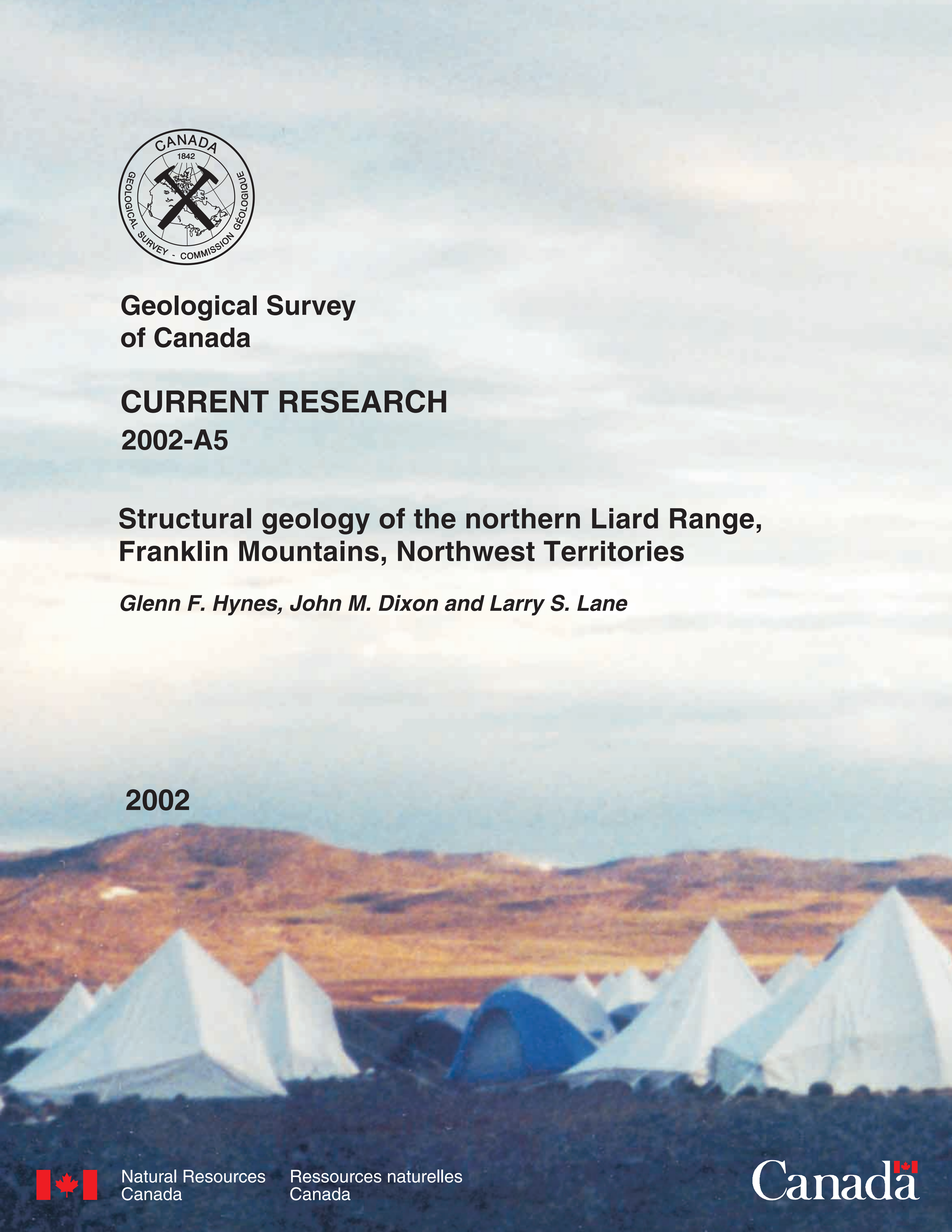

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Structural geology of the northern Liard Range, Franklin Mountains, Northwest Territories[1]

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Abstract: The northern Liard Range is a complex, faulted anticline cored by resistant Early Carboniferous clastic and carbonate rocks, and flanked on both sides by Early Cretaceous clastic rocks. In the study area, the Liard Range defines an eastward-opening arc, striking north-northwest in the south, but swinging toward the northeast, in the north. In the south, the Carboniferous Prophet Formation is thrust over Carboniferous sandstone of the upper Mattson Formation. This east-directed thrust appears to terminate in the apex of the arc. North of the arc, the structure is defined by the southwest-plunging Mattson anticline. In the vicinity of the arc, box folds are common on the east side of the range. The box folds have shallowly east-dipping crestal surfaces and steeply dipping limbs. The folds vary in complexity from ridge to ridge with some folds being harmonic while others display various types of disharmony.

Résumé : La partie nord du chaînon Liard est un anticlinal à géométrie complexe recoupé par des failles, dont le coeur est formé de roches clastiques et carbonatées résistantes du Carbonifère inférieur et les flancs, de part et d'autre, se composent de roches clastiques du Crétacé inférieur. Dans la région d'étude, le chaînon Liard décrit un arc qui s'ouvre vers l'est; d'une direction nord–nord-ouest au sud il s'incurve vers le nord-est dans sa partie nord. Au sud, la Formation de Prophet du Carbonifère chevauche les grès carbonifères de la partie supérieure de la Formation de Mattson. Ce chevauchement à vergence est semble se terminer à la pointe de l'arc. Au nord de l'arc, le style structural est défini par la présence de l'anticlinal de Mattson à plongement sud-ouest. Aux environs de l'arc, les plis coffrés sont communs du côté oriental du chaînon. Les plis coffrés présentent des surfaces sommitales faiblement inclinées vers l'est et des flancs abrupts. La complexité des plis varie d'une crête à l'autre, certains étant harmoniques et d'autres disharmoniques à des degrés divers.

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[1] Contribution to Central Foreland NATMAP Project

INTRODUCTION

The Liard Range lies within the southern portion of the Franklin Mountains in the Northwest Territories (Fig. 1). The area, which is part of the Canadian Cordillera foreland fold and thrust belt, is underlain by Paleozoic and Mesozoic strata. The topography is structurally controlled and the area is host to important gas reserves, with production from fields such as the Beaver River, Kotaneelee, Pointed Mountain, and La Biche fields. The Liard Range hosts some of the most prolific gas-producing wells in Canada.

The Fort Liard area encompasses a fundamental change in the character of the Cordilleran foreland. This is manifest as a change from a thin, narrow, Paleozoic carbonate shelf in the south to a broad, thick platform in the north (Cecile and Norford, 1993); and as an abrupt 200 km eastward swing in the Cordilleran deformation front (Wheeler and McFeely, 1991). The craton beneath western Canada can be divided into five distinct segments bounded by major northeast-trending features defined by surface or subsurface expression. One of these segment boundaries is the Liard line, which has been interpreted as a crustal-scale transfer fault active during the Late Proterozoic rifting that created the paleo-Pacific continental margin. This crustal feature has been interpreted as the essential control that produced the profound character changes noted above (Cecile et al., 1997b).

Approximately 100 km north of the Liard line, a second, less prominent feature is suggested by the sigmoidal geometry of the Kotaneelee and Liard ranges, as well as by other surface features. Morrow and Miles (2000) have used these surface expressions, based on regional reconnaissance mapping (Douglas, 1976; Douglas and Norris, 1976), combined with potential field signatures and physiography to postulate the existence of a second subsurface feature, the Beaver River structure, which comprises a secondary element of the Liard transfer fault system (Cecile et al., 2000).

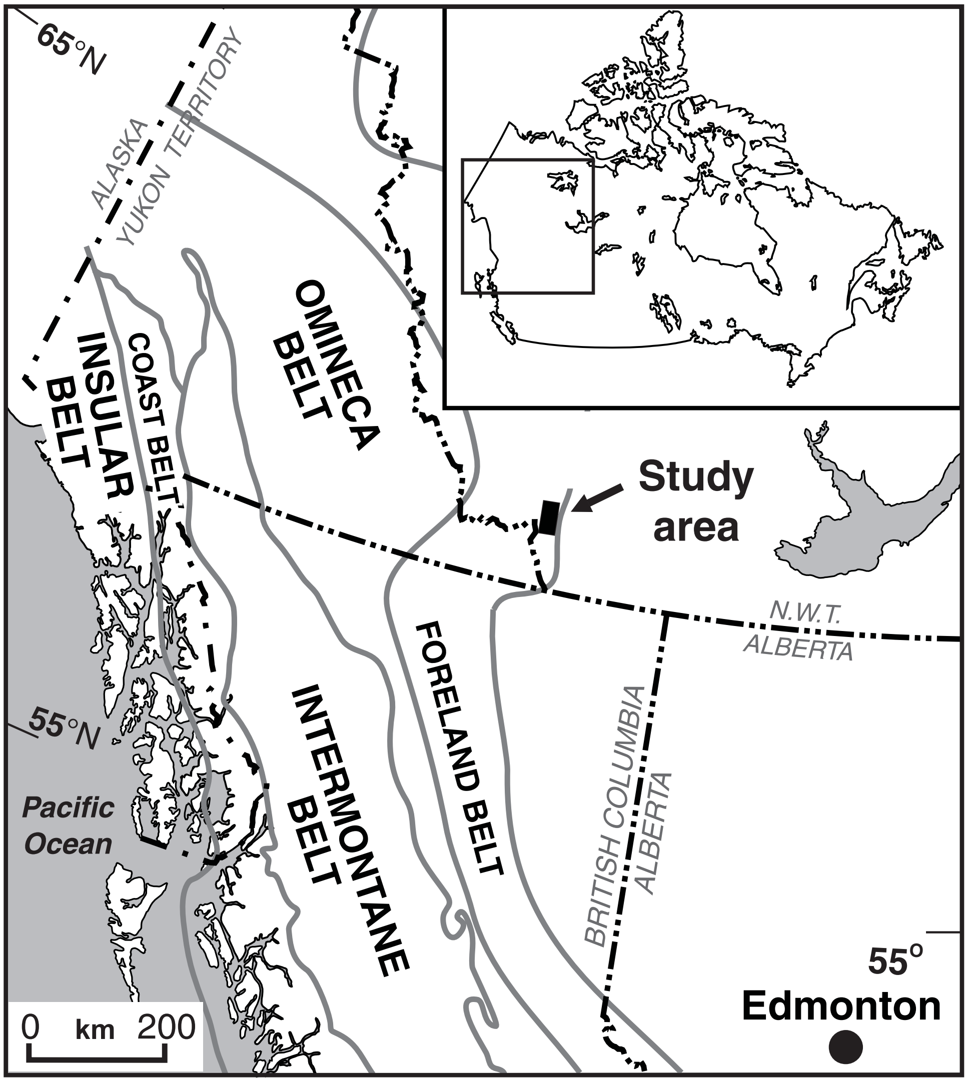


***Figure 1.** Location map of the project area (*modified from *Fallas and Lane, 2001).*

The work reported on here is part of a project for a M.Sc. study being carried out by the first author at Queen's University. The project is sponsored by the Central Foreland NATMAP Project, a multidisciplinary, multipartner geological study of parts of southwestern Northwest Territories, southeastern Yukon Territory, and northeastern British Columbia; and by the Fold-Fault Research Project, a joint project between Queen's University and the University of Calgary that is focused on geological and geophysical research of the structural geometry, kinematics, and dynamics of fold and thrust belts from an economic and academic point of view. Fieldwork is expected to resume in the summer of 2002 in the Liard and Kotaneelee ranges.

A major theme of the Central Foreland NATMAP Project is to compare the three dimensional structural geometries across the Liard line and document its role in the tectonic evolution of the Cordillera (Cecile et al., 1997a; 2000). This study will contribute toward that theme in two ways. First, mapping of the flexure in the northern Liard Range will contribute to the documentation of surface structures that might be related to the subsurface Beaver River structure. Later, centrifuge modelling to be carried out at Queen's University will investigate how the mechanical stratigraphy controls the geometry of the mesoscopic structures, and suggest possible causes of the dramatic change in structural trend of the range. These can be compared with subsurface features interpreted through geophysical data and potential field modelling.

Mapping of the Liard Range, at a scale of 1:50 000 in the western half of the Sawmill Mountain (NTS 95 B/13) and eastern half of the Etanda Lakes (NTS 95 C/16) map areas was initiated in the summer of 2001 (Fig. 2A). Detailed structural mapping was carried out on the ridges while contacts in the low-lying areas were established locally, then extrapolated from topographic expressions and from previous mapping in the area at a scale of 1:250 000 (Fig. 2B; Douglas, 1976; Douglas and Norris, 1976).

PREVIOUS WORK

One of the first maps of the study area was produced by Kindle (1944) at a scale of 1:63 360. Later, the La Biche River (Douglas, 1976) and Fort Liard (Douglas and Norris, 1976) map areas were published at a scale of 1:250 000. Current mapping by the Central Foreland NATMAP Project is ongoing, and has produced seven new maps adjacent to this study area at 1:50 000 scale (Allen and Pigage, 2000; Currie et al., 2000a, 2000b; Fallas, 2001; Lane, 2001; K.M. Fallas and C. Evenchick, unpub. map, 2001; A.K. Khudoley, unpub. map, 2001). Previous stratigraphic work in the area includes major studies on the Devonian (Morrow et al., 1986, 1990), the Carboniferous (Richards, 1989; Richards et al., 1993), and the Cretaceous (Stott, 1982; Leckie et al., 1991) rocks. Also, earlier centrifuge modelling was conducted by Hodder et al. (1998) to simulate the geometry of the Liard line.

STRATIGRAPHY

In the study area mapped in 2001, the exposed rock units range from Early Carboniferous to Early Cretaceous (Fig. 3). The Lower Carboniferous units, which include the Prophet, Flett, Golata, and Mattson formations, are commonly very well exposed and underlie the range that runs approximately north-south. The Lower Cretaceous rocks consist of the Chinkeh, Garbutt, Scatter, Lepine, Sikanni, and Sully formations. These units are generally poorly exposed and are restricted to low-lying areas; therefore, many of these contacts are inferred from their topographic expressions.

Lower Carboniferous

Prophet Formation

The base of the Prophet Formation is not seen in the study area. The formation is conformably overlain by the Flett Formation. The upper contact of the Prophet Formation is defined by the presence of the first shale-dominated section (Richards, 1989). The formation is dominantly a dark grey to buff limestone with interbeds of black shale. Trace fossils and skeletal fragments are not common in the Prophet Formation. The limestone of the Prophet Formation near Mattson Pass is commonly laminated.

Flett Formation

The Flett Formation is characterized by massive, resistant, dark grey limestone. Skeletal fragments and bioturbation features are abundant. Dark grey chert nodules are also common in the Flett Formation. Limestone beds range from 1 cm to 1 m in thickness. The Flett Formation can be subdivided into the Tlogotsho, Jackfish Gap, and Meilleur members (Richards, 1989); however, for the purposes of this study the division was not made.

Golata Formation

The Golata Formation is a dark grey to black shale. It underlies only a very minor portion of the field area. The unit is not commonly seen in outcrop and can generally be mapped by identifying small saddles on ridges. In the field area, the Golata Formation ranges from 5 m to 10 m thick. The rocks of the Golata Formation were deposited basinward of carbonate platform lithofacies, represented by the Prophet and Flett formations. The Golata Formation also defines the onset of a major period of siliciclastic deposition, recorded by the Mattson Formation (Richards et al., 1993).

Mattson Formation

The Mattson Formation is dominantly a fine- to medium-grained white to buff sandstone with thin intervals of shale, limestone, and dolomite. The Mattson Formation is interpreted as comprising sediments deposited in fluvially dominated, wave- and tide-influenced deltas (Richards et al., 1993) and was informally divided into lower, middle, and upper "parts" by Douglas and Norris (1959, 1976) and Douglas (1976). Currie et al. (1998) estimated that the thickness of the Mattson Formation ranges from 1440 m to 1700 m.

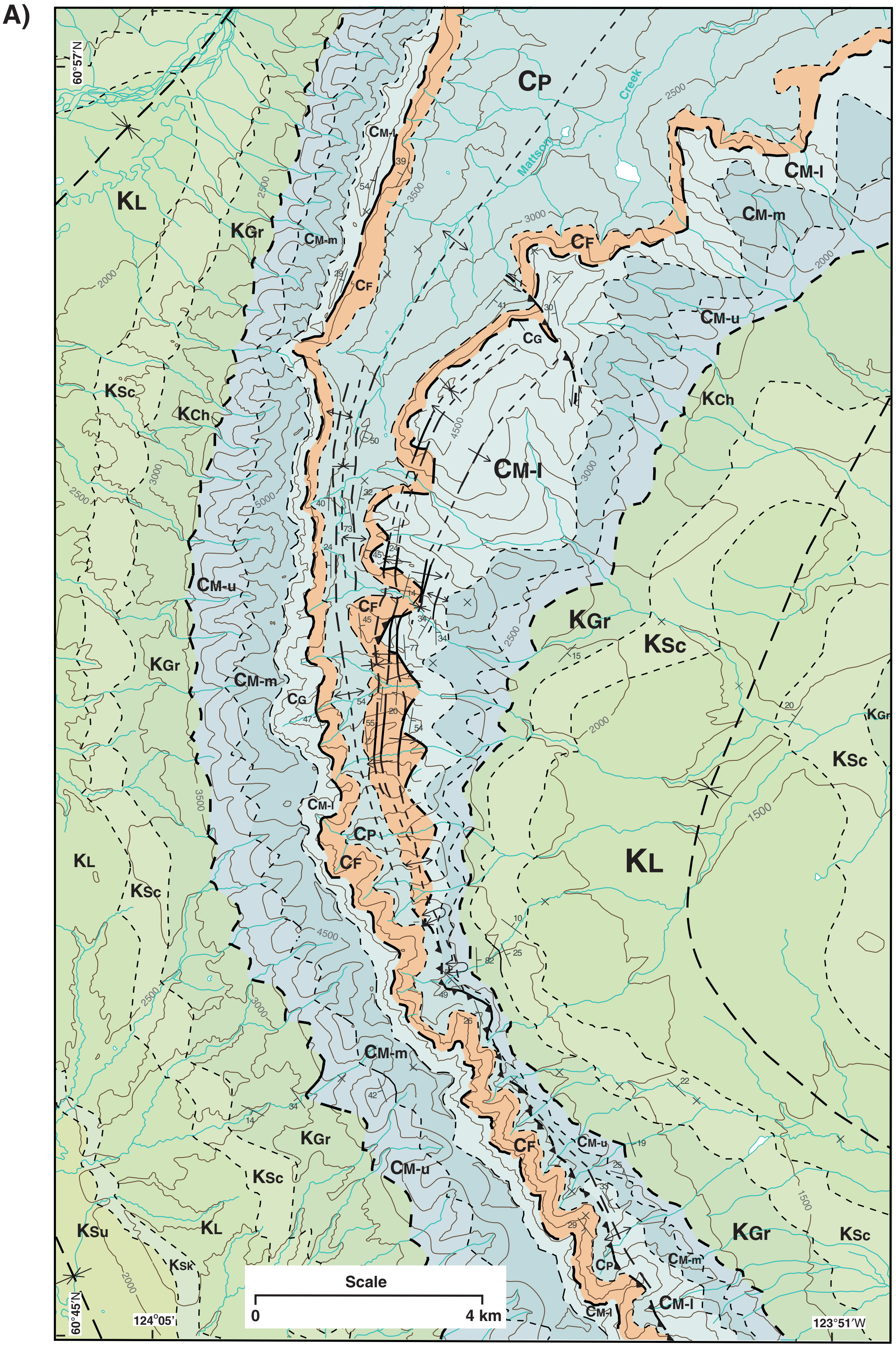


Figure 2. Geological maps of the study area. ***A****) Geological map of parts of NTS 95 C/16 and 95 B/13. This is compiled from mapping in 2001 and from previous regional mapping (Douglas, 1976; Douglas and Norris,1976).* ***B****) Simplified geological map of study area,* (from *Douglas, 1976; Douglas and Norris, 1976) at a scale of 1:250 000.*

MESOZOIC

LOWER CRETACEOUS

KSu	*SULLY FORMATION: dark grey shale with minor sideritic concretions.*
KSk	*SIKANNI FORMATION: rusty-weathering, thinly bedded, medium-grey to greenish-grey siltstone with interbedded medium- to dark-grey shale.*
KL	*LEPINE FORMATION: dark grey to black concretionary shale with thin Fe-stained, orange-weathering siltstone beds, and minor quartz arenite*
KSc	*SCATTER FORMATION: distinctive olive-green- to medium-brown-weathering, medium- to thick-bedded, very fine-grained sandstone to siltstone, with minor interbedded concretionary dark grey shale.*
KGr	*GARBUTT FORMATION: dark-weathering concretionary shale.*
KCh	*CHINKEH FORMATION: basal silicified breccia with very angular clasts of white chert in a matrix of dark grey silicified siltstone (8–10 cm thick), interbedded shale, bioturbated siltstone and fine-grained sandstone with abundant zoophycos.*

PALEOZOIC

LOWER CARBONIFEROUS

CM-u	*UPPER MATTSON FORMATION: quartz arenite, shale, fossiliferous limestone and dolostone, poorly indurated, dolomitic quartz arenite, and minor subchertarenite.*
CM-m	*MIDDLE MATTSON FORMATION: poorly to well indurated, medium-grained, buff-weathering quartz arenite and medium- to dark-grey shale, with minor dark-orange-weathering limestone and sandy limestone near the base.*
CM-l	*LOWER MATTSON FORMATION: rusty-weathering, locally bioturbated, fine- to medium-grained quartz arenite and medium to dark grey shale.*
CG	*GOLATA FORMATION: shale, black to dark grey, carbonaceous and partly calcareous; interbeds of bioclastic grainstone, very fine-grained calcareous sandstone.*
CF	*FLETT FORMATION: grey fossiliferous limestone; shale.*
CP	*PROPHET FORMATION: buff-weathering, dolomitic or calcareous black shale and siltstone; siliceous or spicularitic locally; thin-bedded and planar-laminated.*
CC	*CLAUSEN FORMATION: black shale*
CY	*YOHIN FORMATION: sandstone.*

DEVONIAN TO LOWER CARBONIFEROUS

DMBR	*BESA RIVER FORMATION: dark grey shale; siltstone.*

MAP SYMBOLS

Geological boundary (defined, approximate, assumed)

Bedding form lines (defined, approximate, assumed)

Outcrop stations

Bedding (inclined, vertical)

Anticline (defined, approximate, assumed)

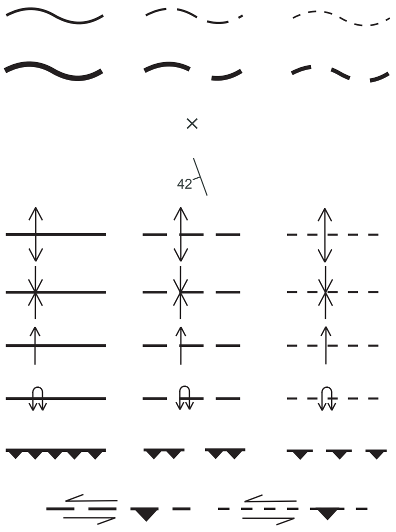
Syncline (defined, approximate, assumed)

Box anticline (defined, approximate, assumed)

Overturned anticline (defined, approximate, assumed)

Thrust (defined, approximate, assumed)

Oblique thrust (approximate, assumed)



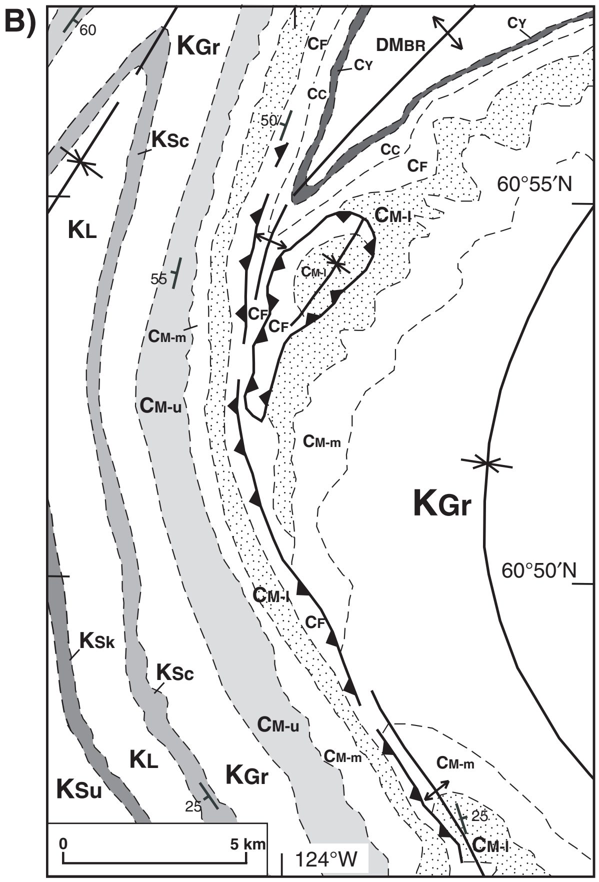


Figure 2B.

Lower Mattson Formation

The lower Mattson Formation consists of buff, thin-bedded, fine- to medium-grained quartz arenite interbedded with dark grey shale. Quartz arenite-dominated units are typical and range from 0.50 m to 25 m thick, while shale-dominated units are less common and are 0.25–10 m thick. Quartz arenite beds vary in thickness from 0.2 m to 1 m and commonly contain wave ripples and crossbeds. The quartz arenite beds are characteristically rusty weathering and are commonly bioturbated.

Middle Mattson Formation

The base of the middle Mattson Formation is defined by the lowest thick, massive, continuous quartz arenite layer (Currie et al., 1998). In isolated outcrops the middle member is commonly difficult to distinguish from the lower Mattson Formation due to the presence of channels in the upper parts of the lower unit. The middle Mattson Formation is characterized by a buff, medium-grained quartz arenite. Crossbedding and wave-formed ripples are characteristic of the formation. Bioturbation is not common in the middle Mattson Formation and beds can be 4–5 m thick. The middle Mattson Formation

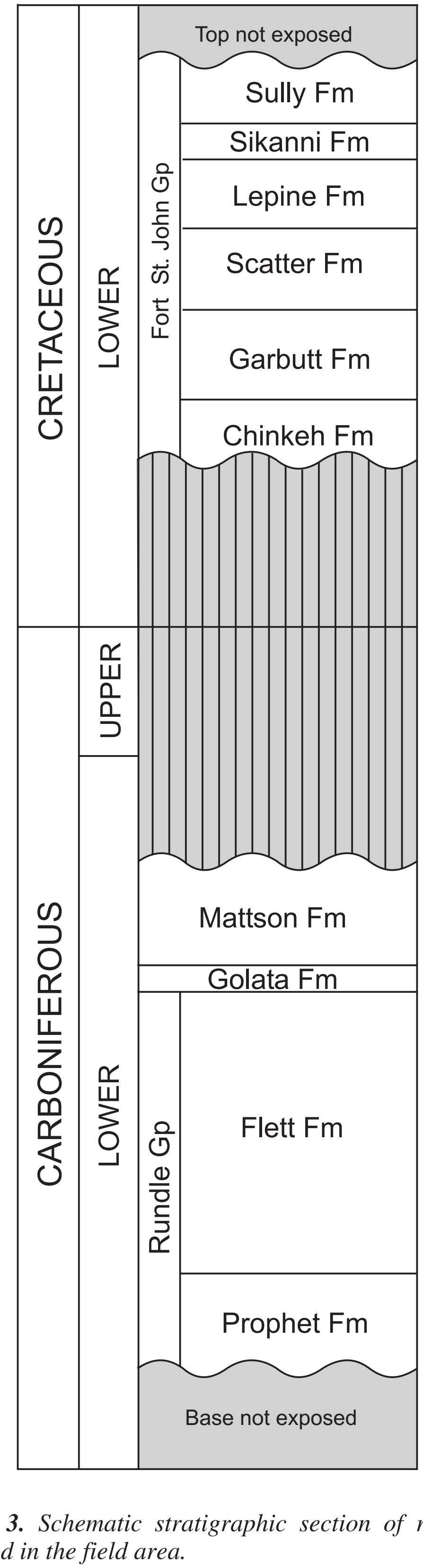


Figure 3. *Schematic stratigraphic section of rock units observed in the field area.*

can also be distinguished from the lower Mattson Formation by its fining-upward, rather than coarsening-upward sequences (Currie et al., 1998).

Upper Mattson Formation

The base of the upper Mattson Formation is defined as the lowest thick limestone layer (Currie et al., 1998). The limestone layers contain abundant brachiopod and bryozoan fragments. Like the rest of the Mattson Formation, the upper Mattson Formation also contains fine- to medium-grained quartz arenite; however, it also contains significant beds of limestone, chert, dolomite, and poorly cemented, calcareous quartz arenite. The quartz arenite layers commonly display trough crossbedding, hummocky cross-stratification, and planar-laminar bedding. The upper Mattson Formation had not been mapped previously on the east side of the Liard Range.

Lower Cretaceous

Fort St. John Group

The formations of the Early Cretaceous Fort St. John Group are typically poorly exposed and are confined to low-lying valleys. Many of the contacts were inferred from the topographic expression of the individual units. The group represents a series of transgressive-regressive sequences consisting of sediments derived from an eastward-advancing deformation belt (Stott, 1982). The Chinkeh, Garbutt, and Scatter formations were observed in the field and are briefly discussed below.

Chinkeh Formation

In the study area, the Chinkeh Formation has a thickness of 20 m and unconformably overlies the Lower Carboniferous upper Mattson Formation. The formation is characterized by a basal conglomerate and overlying sandstone. The conglomerate is buff and contains clasts that range in diameter from 0.5 cm to 40 cm. The sandstone is also buff and has a very mottled appearance. Bed thicknesses range from 2 cm to 15 cm and bioturbation is extensive. Wood fragments are also common. This unit was observed on the west side of the range. It is assumed to be present on the east side, but has not been seen there due to poor exposure.

Garbutt Formation

The Garbutt Formation is a 200–265 m thick succession of black shale that conformably overlies the Chinkeh Formation in the field area. The shale is fissile and rusty weathering. Minor dark grey siltstone concretions and thin layers of glauconitic sandstone are present in the formation. The Garbutt Formation has a transitional upper contact with the Scatter Formation.

Scatter Formation

The Scatter Formation is dominated by a resistant, glauconitic sandstone. Interbedded black mudstone and dark grey siltstone are common within the formation. Bioturbation is not common in this unit, although *Zoophycos* are locally found. The Scatter Formation is conformably overlain by black shale of the Lepine Formation.

STRUCTURE

Within the study area comprising the Etanda Lakes (NTS 95 C/16) and Sawmill Mountain (NTS 95 B/13) map areas, the Liard Range is underlain by the Lower Carboniferous Prophet, Flett, Golata, and Mattson formations. Lower Cretaceous rocks of the Chinkeh, Garbutt, Scatter, Lepine, Sikanni, and Sully formations occupy the Kotaneelee and Liard synclines to the west and east of the range, respectively. The Liard Range changes trend from northwest-southeast in the south, to north northeast-south southwest in the north (Fig. 2A).

In the southern portion of the study area, the Liard Range trends northwest. In this area the Flett Formation is thrust on top of the lower Mattson Formation (Fig. 4). The strata in the hanging wall of the thrust dip to the southwest at 30°, whereas the footwall contains a northwest-plunging anticline. On both sides of the range, the dips shallow toward the synclines in the centres of the flanking valleys.

The northern part of the field area is dominated by the Mattson anticline. In this area, the Mattson anticline trends north-northeast with east and west limbs dipping at approximately 40°. The Mattson anticline is cored by the Prophet Formation and plunges to the southwest.

Also in the north, a southeast-striking oblique thrust fault occurs in the ridge east of the valley (Fig. 5). This structure was interpreted as a klippe by Douglas (1976; Douglas and Norris, 1976; *see* Fig. 2B). The oblique thrust places the Flett Formation above the lower Mattson Formation. The strata in the footwall are parallel to the thrust and dip to the southwest at 30°. The structure is not extensive and is interpreted to terminate in the lower Mattson Formation; however, more detailed investigation is required to confirm this.

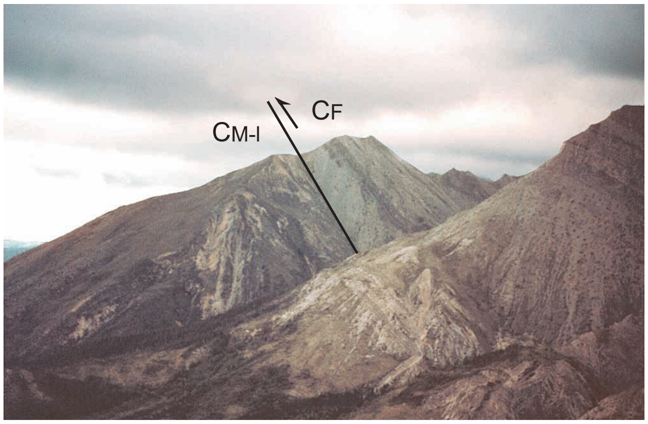


***Figure 4.** Thrust fault in the Liard Range. View is to the south (CF = Flett Formation; CM-l = lower Mattson Formation).*

In the area of the flexure (middle of Fig. 2A), a number of short, steep-sided, east-trending ridges extend perpendicular to the structural trend on the east side of the range. The short ridges expose north-trending box anticlines. The box folds are cored by the Flett and Mattson formations and consist of shallowly east-dipping crestal panels with steeply east- and west-dipping limbs. Tight to isoclinal, east-verging synclines occur on the west limbs of the box folds. In one instance the syncline is cut by a thrust which places the Flett Formation above the lower Mattson Formation. The complexity of the box folds varies from ridge to ridge. Some of the ridges exhibit harmonic folding where all the layers are folded parallel to one another (Fig. 6), whereas others display much more complex structures with back-thrusting and several geometries of folds. The structure of the ridges is more complex toward the south.

The flexure is interpreted to mark the northern termination of the thrust that extends through the southern portion of the Liard Range. Douglas (1976) and Douglas and Norris (1976) mapped this thrust as extending north of the flexure (*see* Fig. 2B); however, during the current mapping, no direct evidence of thrusting was found in the valley. Several large slumped blocks of the lower Mattson Formation appear stratigraphically lower than the Flett Formation in the valley, and these may have led to the earlier thrust fault interpretation. The slumping caused large blocks of the lower Mattson Formation to slide from the range as largely coherent blocks. In some areas, the large slumps appear to be in place and would allow for interpretation of a thrust; however, the topographic form clearly indicates that these exposures resulted from slumping.

***Figure 5.** Oblique thrust in the northern part of the map area. View is to the southeast. (CF = Flett Formation; CM-l = lower Mattson Formation).*

***Figure 6.** Harmonic box fold in the Liard Range. View is to the south.*

The flexure also coincides with the southern terminus of the Mattson anticline. In the central part of the flexure, there are two tight anticlines with an intervening syncline. As the valley widens to the north the structure changes to one anticline with moderately dipping east and west limbs.

FUTURE WORK

Fieldwork in 95 C/16 and 95 B/13 will resume in the summer of 2002. Mapping will continue north of the flexure to study the changes in structural trend of the Liard Range. Also, coverage may be extended farther west into the Kotaneelee Range, to investigate the effects of the flexure in that area.

Physical analogue modelling of structures seen in the Liard Range are planned to commence in the winter of 2002. Previous physical models by Dixon et al. (e.g. 1996, 1997) display box-fold geometries somewhat similar to those seen in the Liard Range (e.g. Fig. 6). By constructing the models with mechanical stratigraphy that more accurately represents the lithostratigraphy of the field area, we should be able to reproduce the geometry of the box-fold structures in the range and study their relationships to the large-scale structures.

Hodder et al. (1998, 1999) used centrifuge modelling to investigate possible origins of the change in structural trend across the Liard line. We intend to build upon that work with more detailed modelling that takes into account the results of mapping in the Liard Range. Centrifuge modelling can be used to investigate how different boundary conditions influence the observed surface structures. A key question is whether the change in structural trend is due to contrasting deformation related to local stratigraphic variations across the area, or to an underlying tectonic cause such as differential rates or amounts of tectonic shortening and/or displacement on an underlying strike-slip basement fault.

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