uncommon in more eastern exposures. Sandstone is medium to dark grey, light grey to orange-brown weathering, medium to very thick bedded, very fine to fine grained and calcareous (Fig. 6f). Medium-grained calcareous sandstone occurs locally. Crossbeds, ripples, laminations, scour features, burrows and concretionary or coquinoïd layers are locally common. Limestone is buff to light to dark grey, light grey weathering, medium to very thick bedded and varies from massive and hard to sandy or conglomeratic. Kindle (1948) reported limestone intervals of up to 15 m (50 ft.) thick in the type area. Minor interbedded dark grey weathering, dark grey siltstone and shale occurs locally. The Liard Formation is 82 m thick on the Liard River, 14.5 km upstream from the mouth of the Toad River, 183 m thick 6.4 km upstream from the island by Hell Gate on the Liard River and 122 m thick on Ewe Mountain (Pelletier, 1961).

## LUDDINGTON FORMATION

The Luddington Formation (Gibson, 1971) consists of calcareous sandstone, calcareous siltstone, siltstone and limestone. Limestone forms a minor component in the Ewe Mountain area (Pelletier, 1961) but is more common further west. Sandstone is calcareous and ranges from medium to dark grey, dark brown to orange-brown weathering, very thick bedded and very fine grained, to light grey weathering, light grey, thick bedded, crossbedded and medium to coarse grained. Calcareous siltstone is dark grey to buff weathering, medium grey to black, laminated, and commonly interlaminated to thinly interbedded with calcareous, laminated, very fine grained sandstone (Fig. 7a). Noncalcareous siltstone is dark grey, medium grey weathering, thick bedded, laminated and blockier weathering than calcareous siltstone. Limestone is mainly grey-brown weathering,

medium grey, very thin to thin-bedded, platy and variably silty. Parallel lamination is common; ripple cross lamination, cut and fill structures occur locally. Minor medium grey weathering, black, thin- to medium-bedded, locally bioclastic, silty limestone also occurs. The Luddington is more than 290 m thick at Ewe Mountain and more than 450 m thick in the Mount McLearn area (Pelletier, 1961; adjusted to exclude limestone of the Baldonnel and Pardonet formations at top).

## BALDONNEL FORMATION

The Baldonnel Formation (Hunt and Ratcliffe, 1959) is a resistant, light weathering limestone recognized in the western Rocky Mountain Foothills. The formation consists of light to medium grey, light grey weathering, medium- to very thick bedded, crinoidal lime grainstone to packstone (Fig. 7b). Crossbeds and irregular light grey cherty nodules are common. The Baldonnel Formation is estimated to be approximately 150 m thick north of Sulphur Creek and at Mount McLaren in the western Rocky Mountain Foothills.

## PARDONET FORMATION

The dark limestone and siltstone of the Pardonet Formation (McLearn, 1960) is preserved locally at the tops of ridges in the western Rocky Mountain Foothills. Limestone is dark grey, medium to dark grey to dark brown-grey weathering, thin- to thick-bedded with common wavy crenulated laminations (Fig. 7c) and fossils. Limestone varies from lime wackestone to grainstone and is commonly carbonaceous, argillaceous and silty (Gibson, 1971). Dense coquina beds consisting of whole and fragmented pelecypod and brachiopod beds are relatively common. Siltstone is dark grey, dark grey to dark brown-grey weathering, thin- to thick-bedded and commonly laminated. To the south, siltstone occurs mainly in the upper part of the formation (Gibson, 1971). Less than 100 m of the Pardonet Formation is preserved in the western Rocky Mountain Foothills.

## *Cretaceous*

The base of the Cretaceous is marked by a regional erosional unconformity that, in the Toad River area, downcuts underlying Triassic strata in the northward and eastward directions. An abrupt change in the thickness of Triassic strata preserved beneath this unconformity occurs in the Rocky Mountain Foothills and suggests local pre-Cretaceous (pre-Albian) downfaulting (Fig. 8). The overlying thick shale-dominated section is divided into several recessive weathering, marine shale formations (Garbutt, Lepine, Sully, Kotaneelee) separated by more resistant sandy or conglomeratic formations (Scatter, Sikanni, Dunvegan, Wapiti; Stott, 1968). Sandstone and conglomerate of the Chinkeh Formation locally occur at the base. In the southern part



Figure 7. a) Very thinly interbedded, parallel-laminated, variably calcareous siltstone and very fine grained sandstone of the Ludington Formation, western Rocky Mountain Foothills; b) resistant, light grey weathering limestone of the Baldonnel Formation with irregular cherty nodules and layers, western Rocky Mountain Foothills; c) crinkly laminated Pardonet Formation, western Rocky Mountain Foothills.

of the area, the Scatter Formation is not developed and the Buckingham Formation forms a thick shale succession at the base of the Cretaceous. Only the Garbutt, Buckingham and Scatter formations were examined in this study and the following descriptions are based mainly on Stott (1968, 1982).

### CHINKEH FORMATION

The Chinkeh Formation (Leckie et al., 1991) locally forms a thin sandstone and conglomerate unit north of the confluence of the Toad and Liard rivers. Leckie et al. (1991) reported a coarsening-upward sequence of very fine to medium-grained glauconitic sandstone with hummocky crossbedding capped by a thin unit of log-bearing conglomerate on Lepine Creek. Stott (1968) reported up to 1.5 m (4–5 ft.) of fine-grained, glauconitic, argillaceous sandstone with a few chert pebbles and wood fragments that occur locally beneath the Garbutt Formation in the Scatter River area. The Chinkeh Formation is 9 m thick on Lepine Creek (Leckie et al., 1991).

### GARBUTT FORMATION

Shale of the Garbutt Formation (Kindle, 1944) forms the basal unit of the Cretaceous where the Chinkeh Formation is not developed and the Scatter Formation is developed. In these areas, glauconitic mudstone or a few chert nodules occur at the base of the formation (Stott, 1968; Ferri et al., 2011b). In the Scatter River area, the Garbutt consists of two main parts (Stott, 1968). The lower part consists of striped dark grey weathering, silty shale with numerous thin, commonly parallel laminated or cross-laminated, silty or sandy lenses and beds, capped by a unit of thin-bedded, fine-grained, silty sandstone. The upper part (Fig. 9a) consists of dark grey, commonly rusty weathering, rubbly mudstone and shale with rows of reddish-brown weathering concretions and common interbeds of grey, planar or cross-laminated, very fine grained sandstone to siltstone near the top. Slump structures occur locally. The Garbutt Formation is 290 m thick in the Chimney Creek–Scatter River area (Stott, 1968, 1982).

### SCATTER FORMATION

The Scatter Formation (Kindle, 1944) is best developed in the Scatter River area where three members (Bulwell, Wildhorn and Tussock; Stott, 1982) are present. The Bulwell member (Fig. 9a, b) consists of grey and greenish-grey, thin- to thick-bedded, fine- to very fine grained, commonly glauconitic sandstone and interbedded argillaceous silty sandstone and silty mudstone. The sandstone is commonly laminated and contains abundant ripple marks, worm burrows, trails and castings and crossbedding (Stott, 1982). South of 50°25'N, the sandstone becomes more shaly and eventually grades into shale. The Wildhorn member (Fig. 8b) consists of dark grey to black, dark grey to rusty

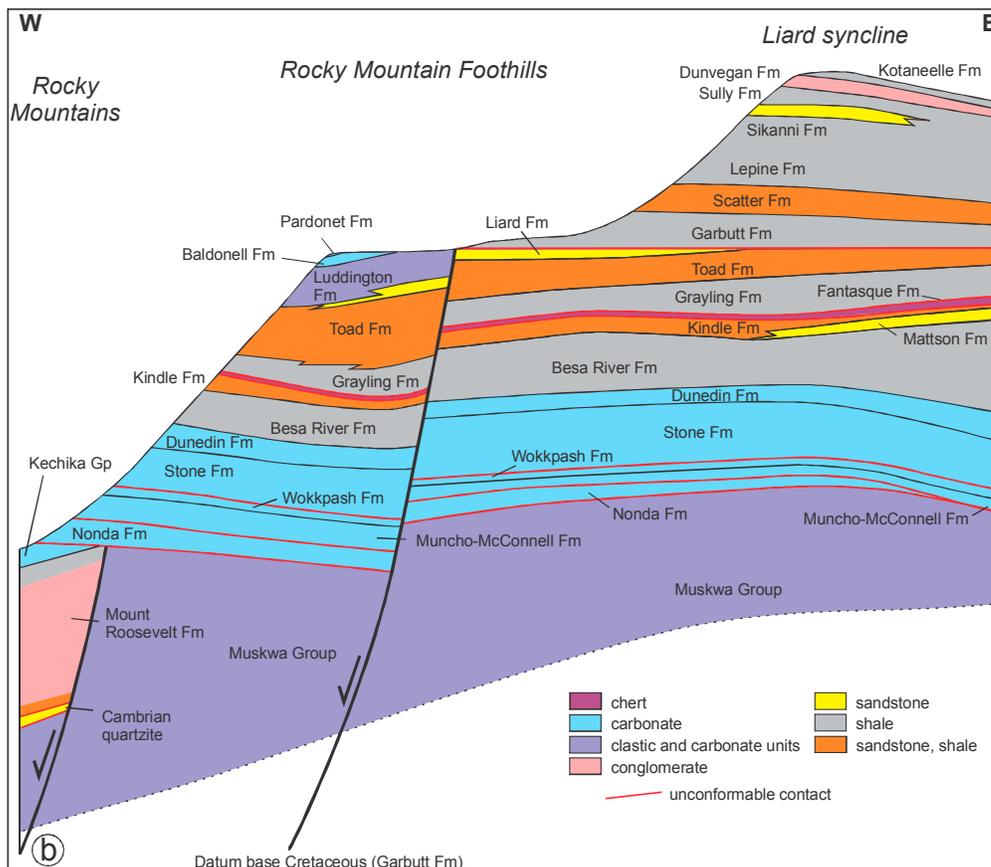
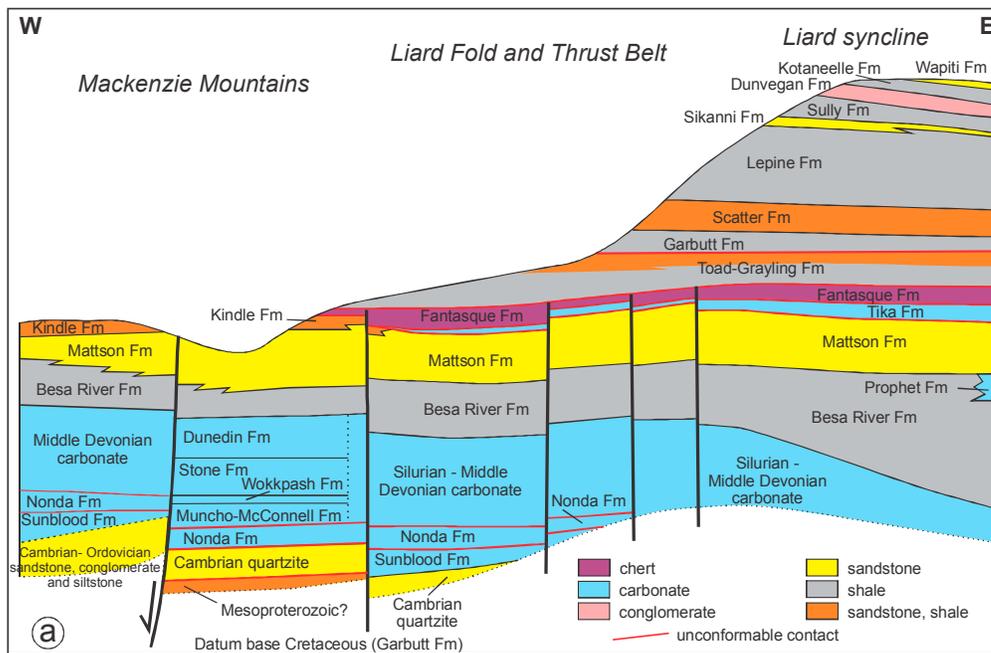


Figure 8. a) Schematic stratigraphic cross-section across the northern Toad River map area; b) schematic stratigraphic cross-section across the southern Toad River map area. Pre-Triassic (Toad/Grayling) small displacement faults similar to those in the northern cross-section may occur in the subsurface east of the unnamed pre-Garbutt Formation fault. None are shown due to the absence of seismic control.

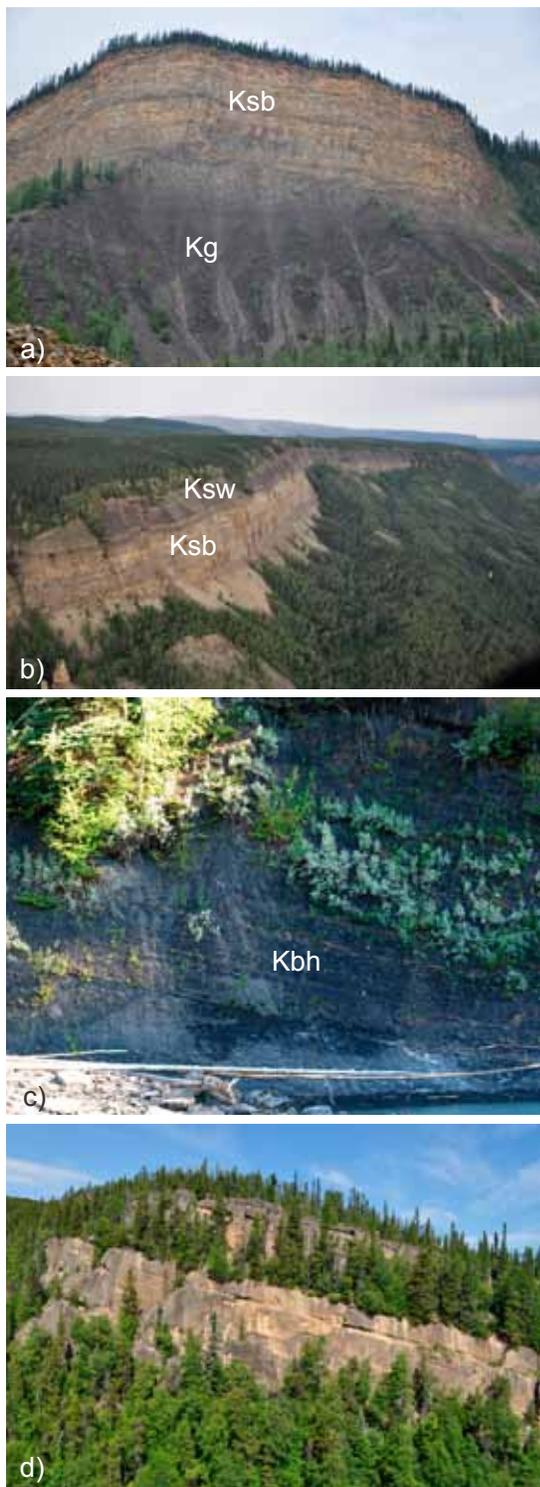


Figure 9. a) Dark weathering shale of the Garbutt Formation (Kg) gradationally overlain by Bulwell member sandstone of the Scatter Formation (Ksb) along the type section of the Garbutt Formation, lower Toreva Creek; b) Bulwell member sandstone of the Scatter Formation (Ksb) is overlain by dark silty shale of the Wildhorn member of the Scatter Formation (Ksw), Liard Fold and Thrust Belt, north of Scatter River; c) dark weathering silty shale with sideritic concretionary bands exposed along Toad River near the base of the Buckingham Formation (Kbh); d) resistant conglomerate of the Dunvegan Formation along Dunedin River.

weathering silty mudstone with reddish-brown weathering sideritic concretions becoming more common in the upper part. Thin beds of argillaceous siltstone and sandstone occur near the top. The Tussock member comprises alternating units of sandstone, siltstone and silty mudstone. Sandstone is generally greenish-grey, argillaceous, silty and glauconitic, thin- to thick-bedded with common burrow mottling, worm trails and laminae. Beds of cleaner, grey, crossbedded sandstone occur locally near  $50^{\circ}30'N$  (Chimney Creek area; Stott, 1982). Siltstone is dark grey, grey or rusty weathering, argillaceous and finely laminated. Silty mudstone is black and weathers blocky and rusty (Stott, 1982). South of  $50^{\circ}30'$ , sandstone of the Tussock Member grades laterally into argillaceous siltstone and mudstone strata that are included in the Lepine Formation. The Scatter Formation, at its type section on the Scatter River, is 347 m thick and an estimated 378 m thick on Chimney Creek (Stott, 1982).

### LEPINE FORMATION

The Lepine Formation (Kindle, 1944) comprises the thick shale succession between sandstones of the Scatter and Sikanni formations. Between approximately  $50^{\circ}20'$  and  $50^{\circ}29'N$ , the Lepine Formation includes the equivalents of the middle and upper members of the Scatter Formation. In this area, the basal part of the Lepine Formation comprises black, silty, concretionary mudstone with a few units of argillaceous siltstone. Ammonites are common in concretions. Elsewhere, the Lepine Formation comprises a basal unit of black, flaky to fissile shale overlain by dark grey, commonly rusty weathering, silty mudstone with reddish-brown weathering concretions. Minor interbedded platy siltstone occurs in the middle and in the uppermost part of the formation (Stott, 1968, 1982). The Lepine Formation is approximately 910 m (3000 ft.) thick on the Liard River opposite Chimney Creek and approximately 1100 m thick where only the Bulwell Member is left in the Scatter Formation (Stott, 1968, 1982). The Lepine Formation is 893 m thick in the subsurface east of the Liard River (Stott, 1968, 1982).

### BUCKINGHORSE FORMATION

The Buckingham Formation (Hage, 1944) forms the basal unit of the Cretaceous where the Scatter Formation is not recognized. It includes the correlatives of the Chinkeh, Garbutt, Scatter and Lepine formations. The lower part of the Buckingham Formation consists of dark grey to black, locally rusty weathering, silty shale with orangish weathering sideritic concretions (Fig. 9c) and a few thin bentonite seams. The middle part of the succession consists of very thin to thin-bedded siltstone with dark grey silty shale interbeds. The upper part of the succession is assumed to be dark grey concretionary mudstone (Taylor and Stott, 1973;

Stott, 1982). The thickness of the Buckinghorse Formation should be approximately 1200 m along Toad River.

#### **SIKANNI FORMATION**

The Sikanni Formation (Hage, 1944) consists of sandstone units separated by mudstone units. In the southern half of the area, it consists of three or four resistant sandstone units up to 30 m thick, comprising mainly grey, light brown-grey weathering, finely laminated, locally cross laminated, siliceous fine-grained sandstone. Coarse-grained sandstone and conglomeratic sandstone occur locally (Stott, 1982). Sandstone units are separated by intervals of dark grey to black mudstone with a few concretions. In the northern part of the area, the Sikanni Formation loses its resistant character and the upper sandstone grades into mudstone included in the Sully Formation, and the lower sandstone grades into argillaceous sandstone and mudstone (Stott, 1982). The Sikanni Formation is 132 m thick opposite Scatter River and more than 140 m thick northeast of Lepine Creek (Stott, 1968, 1982). On the La Biche River, immediately north of the Toad River map area, sandstone appears to have disappeared completely and the Sikanni Formation is not present (Fallas, 2006).

#### **SULLY FORMATION**

In the northern part of the Toad River map area, the Sully Formation (Stott, 1960) consists of lower and upper members comprising dark grey to black, rusty weathering, silty mudstone with reddish-brown weathering sideritic concretions separated by a middle member comprising medium grey to black, light grey weathering, flaky to fissile shale containing some interbeds of light grey weathering platy siltstone. Thin beds of grey, fine-grained, laminated and cross-laminated sandstone occur in the upper member. The upper member becomes extremely silty as it grades into the sandstone at the base of the overlying Dunedin Formation (Stott, 1982). The lower member is replaced by sandstone of the Sikanni Formation in the southern part of the area. The Sully Formation is 305 m thick opposite Scatter River (Stott, 1982).

#### **DUNVEGAN FORMATION**

The cliff-forming Dunvegan Formation (Fig. 9d; Dawson, 1881) comprises a basal sandstone overlain by conglomerate-dominated cycles of carbonaceous mudstone, massive conglomerate and coarse-grained sandstone. The basal sandstone is brown weathering, fine to coarse grained and laminated or crossbedded. It is commonly capped by a thin unit of coal or carbonaceous mudstone. Pebble to cobble conglomerate forms thick resistant units that commonly show crude horizontal stratification or large-scale crossbeds. Clasts are quartz, quartzite and chert, and are set in a coarse-grained cherty sandstone matrix. Sandstones vary from fine grained to conglomeratic, are commonly

laminated and may grade upward into siltstone and silty mudstone (Stott, 1968, 1982). The Dunvegan Formation is 183 m thick opposite Scatter River and 160 m thick at the big bend of the Liard River (Stott, 1982).

#### **KOTANEELEE FORMATION**

The Kotaneelee Formation (Hage, 1945) consists mainly of dark grey to black, rusty weathering shale with sideritic concretions. An interval of thin-bedded, fine-grained sandstone occurs in the upper part of the formation in the Beaver River area (Stott, 1968). Immediately east of the map area at La Jolie Butte on Liard River, the sandstone is 14 m thick and occurs 38 m below the top of the formation (Stott, 1968). The Kotaneelee Formation is estimated to be approximately 180 m thick in the northeastern corner of the map area.

#### **WAPITI FORMATION**

A thin veneer of the Wapiti Formation (Dawson, 1881) caps some of the ridges in the map area. No outcrops have been examined by Stott (1968, 1982) or in this study. Taylor and Stott (1980) described the formation as sandstone, mudstone and coal in the legend accompanying their map.

### **STRUCTURE**

The Toad River area encompasses a dramatic swing in the orientation of structures in the Foreland Belt, from northwest south of the Liard River, to north and northeast north of the Liard River (Fig. 2). Cecile et al. (1997) attributed this change to the Liard Line (Cecile and Norford, 1991), a northeast-trending fault zone interpreted to have formed during Neoproterozoic rifting as a transfer fault. The structural style of the Toad River area was largely controlled by the lithological character of the deformed stratigraphic sequences and to a lesser extent by the amount of shortening. Thick competent Proterozoic and latest Neoproterozoic to Middle Devonian carbonate and sandstone successions favoured the development of thrust faults. Interlayered incompetent and competent Upper Devonian to Cretaceous shale and sandstone successions favoured the formation of detachment folds. Interlayered successions are exposed over most of the map area and folds dominate the structural style. Most structures in the Toad River area formed during Cretaceous Cordilleran compressive deformation. In some places, older structures are observed or inferred from abrupt changes in the stratigraphic record. These older structures appear to have controlled the trend and location of subsequent Cordilleran-aged structures, particularly in the northern part of the area.

## ***Older pre-Cordilleran deformation structures***

Muskwa Group strata were folded, faulted and weakly metamorphosed prior to the deposition of the unconformably overlying latest Neoproterozoic to early Paleozoic strata. Immediately south of the Toad River area, Mesoproterozoic Muskwa Group strata were folded and cut by reverse and normal faults prior to the intrusion of Neoproterozoic mafic dikes (Taylor and Stott, 1973). Immediately north of the Toad River area, Mesoproterozoic or Neoproterozoic strata were folded and faulted prior to deposition of lower Paleozoic sandstone, conglomerate and siltstone (Fallas et al., 2004).

Changes in thickness and/or facies outline several older structures formed prior to Cretaceous compressive deformation. South of the Liard River, two northwest-trending structures have been recognized on the basis of surface geology (Fig. 10). The Forcier fault zone (Taylor and Stott, 1973), in the west, is the most obvious older structure in the map area. It separates up to 1.8 km of predominantly conglomeratic Middle Cambrian Mount Roosevelt strata on the west from an uplifted block on the east where Silurian rocks rest unconformably on Middle Proterozoic rocks, and is one of the faults defining the eastern edge of the lower Paleozoic Kechika graben (Post and Long, 2008). South of the map area, the Forcier fault becomes north-trending and has west-side-down normal stratigraphic separation (Taylor and Stott, 1973). The eastern fault exposed south of the Liard River is indicated by an abrupt change in the thickness of Triassic strata preserved beneath the sub-Cretaceous unconformity (see Fig. 8b). To the south, at the latitude of the Alaska Highway, a large change in facies and preservation of Mississippian and Pennsylvanian strata beneath the sub-Permian (Fantasque) unconformity (Bamber et al., 1968; Chung, 1993) indicates episodic motion on this structure. The thickness of the Mount Roosevelt Formation decreases markedly across a transverse east-northeast-trending fault exposed in the Terminal Range. This suggests the transverse fault may be following a Middle Cambrian antecedent structure.

North of the Liard River, several pre-Cordilleran compressive deformation structures have been recognized on the basis of surface geology and well control (Fig. 10). These structures trend north to northeast. Older motion on the north-trending Larsen fault is inferred from relationships exposed along strike to the north, where conglomeratic Cambrian and Ordovician strata occur west of the fault and latest Neoproterozoic to Cambrian orthoquartzite and no Ordovician strata occur east of the fault in the Caribou Range (Fallas et al., 2004). Motion on the curvilinear northeast- to north-trending Bovie structure greatly affected the thickness of Mississippian, Pennsylvanian, Permian, Triassic and Lower Cretaceous strata on either side of it (e.g., Leckie et al., 1991; Wright et al., 1994; MacLean and

Morrow, 2004). Main periods of precompressive deformation motion along the structure occurred in the Pennsylvanian to Permian and in the Early Cretaceous (MacLean and Morrow, 2004). The northeast-trending segment of the structure had minor early Paleozoic motion (Fig. 17 in MacLean and Morrow, 2004). The other older faults shown in Figure 10 are indicated by changes in the thickness of Permian units across each fault. The absence of Ordovician strata in the Caribou Range suggests that the westernmost of these may have undergone pre-Silurian movement (Fig. 8a). Smaller faults with Mississippian- to Permian-aged displacement (and limited or no reactivation) occur in the subsurface near the big bend in the Liard River (Hodder, 2002). Access to proprietary seismic data will be needed to map these and similar structures in the subsurface of the Toad River area.

## ***Structural style of the Foreland Belt***

Thrust faults and faulted folds dominate the surface structural geometry of the competent Mesoproterozoic to Middle Devonian succession. These strata are only exposed in the Caribou Range and Rocky Mountains (Fig. 2). In the Caribou Range, the west-directed Larsen fault dies out southward into the core of a west-facing anticline and most of the range is a gently east-dipping (20–30°) homoclinal panel. Two longer strike-length thrust faults occur in the Rocky Mountains: the Forcier and Sulphur Creek faults (see Fig. 2, 10 for locations). These underlie the Terminal and Sentinel ranges, respectively. Other less continuous northeast-directed thrust faults (discussed below) are common. In the Terminal Range, a north-trending cleavage has developed in Middle Cambrian and Ordovician argillaceous sediments associated with open folding. Structural relationships in the Forcier fault change markedly across a transverse east-northeast-trending fault exposed near the western boundary of the map area. North of this transverse fault, a prominent fold pair has developed in the immediate hangingwall of the Forcier fault that is absent south of the transverse fault. The fault acted as a primary tear fault during compressive deformation. This tear fault, the Larsen fault and the Forcier fault all appear to have followed older structures.

Thrust faults are readily observed in the well-defined Paleozoic carbonate section exposed in the Sentinel Range and west-directed back thrusts occur locally. Map-scale hangingwall anticlines have developed along the Sulphur Creek fault (Fig. 11a) and in the southern part of the map-area, two structurally higher faults. The structurally higher of these truncates an anticline and back thrust in its footwall and clearly formed later (Fig. 11b). The Sulphur Creek fault forms the boundary between the Rocky Mountains and Rocky Mountain Foothills structural subprovinces. At the north end of the Sentinel Range, the Sulphur Creek fault

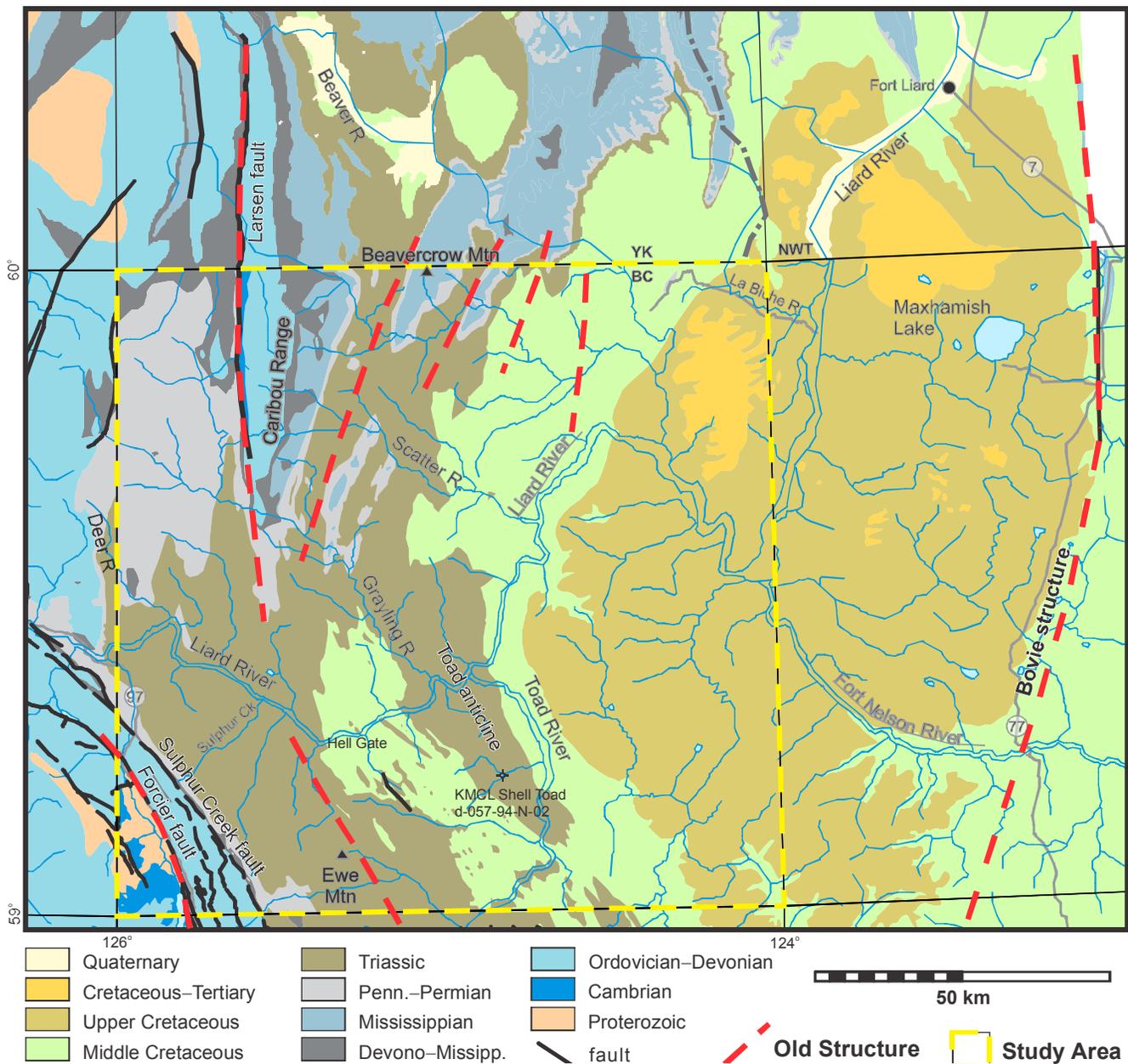


Figure 10. Map showing location of older pre-Cordilleran deformation structures. Several of these appear to have been reactivated during Cordilleran compressive deformation.

cuts across the anticline in its hangingwall and a syncline occurs in the hangingwall. At the southern edge of the map area, conical, close to tight-folded, faulted, chevron folds have formed in the Dunedin Formation along the leading edge of the Sulphur Creek fault (Fig. 11c).

Upper Devonian to Lower Cretaceous strata exposed in the Rocky Mountain Foothills, the Mackenzie Mountains and the Liard Fold and Thrust Belt have been deformed primarily by folding (Fig. 2). Fold wavelength is largely controlled by the thickness of the dominant (more competent) member (Currie et al., 1962). Mappable faults are uncommon. Even good exposure and detailed 1:10 000 scale mapping along the Liard River revealed only a few

laterally discontinuous thrust faults with small stratigraphic separation (Geotex Consultants, 1984). Small-scale faults and detachment folds are locally common in the Besa River and Toad/Grayling (Fig. 12a) formations and in the cores of folds.

In the Rocky Mountain Foothills, changes in fold wavelength, amplitude and geometry from one stratigraphic level to another indicate three main detachment horizons: Besa River, Toad/Grayling and Garbutt/Buckingham were used (Fig. 8b). The Besa River Formation separates fault and fold structures in the Paleozoic carbonate succession from much smaller amplitude and wavelength folds in the Kindle and Fantasque formations (Fig. 12b). Most folds in

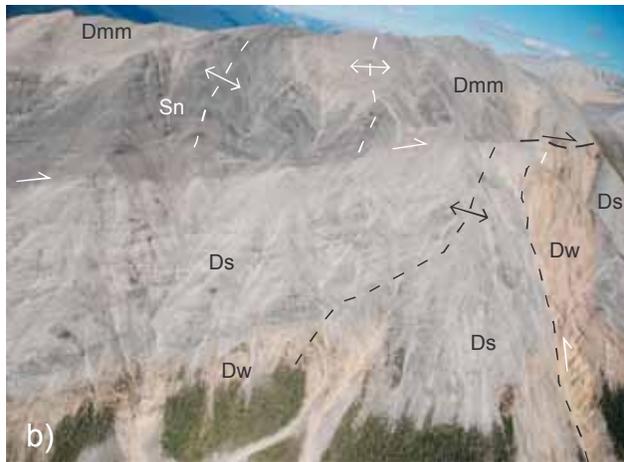
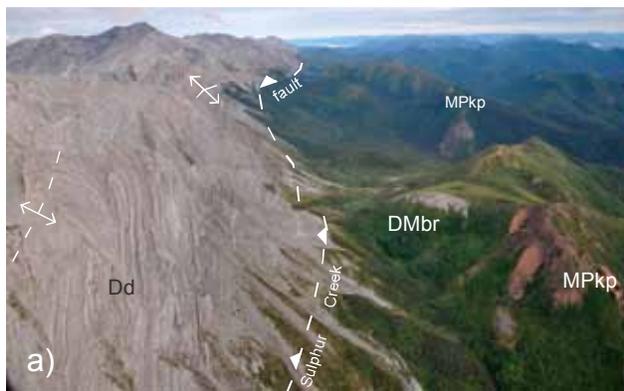


Figure 11. a) Hangingwall anticline along the Sulphur Creek fault outlined by well-bedded Dunedin limestone (Dd), eastern edge of the Sentinel Range, view to the northwest. The low ridge to east is held up by siltstone and siliceous sediments of the Kindie and Fantasque formations (MPkf). The treed valley in between is underlain by recessive shale of the Besa River Formation (DMbr); b) a knife-sharp thrust fault with hangingwall folds truncates the east limb of a hangingwall anticline and a west-directed back thrust in the underlying thrust sheet; southern Sentinel Range, view to the northwest. Abbreviations: Dmm, Muncho-McConnell Formation; Ds, Stone Formation; Dw, Wokpash Formation; Sn, Nonda Formation; c) tight, faulted chevron folds in the immediate hangingwall of the Sulphur Creek fault, eastern edge of the Sentinel Range near the southern end of map area, view to the southeast. Well-bedded Dunedin Formation limestone (Dd) is faulted over black Besa River shale (DMbr).

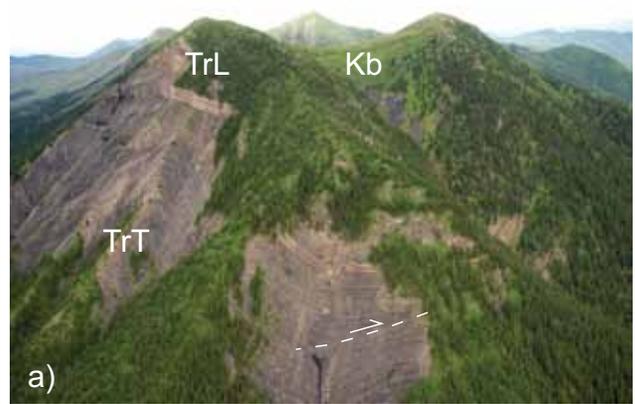


Figure 12. a) Minor fault and detachment folds within interlayered siltstone, sandstone and shale of the upper Toad Formation (TrT), in the central part of the Rocky Mountain Foothills. Resistant sandstone of the Liard Formation (TrL) forms a large asymmetric syncline cored by dark marine shale of the Buckingham Formation (Kb); view to the northwest; b) folded Kindie Formation, western edge of the Rocky Mountain Foothills; view to the northeast; c) rounded concentric and box-folded anticlines in the Liard Formation, southeastern Rocky Mountain Foothills. In this area, resistant sandstone of the Liard Formation is directly overlain by recessive shale of the Buckingham Formation and the geometry of anticlines in the Liard has controlled the topography of the underlying ridge.

the Kindie-Fantasque interval are chevron folds with planar limbs and narrow hinge zones (Fig. 12b). In contrast, folds in the Liard Formation range from rounded concentric to planar-limbed chevron folds (Fig. 12c). These have broad cores and relatively steep limbs. Where the Liard Formation is overlain by Cretaceous shale, fold geometry is beautifully portrayed by the topography (Fig. 12c). Unlike straight-limbed chevron folds, rounded concentric folds require upper and lower detachments (Dahlstrom, 1969). In

this area, they indicate the presence of detachments in the overlying Cretaceous shale and the underlying Toad/Grayling intervals. Mapping in the easternmost Rocky Mountain Foothills, where the Liard Formation has been removed by pre-Cretaceous erosion, suggests much of this detachment occurs within the Toad Formation. In the westernmost Rocky Mountain Foothills, changes in fold geometry from the Kindle-Fantasque to Luddington intervals require the use of detachments in the Toad/Grayling interval. Folds in the Luddington Formation are mainly chevron folds. Flat-bottomed synclines (Fig. 13a) are relatively common. Most folds in the eastern Rocky Mountain Foothills are upright and fairly symmetric. In the western Rocky Mountain Foothills, asymmetric, northeast-facing folds with an associated axial-planar cleavage are common and overturned folds occur locally. Typical fold wavelengths are 2–4 km in the Luddington-Baldonell intervals in the western Rocky Mountain Foothills, 1–2 km in the Liard Formation and 1 km in the upper Toad Formation near Toad River in the easternmost Rocky Mountain Foothills. Smaller-wavelength (200–300 m) fold trains are developed locally in the Grayling Formation near the Liard River (Geotex Consultants, 1984). Estimated shortening of folded strata exposed at the top of the Triassic in the southeastern Rocky Mountain Foothills near Toad River is 5–6 km (20–25%).

In the Mackenzie Mountains, the Besa River Formation forms a prominent detachment horizon separating folds in the Mattson, Tika, Kindle and Fantasque intervals from the underlying Paleozoic carbonate. Fold wavelength is highly dependent on the thickness of the more competent Mattson sandstone in the succession. Where this sandstone is thick in the northern Caribou Range, the fold wavelength is approximately 5 km. Where the sandstone interval is thinner and the Tika-Kindle interval is more silty, the fold wavelength is commonly 1–2 km.

In the Liard Fold and Thrust Belt, well data indicates the Besa River Formation continues to form a detachment horizon even though surface features such as the Beaver River anticline (Fig. 13b) coincide with the subsurface anticline of fractured Middle Devonian carbonate that forms the Beaver River gas field (Snowdon, 1977). Although poor exposure and limited shortening make it more difficult to discern, changes in fold geometry from the Mattson-Fantasque interval to the Liard Formation in the southwest or the Scatter Formation in the east indicate the Toad/Grayling formations formed a detachment zone, at least locally. The surface geology near 60°N is dominated by four large, south-plunging anticlines (Fig. 2). Each anticline faces northwest with a steeper western limb. Small west-directed thrust faults die out southward along the west limb of the two anticlines east of Beaver Mountain (e.g., Fig. 14). The anticlines are long wavelength structures (approximately 10 km) and show that relatively little shortening occurred in the Mattson Formation and younger strata across the Liard Fold and Thrust Belt at this latitude. To the south

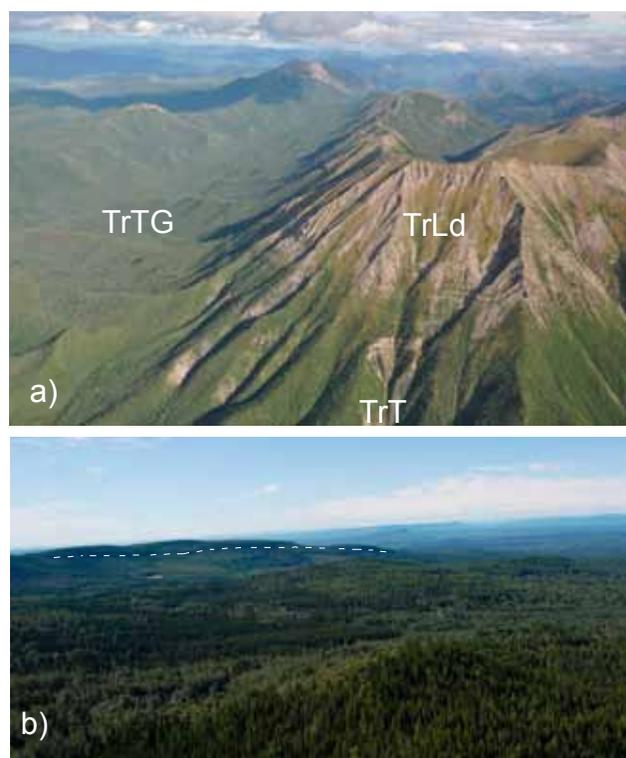


Figure 13. a) Flat-bottomed syncline in the western Rocky Mountain Foothills near Liard River. The adjacent valley is underlain by siltstone, sandstone and shale of the Toad/Grayling formations. Abbreviations: TrLu, Luddington Formation; TrT, Toad Formation; TrTG, Toad/Grayling formations; b) looking south along the Beaver River anticline at the south end of Beaver River gas field. The dotted line outlines the base of the sandstone in the Scatter Formation.

in the Scatter River area, the eastern part of the Liard Fold and Thrust Belt is composed of gentle- to open-folded Scatter Formation with less than 1 km of shortening.

In the Toad River map area, interference fold structures between northeast and northwest trends are developed locally in the northern part of the map area (for example, north of the Crow River gas field). The only example observed in the Rocky Mountain Foothills occurs immediately east of the Sentinel Range, where a northwest-facing, overturned syncline has developed in the northwest-trending folded panel of the Kindle and Fantasque formations.

### ***Subsurface structural style of the Foreland Belt***

Deep drilling shows that Proterozoic and Paleozoic carbonate strata are involved in Cretaceous compressive structures under the Rocky Mountain Foothills and the Liard Fold and Thrust Belt. Without seismic control, the interpretation of subsurface structural geometry is extremely difficult due to the presence of detachment horizons separating different fold geometries, together with precompressive deformation faults. For example, the KMCL Shell

Toad d-057-94-N-02 well was drilled into uplifted Mesoproterozoic rocks in the Toad anticline (Fig. 10). Immediately east of the well, the west limb of the Toad anticline forms an east-dipping homocline and the west limb of the Liard syncline. The geometry of the fault carrying the Mesoproterozoic to Middle Devonian section is unknown. It could be a small displacement east-directed blind thrust, a larger displacement west-directed blind thrust or a pop-up structure. In the future, it is hoped that access to proprietary seismic information will help guide the construction of a series of structural cross-sections across this geologically interesting part of the Foreland Belt.



Figure 14. Draped orthophoto–digital elevation model image giving a three-dimensional perspective view of large Mattson cored anticline east of Beavercrow Mountain; view to the south-southwest from near 60°N latitude.

## SUMMARY

- Results from mapping during the summer of 2011 will be combined with unpublished and published historical information to produce new GIS-enabled bedrock geological maps of the Toad River area.
- More than 8000 m of Mesoproterozoic; Neoproterozoic-Cambrian; Lower, Middle and Upper Paleozoic; Triassic; and Cretaceous strata are exposed in the Toad River, including three organic-rich units with shale gas potential.
- Local abrupt changes in thickness and/or facies indicate that block faulting occurred in the area during the Middle Cambrian, Ordovician–Silurian, Mississippian–Permian and Jurassic–Early Cretaceous (pre-Albian). Most older faults recognized at the surface were reactivated during Cretaceous compressive deformation.

- Shortening in the more competent Mesoproterozoic and Paleozoic successions was primarily by thrust faulting.
- Shortening in the interlayered competent and incompetent Upper Devonian to Cretaceous successions was primarily by folding. Locally important detachment horizons occur in upper Devonian–Mississippian (Besa River) shale, Triassic (Toad/Grayling) shale and siltstone and Lower Cretaceous (Buckinghorse/Garbutt) shale.
- Estimated shortening at the top of the Triassic across the eastern part of the Rocky Mountain Foothills near the Toad River is 5–6 km. Even less shortening occurs at top of the Triassic across the eastern part of the Liard Fold and Thrust Belt.
- Future plans include the construction of regional balanced structural cross-sections. Access to proprietary seismic information would greatly assist this process.

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