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Abstract: The early Paleozoic Selwyn Basin is a geometrically complex deep-water environment that contains SEDEX deposits. The evolution and mineral potential of one of its associated subbasins, the Misty Creek embayment, are poorly known. In order to update and refine the reconnaissance-level understanding of the history of the embayment, an almost complete composite stratigraphic section spanning 2920 m of strata in the Hess River, Rabbitkettle, Duo Lake, and Cloudy formations was documented in the centre of the embayment (central NTS 106-B). These formations are distinguished from one another by subtle differences. The Hess River Formation is dominated by fine-grained carbonate turbidite deposits that accumulated on a gentle slope. The Rabbitkettle Formation contains conspicuous evidence (slump folds and creep folds) of a carbonate slope environment, but may have been near storm wave-base at the study location. The Duo Lake Formation was deposited in a deep-water environment with no significant topographic gradient and a dearth of calcareous material. The Cloudy Formation probably formed in a deep-water slope environment, because it contains a large block (kilometre-scale) of slump-folded strata (an olistostrome). The Misty Creek embayment has unknown economic potential, but it has characteristics that are known to be associated with SEDEX potential, such as black shale intervals, associated subaqueous volcanic rocks, evidence of deep-water slopes, and extension-related basin-floor compartmentalization.

Résumé : Le bassin de Selwyn du Paléozoïque précoce représente un milieu d'eau profonde à géométrie complexe renfermant des gîtes de sulfures exhalatifs dans des roches sédimentaires (sedex). L'évolution et le potentiel en ressources minérales de l'un de ses sous-bassins, le rentrant de Misty Creek, sont peu connus. Afin de mettre à jour et d'améliorer notre compréhension, à l'échelle de la reconnaissance, de l'évolution du rentrant, nous avons documenté une coupe stratigraphique composée presque complète, couvrant 2920 m de strates attribuées aux formations de Hess River, de Rabbitkettle, de Duo Lake et de Cloudy, dans le centre du rentrant (centre du feuillet 106-B du SNRC). Ces formations se distinguent les unes des autres par de subtiles différences. Des turbidites carbonatées à grain fin, qui se sont accumulées sur une pente douce, sont prédominantes dans la Formation de Hess River. La Formation de Rabbitkettle donne des indications (plis synsédimentaires et plis de reptation) d'un milieu de talus carbonaté, mais il est possible qu'elle se soit accumulée près du niveau de base des ondes de tempête à l'emplacement de l'étude. La Formation de Duo Lake s'est déposée dans un milieu d'eau profonde sans gradient topographique important et sans apport significatif de matériaux calcareux. La Formation de Cloudy s'est probablement formée dans un milieu de talus en eau profonde, puisqu'elle contient un grand bloc (échelle kilométrique) de strates déformées par un glissement synsédimentaire (un olistostrome). Bien que son potentiel économique ne soit pas encore connu, le rentrant de Misty Creek possède des caractéristiques qui sont reconnues pour être associées à des gîtes sedex, notamment des intervalles de shale noir, l'existence de roches volcaniques subaquatiques, la présence manifeste de talus en eau profonde et une compartimentation du fond du bassin liée à une distension.

INTRODUCTION

The Misty Creek embayment (MCE) belongs to an array of deep-water embayments and high-standing blocks that characterized northwestern Laurentia's newly developed passive margin in the early Paleozoic. The Misty Creek embayment, a northeastern extension of the deep-water lower Paleozoic Selwyn Basin, is immediately east of the Northwest Territories–Yukon border, and opens to the southwest into the Selwyn Basin (Fig. 1). First described by Cecile (1982), the geology of the Misty Creek embayment includes five formations: deep-water carbonate and siliciclastic strata of the Hess River (Early to Middle Cambrian), Rabbitkettle (Late Cambrian–Early Ordovician), Duo Lake (Early Ordovician–late Early Silurian), and Cloudy (Late Ordovician–Early Silurian) formations, and mafic volcanic rocks of the Marmot Formation (Middle Ordovician–(?)Devonian).

Sedimentary exhalitive (SEDEX) deposits are Pb-Zn-Ag±Ba hydrothermal deposits that accumulate in subtly extensional deep-water sedimentary environments and are associated with subaqueous volcanism and/or anomalous heat flow, normal faulting, deep-water subbasin development, sediment starvation, and anoxia to euxinia in the lower water column (Goodfellow, 2007; Goodfellow and Lydon, 2007). Cecile (1982) suggested that the Misty Creek embayment may have base-metal potential, because its strata are of the same age and character as Late Cambrian to Early Silurian strata in the Selwyn Basin that are known to contain Cambrian to Silurian SEDEX deposits. The numerous deposits of the Anvil district are hosted by the Cambrian Mount Mye and Vangorda formations, which are equivalent to the Rabbitkettle Formation (Pigage, 2004); the Vulcan deposit is hosted by Middle Ordovician strata equivalent to Duo Lake Formation (Mako and Shanks, 1984); and the Howard's Pass deposits are hosted by Early Silurian strata equivalent to the Cloudy Formation (Goodfellow, 2007).

Scientific research, mapping, and mineral exploration in the western Mackenzie Mountains have been sparse, leaving the tectonostratigraphic history of the area and its economic potential largely unknown. Reconnaissance-level field stratigraphy undertaken in the 1970s (Cecile, 1982) has not since been revisited with a view to refining the history of the basin or understanding its mineral potential. This project aims to expand on the existing understanding of the Misty Creek embayment by providing refined lithostratigraphic descriptions and tectonostratigraphic interpretations for it.

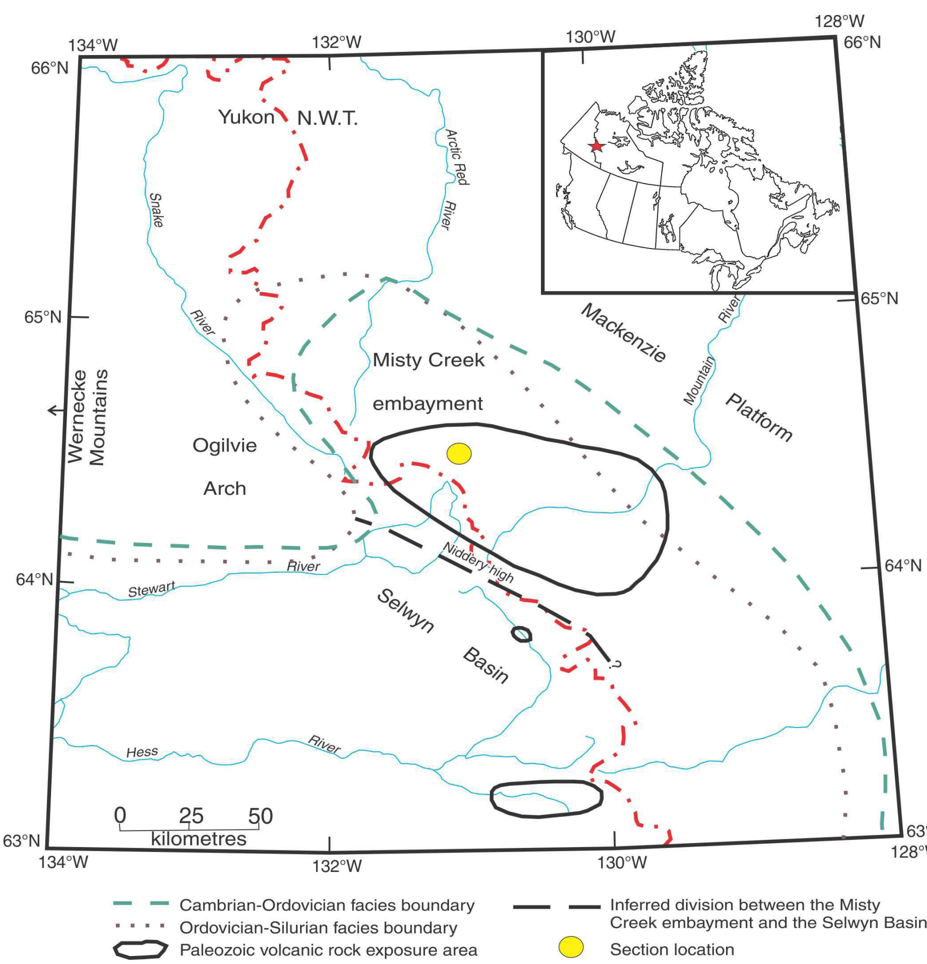


Figure 1. The inset on the map shows the location of the study area. The map represents the outline of the Misty Creek embayment in the Mackenzie Mountains (*modified after* Cecile, 1982), showing study area and the mapped boundaries between shallow- and deep-water paleoenvironments.

The Misty Creek embayment is exposed in NTS map areas 106-A, B, C, and 105-P (Cecile, 1982). The field location for this study is in NTS 106-B (UTM zone 9, NAD83, 403171E, 7155232N, ±10 m), in the western part of the northern Mackenzie Mountains. Fieldwork conducted in August 2012 focused on detailed description and sampling through approximately 3 km of Misty Creek embayment strata. The almost complete section was measured in three segments along creeks, in gullies, and along ridges.

GEOLOGICAL BACKGROUND

Rifting along the western margin of Laurentia during the late Proterozoic, along with a marked sea-level rise at the beginning of the Phanerozoic, resulted in widespread deposition of epicratonic and continental-margin carbonate rocks. The early Paleozoic western passive margin of Laurentia was dominated by the epicratonic Mackenzie Platform, and an extensive carbonate system that passed westward to a group of troughs and embayments dominated by deep-water carbonate rocks and fine terrigenous clastic rocks (Fritz et al., 1991) that were separated by high-standing subaqueous blocks and sills that accumulated shallow-water carbonate sediment. The Selwyn Basin is the best known of these deep-water troughs, largely because of its associated base-metal SEDEX deposits, and recent discovery of Carlin-type gold deposits (*see* Yukon Geological Survey and industry exploration work). The Misty Creek embayment, a poorly known part of the Selwyn Basin, was defined by Cecile (1982) as a subrectangular depression (100 km by 150 km) containing slope and basin-floor strata, bounded on three sides (northwest, north, and northeast to east) by shallow-water carbonate rocks belonging to the Ogilvie Platform (northwest), and the Mackenzie Platform (north to east); the embayment extends toward the southwest into the Selwyn Basin across the Niddery high, which consists of basinal strata that are thinner than, but similar to those present in the Misty Creek embayment. Lower Paleozoic strata of the Misty Creek embayment were deformed during the Jurassic–Tertiary Cordilleran Orogeny, resulting in predominantly northwest-trending fold axes and thrust faults (Gabrielse, 1967; Gordey et al., 2011).

The regional tectonic features of the area now occupied by the northern Mackenzie Mountains (Northwest Territories) and eastern Wernecke Mountains (Yukon Territory) included the Selwyn Basin, the Mackenzie 'Platform', and the Ogilvie Arch (Gabrielse, 1967; Fig. 1). Strata deposited in these areas during and after early Paleozoic transgression belong to the Sauk and Tippecanoe sequences (Fritz et al., 1991). Located in the northeastern Selwyn Basin and Misty Creek embayment are late Early Cambrian dolostone, lime mudstone and wackestone, calcareous siltstone, and shale of the Sekwi Formation (Blusson, 1971; Fritz et al., 1991). West-facing carbonate ramp strata of the Sekwi Formation (Dilliard et al., 2010) are overlain conformably, but diachronously by deep-water rocks of the Misty Creek embayment (Cecile, 1982). The deep-water trough system formed as a result of extension postdating rifting (Cecile, 1982; Goodfellow, 2007), although the timing and nature of this event remain controversial. In the Misty Creek embayment, the oldest strata of the Selwyn Basin interval are considered to be those of the late Early Cambrian to Middle Cambrian Hess River Formation (Cecile, 1982; Fritz et al., 1991). The subsequent interaction of sea-level variation and variable subsidence cycles led to the deposition of the Rabbitkettle, Duo Lake, and Cloudy formations during the Late Cambrian to Early Silurian. Collectively, these units have been referred to elsewhere as the 'Road River Group', but in the Misty Creek embayment at least, their division into formations is valid (Cecile, 1982). During the middle Paleozoic, the embayment ceased to exist as a distinct paleobathymetric feature, and Misty Creek embayment rocks are unconformably overlain by Devonian shallow-marine carbonate rocks.

The Hess River Formation, first established by Cecile (1982), was described as silty limestone, siltstone, and variably calcareous shale. It is late Early Cambrian to Middle Cambrian, as constrained by paleontological data (mostly trilobite fauna; Cecile (1982)). The lower contact between the Sekwi Formation and the Hess River Formation is conformable and in some locations thought to be diachronous (Cecile, 1982). The Hess River Formation locally contains an anomalous quartz sandstone interval ("Hess River flysch" in section 5 of Cecile (1982)), which may have been sourced from block faults in the Yukon Platform (northwest of the Misty Creek embayment; Cecile (1982)). During the time of "flysch" deposition, the embayment was not yet fully enclosed and was open to the Richardson Trough, another deep-water zone to the present-day northwest. The deep-water succession of the Misty Creek embayment contains no unconformities but the laterally equivalent shallow-water strata to the Hess River Formation are unknown in all directions, apparently because of erosion during subaerial exposure (Cecile, 1982).

The Rabbitkettle Formation was established by Gabrielse et al. (1973) for thinly bedded lime mudstone and silty lime mudstone with minor calcareous sandstone and siltstone and spectacular slump folds. The depositional age of the Rabbitkettle Formation is constrained by trilobite biostratigraphy to the Late Cambrian to Early Ordovician (Pratt, 1992). The lower contact between the Rabbitkettle Formation and the Hess River Formation is gradational and conformable (Cecile, 1982), and is recognized in both the Misty Creek embayment and Selwyn Basin proper. In Yukon, southwest of the study area in the Selwyn Basin sensu stricto, metamorphosed Rabbitkettle Formation strata contain past-producing SEDEX deposits of the Anvil district (Goodfellow, 2007). The Rabbitkettle Formation is laterally equivalent to the Franklin Mountain Formation in the Mackenzie Platform to the east and north of the Misty Creek embayment (Cecile, 1982; Fritz et al., 1991; Turner, 2011) and to the lower part of the poorly known Bouvette Formation in the Ogilvie Platform (Morrow, 1999).

The term Duo Lake Formation was established by Cecile (1982). The Duo Lake Formation consists predominantly of graptolitic siltstone and is locally interlayered with alkalic basalt and volcaniclastic rocks of the Marmot Formation (Cecile, 1982). Graptolite biostratigraphy indicates that deposition of the Duo Lake Formation took place between Early Ordovician and late Early Silurian (Cecile, 1982). The Duo Lake Formation has a gradational lower contact with the Rabbitkettle Formation and a conformable contact with the overlying Cloudy Formation. The Duo Lake Formation is thought to be laterally equivalent to the upper part of the Franklin Mountain Formation and to shallow-water fossiliferous crystalline dolostone of the Mount Kindle Formation east of the embayment in the Mackenzie Platform. The Mount Kindle Formation disconformably overlies the Franklin Mountain Formation, and its basinward limit extended beyond that of the underlying Franklin Mountain Formation (Cecile, 1982).

The Cloudy Formation, first described by Cecile (1982), consists of lime mudstone with minor siltstone and chert. The depositional age of the Cloudy Formation is constrained by graptolites and colonial corals (near top) to the Late Ordovician to Early Silurian. This formation conformably overlies the Duo Lake Formation and is unconformably overlain in the northeast by the Lower to Middle Devonian Grizzly Bear Formation, a crinoid-grainstone-dominated unit (Cecile, 2000). The Cloudy Formation is partly laterally equivalent to the Mount Kindle Formation (Cecile, 1982).

LITHOSTRATIGRAPHY

Hess River Formation

The base of the Hess River Formation is not exposed in the study area (Fig. 2, 3). The measured section (~1370 m thick; UTM zone 9, NAD83, 403171E, 7155232N, ±10 m) starts where the lowest exposed strata outcrop in the core of an anticline in a creek; the section was measured along a creek, up a gully, and along a gentle mountain spur (Fig. 4a). The gradational upper contact of the formation with the Rabbitkettle Formation is distinguished by a subtle change in weathering colour (Fig. 4b) from medium grey-weathering (Hess River Formation) to pale grey-buff-weathering (Rabbitkettle Formation), and then to medium grey-brown-weathering lime mudstone to skeletal wackestone (Rabbitkettle Formation), and by the appearance of rare starved ripples.

The lowermost strata of the Hess River Formation at this location (unit 1: 155 m thick) consist of subtly graded, mechanically laminated (Fig. 4c), thinly bedded, 15–20 cm thick medium grey-weathering quartz-silty lime mudstone that is cleaved perpendicular to bedding (Fig. 4d). Bed bases are subtle, but sharp and are overlain by silt-grade material that conveys a subtle normal grading to each bed. Some beds contain 1–3 cm thick laminae of pale yellow-brown-weathering, very fine-grained calcareous quartz sandstone (Fig. 4e) with millimetre-scale crystals of subhedral pyrite. At 24 m there is a sharp contact with the overlying unit of medium to dark grey-weathering noncalcareous quartz siltstone (80%), calcareous siltstone (19%), and approximately 1% of very fine- to fine-grained pale orange-brown-weathering calcareous quartzose sandstone laminae (Fig. 4f). The beds of quartzose siltstone and calcareous siltstone are 10–40 cm thick, whereas the calcareous quartz sandstone laminae in these beds range between 1 mm and 50 mm thick. The gradational transition into the overlying unit is marked by an increasing amount of medium grey-weathering quartz-silty lime mudstone and calcareous siltstone and the eventual disappearance of noncalcareous quartz siltstone. Beds are 20–30 cm thick and are cleaved nearly perpendicular to bedding, obscuring sedimentary structures; but where visible, the material consists of graded parallel laminae of calcareous siltstone, very fine-grained calcareous sandstone, and silty lime mudstone. The pale orange-brown-weathering, centimetre-thick, fine-grained calcareous sandstone layers increase in abundance upward, and locally have measurable crosslamination.

A recessive interval that is dominated by black shale (unit 2: 85 m thick; Fig. 4g) consists predominantly of recessive, variably calcareous terrigenous mudstone to siltstone (30/70), with intermittent 10–15 cm thick beds of quartz-silty lime mudstone containing orange, thinly laminated pyritic and locally porous quartzose calcareous sandstone (Fig. 4h). The lower part (30 m) of the shale-dominated interval is variably calcareous, whereas the upper part (55 m) is mostly noncalcareous.

Above the shale unit (unit 2), the Hess River Formation shows little variation (unit 3: 100 m thick; unit 4: 204 m thick; unit 5: 146 m thick; unit 6: 152 m thick); it consists predominantly of repeated packages averaging 0.5–2 m thick of graded (Fig. 5a), centimetre-scale bedded, medium grey calcareous siltstone, locally noncalcareous, pale grey silty lime mudstone to rare sparsely oolitic wackestone; and fine- to medium-grained, orange-weathering millimetre- to centimetre-thick laminae of calcareous quartzose sandstone, with local crosslamination (Fig. 5b) and groove casts (Fig. 5c). The grading in individual packages results in darker coloured recessive and paler resistant layers. Rare sedimentary structures and features at this location are submillimetre-scale undulatory lamination with millimetre-scale white lime mudstone clasts, and pitted lime mudstone containing weathered millimetre- to centimetre-scale pyrite fragments. Rare fossils (sponge spicules, phosphatic brachiopods, and trilobite fragments) are present near the 650 m level in the upper half (unit 5) of section 1. Units 3 to 6 are primarily defined by variations in weathering colour, but also relative abundances of the lithofacies and sedimentary features such as grading and planar laminations.

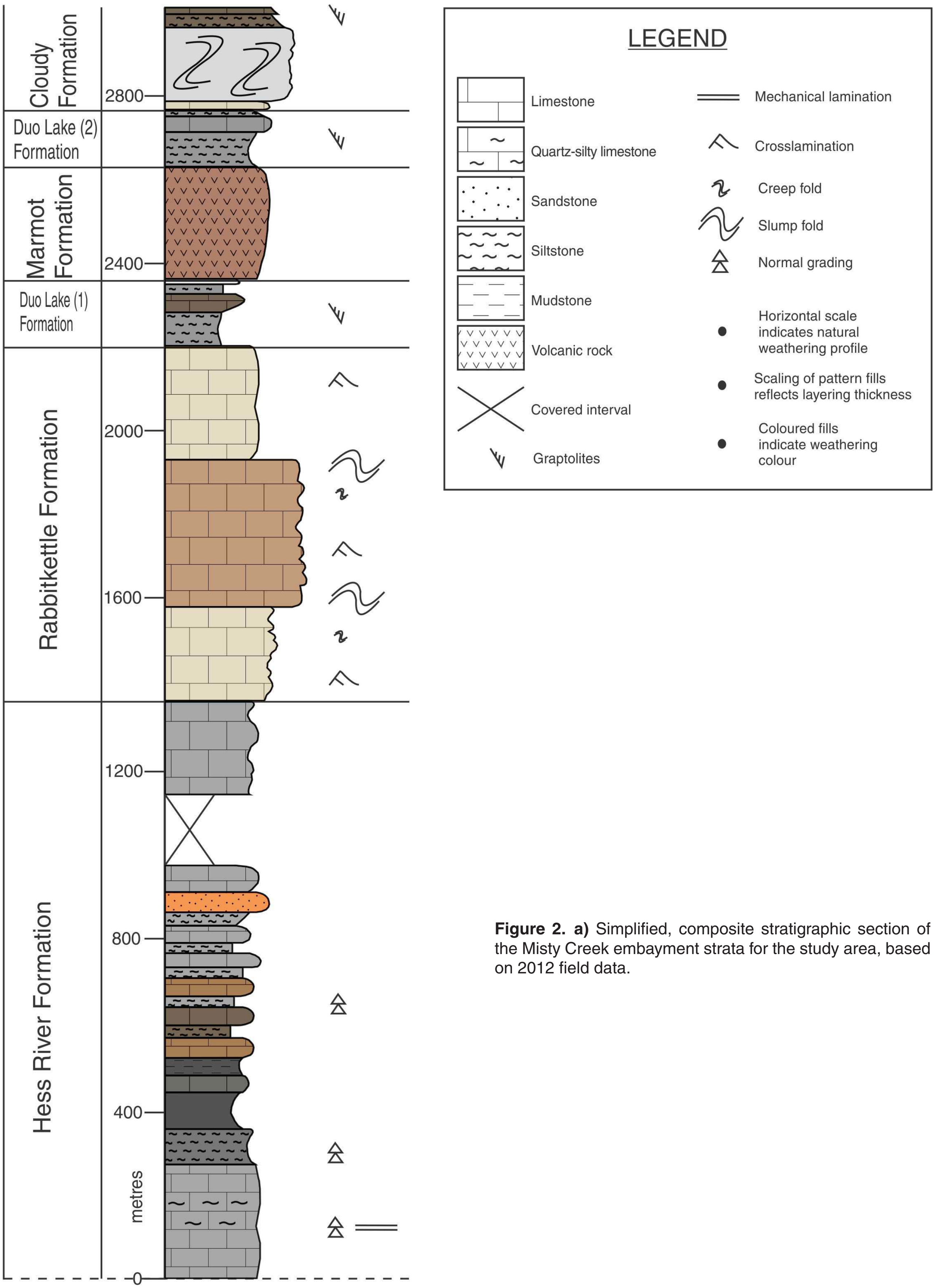


Figure 2. a) Simplified, composite stratigraphic section of the Misty Creek embayment strata for the study area, based on 2012 field data.

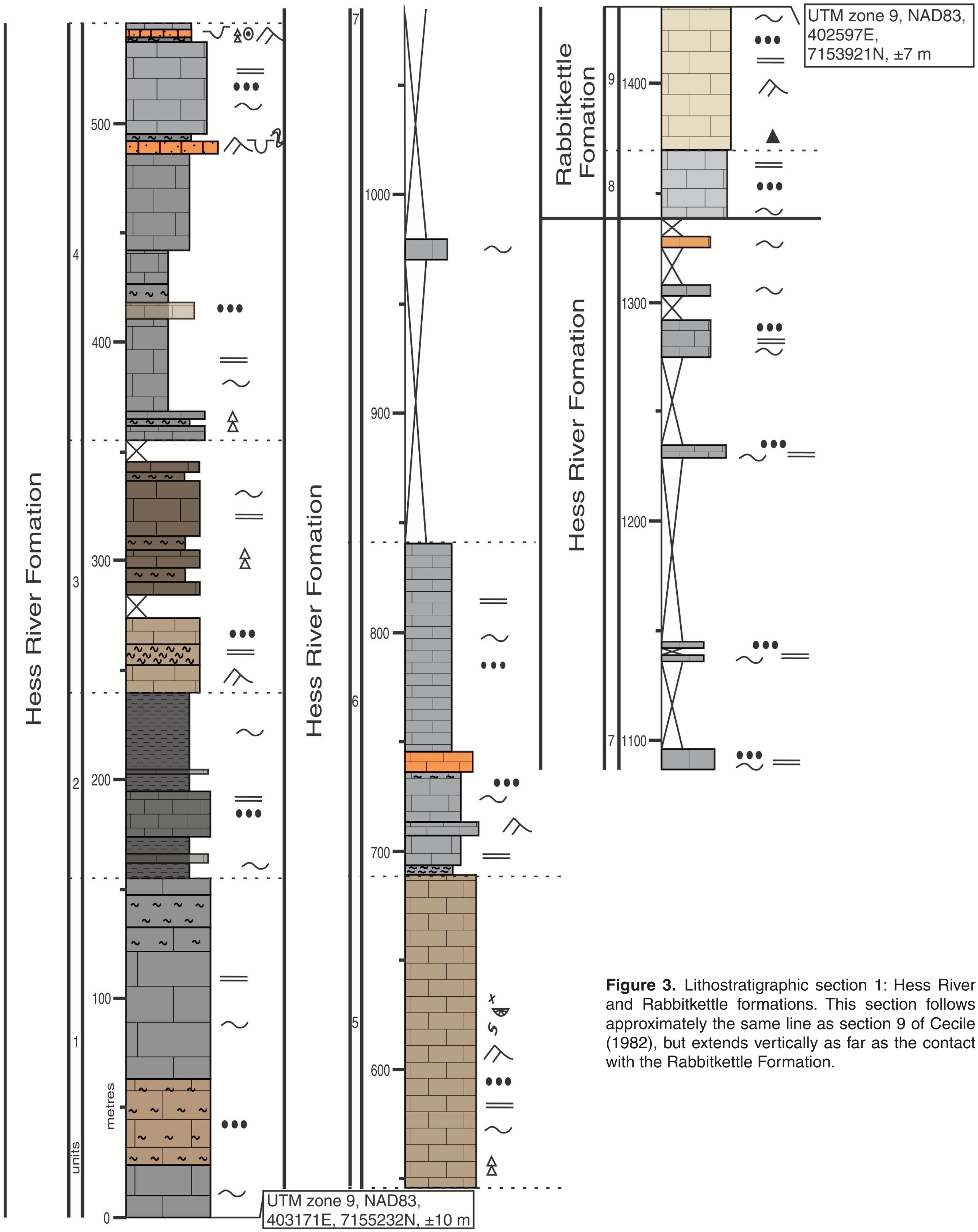
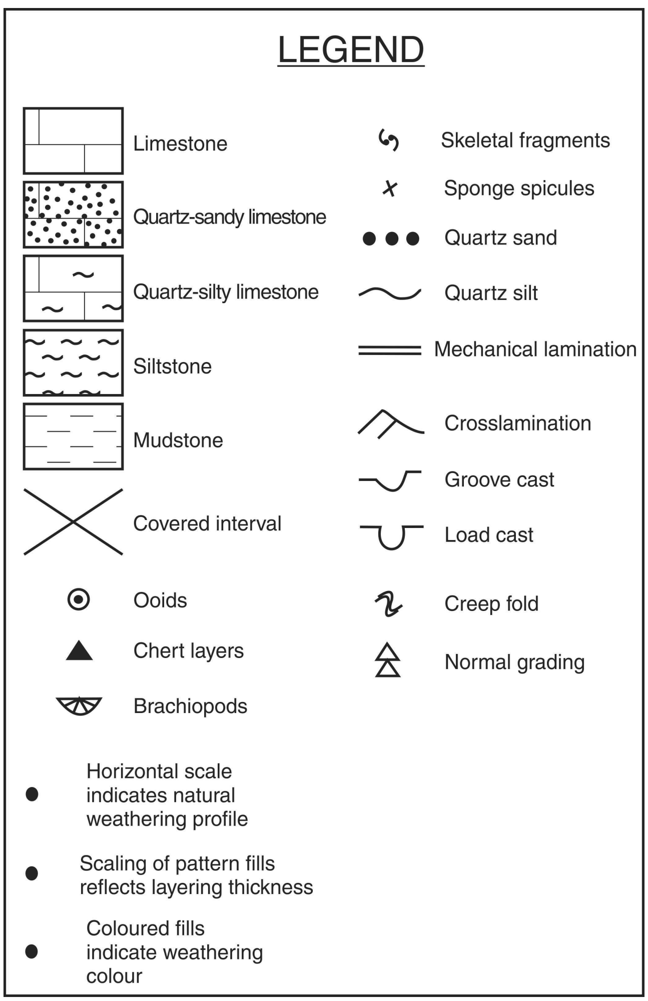


Figure 3. Lithostratigraphic section 1: Hess River and Rabbitkettle formations. This section follows approximately the same line as section 9 of Cecile (1982), but extends vertically as far as the contact with the Rabbitkettle Formation.

Unit 4 consists of two conspicuous (Fig. 5d), approximately 1–2 m thick beds of graded yellow-orange-weathering, resistant fine- to medium-grained, quartzose calcareous sandstone, with planar and crosslamination, gutter casts (Fig. 5e), load casts, and creep folds.

A broad grass-covered interval (unit 7: 499 m thick) with scattered decimetre-thick outcrops of the same lithofacies is present over an approximately 500 m thick interval in the upper part of section 1. Above this covered interval (unit 8: 33 m thick) medium grey-weathering calcareous siltstone is of diminished volumetric importance and pale grey-weathering silty lime mudstone contains centimetre-thick orange-weathering layers of fine- to medium-grained calcareous quartzose sandstone. This is a gradational unit that transitions into similar strata that are pale orange-grey-weathering and have undulatory bed contacts, grey millimetre- to centimetre-sized chert nodules and laminae (Fig. 5f) and slump and conspicuous creep folds.



Rabbitkettle Formation

The Rabbitkettle Formation is 805 m thick at the study location (Fig. 2, 6). Section 2, consisting predominantly of the Rabbitkettle (UTM zone 9, NAD83, 403608E, 7152733N, ±6 m) and Duo Lake (UTM zone 9, NAD83, 402619E, 7152471N, ±6 m) formations, was measured along a creek, in a gully, and along a mountain ridge (Fig. 7a). The lower contact with the Hess River Formation is gradational over a 25 m interval, where characteristics such as starved ripples, creep folds, and chert nodules gradually occur and become the predominant sedimentary structures. At the basal contact of the Rabbitkettle Formation (unit 2: 62 m thick) lime mudstone beds gradually become thicker and more common, siltstone laminae less common, and weathering colours change from medium grey to pale grey and buff, and then to medium orange-brown. This subtle colour change coincides with the appearance of abundant of crosslamination, combined-flow ripples, grey to black chert, millimetre-scale lime mudstone clasts, and slump and creep folds. The upper contact of the formation with the Duo Lake Formation is also gradational over approximately 10–15 m from medium brown-grey lime mudstone and quartz-silty lime mudstone into medium grey-weathering, highly fissile calcareous siltstone.

The Rabbitkettle Formation (unit 3: 201 m thick; unit 4: 297 m thick; unit 5: 198 m thick; unit 6: 24 m thick) consists of repeated lithological packages approximately 0.3–2 m thick. Each of these lithological packages are mostly resistant weathering and consist of 80–90% medium brown-grey- to pale grey-weathering centimetre-thick lime mudstone or quartz-silty lime mudstone, 5–10% pale yellow-orange- to orange-brown-weathering of fine- to medium-grained millimetre- to centimetre-thick calcareous quartzose sandstone with local crosslamination, and 0–5% medium grey-weathering millimetre-thick calcareous to noncalcareous siltstone (Fig. 7b, c, d). Graded bedding and sharp, scoured contacts are common. Unlike the graded, metre-scale recessive-resistant Hess River Formation, grading in the Rabbitkettle Formation is generally at a millimetre scale within the metre-scale recessive and resistant intervals. Undulatory bedding contacts and wavy lamination are common (Fig. 7e, f), and centimetre-sized creep folds and metre-sized slump folds are locally present (Fig. 7g, h).

In general the lithofacies of the Rabbitkettle Formation repeat monotonously throughout the thickness of the formation: centimetre-thick lime mudstone, millimetre- to centimetre-thick calcareous quartzose and fine- to medium-grained sandstone, and millimetre-thick calcareous and rarely noncalcareous siltstone. Instead of compositional variation, this formation is characterized by vertical variation in its sedimentary structures and fossils. Common features throughout the formation are crosslamination (Fig. 8a, b), climbing ripples (Fig. 8c), scours filled with combined-flow ripples or crosslamination (a form of hummocky cross-stratification; Fig. 8d), chert nodules and discontinuous

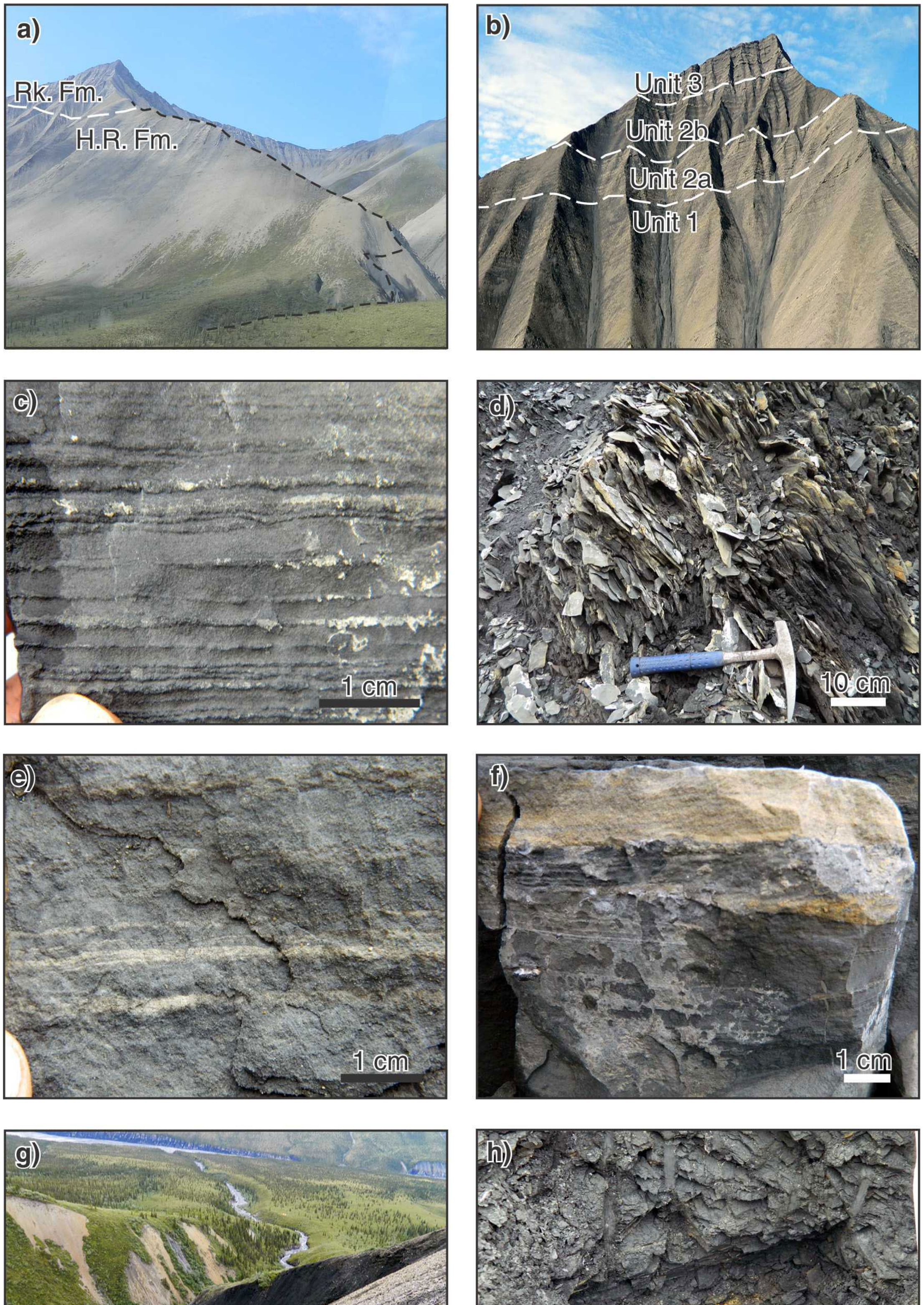

a)
Rk. Fm.
H.R. Fm.
b)
Unit 3
Unit 2b
Unit 2a
Unit 1
c)
1 cm
d)
10 cm
e)
1 cm
f)
1 cm
g)
h)
10 cm

Figure 4. Features of Hess River Formation in section 1. **a)** Outcrop photograph of section with a dotted line depicting the traverse of the measured section; stratigraphic thickness of Hess River Formation measured (dotted line) is approximately 1340 m; H.R. Fm. = Hess River Formation; Rk. Fm. = Rabbitkettle Formation; 2013-110; **b)** contact between the Hess River Formation and the Rabbitkettle Formation; marked units (1–3) are described in section 2 (*see* Fig. 6); units 2a and 2b are together approximately 70 m thick; 2013-132; **c)** (at 3.5 m) mechanically laminated medium grey-weathering quartz silty lime mudstone (3.5 m above base of section); 2013-151; thickness of black shale–dominated interval (from creek at lower left to photographers position) is 85 m; **d)** decimetre-thick beds of strongly cleaved, silty, subtly graded silty lime-mudstone are characteristic of the Hess River Formation (67 m above base of formation); 2013-138; **e)**, **f)** yellow-orange quartz-sandy laminae in dark grey limestone are another distinguishing characteristic of the Hess River Formation at the study location (2 m and 55 m above base of formation, respectively); e) 2013-154, f) 2013-111; **g)** black shale interval (85 m thick) near the base of the Hess River Formation section (base at 155 m); 2013-120; **h)** excavated exposure in the shale interval consisting of black noncalcareous mudstone with centimetre-thick lamina of orange calcareous quartzose sandstone (157 m above base of section); 2013-131. All photographs by T. Chevrier.

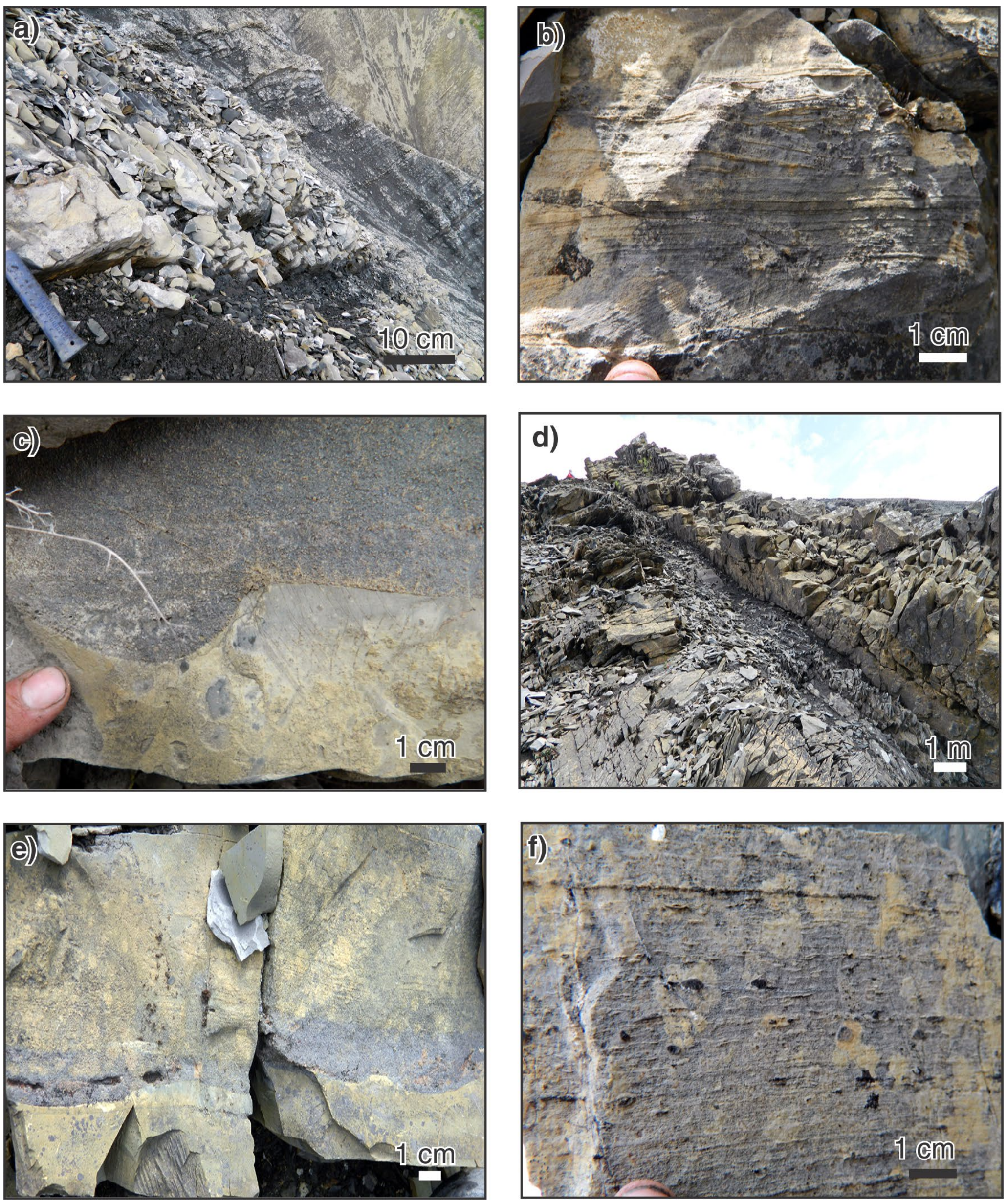


Figure 5. Features of Hess River Formation in section 1. **a)** Metre-thick packages of recessive and resistant intervals of graded lime mudstone, calcareous siltstone, and rare calcareous sandstone (270 m above base of formation); 2013-141; **b)** orange crosslaminated fine-grained calcareous quartz sandstone (465 m above base of formation); 2013-129; **c)** groove casts filled with oolitic wackestone (490 m above base of formation); 2013-140; **d)** one of the two conspicuous 2 m thick intervals of very resistant quartzose calcareous sandstone (490 m above base of section); 2013-113; **e)** gutter casts (530 m above base of section); 2013-116; **f)** pale grey-buff-weathering silty lime mudstone with wavy cherty lamination in basal unit of the Rabbitkettle Formation in section 1; 2013-117. All photographs by T. Chevrier.

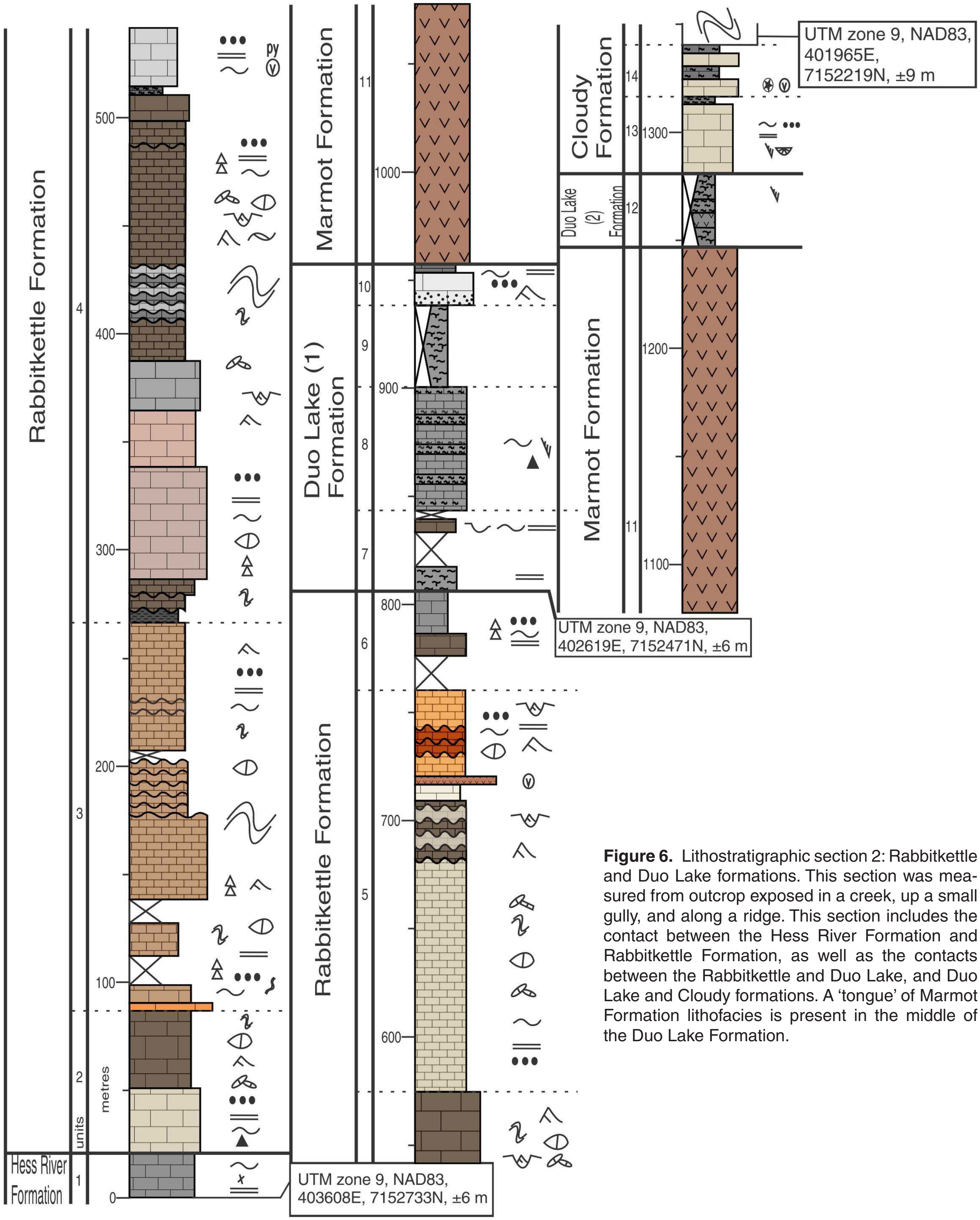
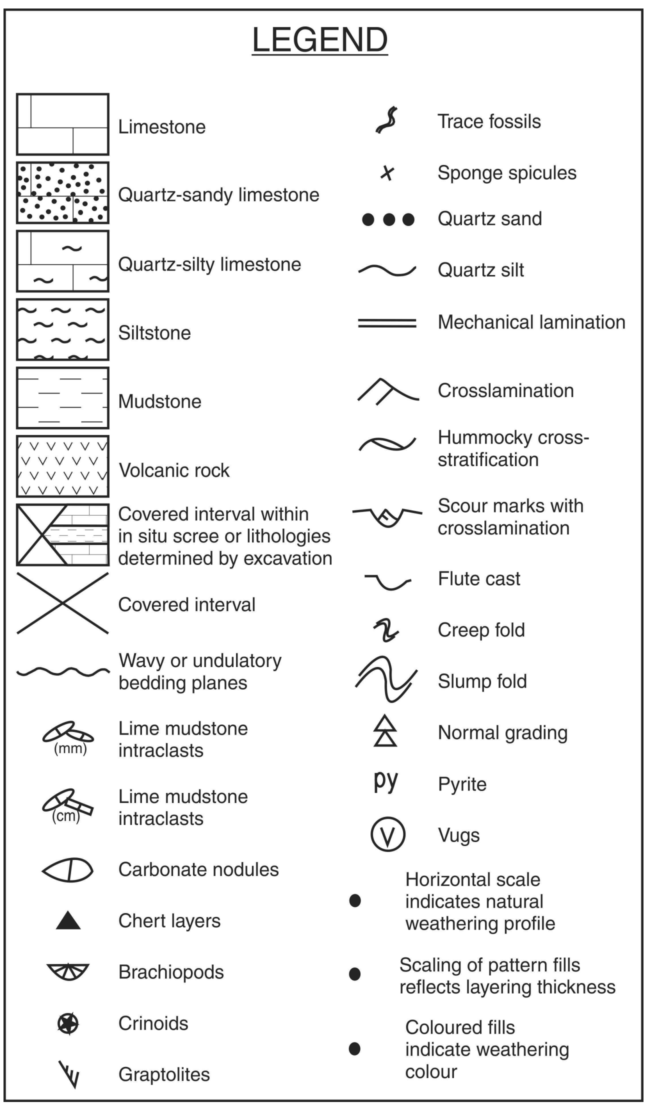


Figure 6. Lithostratigraphic section 2: Rabbitkettle and Duo Lake formations. This section was measured from outcrop exposed in a creek, up a small gully, and along a ridge. This section includes the contact between the Hess River Formation and Rabbitkettle Formation, as well as the contacts between the Rabbitkettle and Duo Lake, and Duo Lake and Cloudy formations. A 'tongue' of Marmot Formation lithofacies is present in the middle of the Duo Lake Formation.

chert laminae (Fig. 8e), limestone nodules (Fig. 8f), and lime mudstone intraclasts (Fig. 8g). Pyrite nodules; dewatering structures (Fig. 8h); and centimetre-sized, subrounded, lime mudstone intraclasts (Fig. 9a) are locally present. Bedding-plane burrows (Fig. 9b) are common near the base of the section and both bedding-plane and infaunal burrows are sparse throughout the 400 m to 500 m interval of the Rabbitkettle Formation section. One possible crinoid ossicle was found near the 800 m interval at section 2. Also not measured in section, but noted while on traverse was an approximately 2 m wide and 1 m thick laterally discontinuous sharp-based channel containing centimetre-sized, angular, lime mudstone intraclasts (Fig. 9c, d).



Duo Lake Formation

The Duo Lake Formation is approximately 220 m thick (Fig. 2, 6) at the study location (UTM zone 9, NAD83, 402619E, 7152471N, ±6 m), but at this location the formation is interrupted by a "tongue" of Marmot Formation lithofacies (295 m thick). The Marmot Formation consists of dark brown- and grey-weathering massive amygdaloidal (Fig. 10a) and vesicular flows to bedded fine- to medium-grained lapilli tuff, sandstone, and siltstone, with planar and rare crosslamination (Fig. 10b; Cecile (1982)); the Marmot Formation is not addressed by this study. The 220 m of Duo Lake Formation strata refers only to the nonvolcanic material that underlies and overlies the Marmot Formation and was assigned to the Duo Lake Formation based on its characteristic graptolitic quartzose siltstone and shale as described and defined by Cecile (1982).

The lower contact of the Duo Lake Formation with the Rabbitkettle Formation is gradational over approximately a 10 m interval, with an upward increase in noncalcareous quartzose siltstone and decrease to zero in the abundance of lime mudstone intervals. The upper contact of the Duo Lake Formation with the Cloudy Formation is marked by a weathering change from medium grey to pale grey and the gradual disappearance of graptolitic calcareous siltstone and quartz-silty lime mudstone, and the appearance of interbedded crinoid wackestone with fragments of coral and calcareous mudstone to siltstone.

The base (unit 7: 33 m thick) of the Duo Lake Formation is poorly exposed. It consists of slightly cleaved centimetre-sized beds of weakly calcareous to noncalcareous quartzose siltstone with faint centimetre-thick planar laminae (Fig. 10c). The well exposed overlying interval (unit 8; 61 m thick) consists of medium grey-weathering with sparse rusty-weathering of thinly bedded mostly noncalcareous quartzose siltstone interbedded with sparse 10–30 cm thick beds of pale grey-weathering lime mudstone (Fig. 10d). Graptolites (Fig. 10e) are abundant in this interval. The overlying, poorly exposed interval (unit 9; 36 m thick) consists of calcareous siltstone and is succeeded by (unit 10; 29 m thick) a resistant pale grey-weathering quartz-sandy lime mudstone (Fig. 10f) with thin planar and rare ripple crosslaminae. The upper part of unit 10 is a gradational unit consisting of quartz-silty lime mudstone interbedded with centimetre-thick beds of variably calcareous quartz siltstone, with very rare graptolites.

The second Duo Lake Formation interval (unit 11: 281 m thick) has a covered lower contact with the Marmot Formation tongue and an upper gradational contact with the Cloudy Formation. The base (unit 12; 34 m thick) is very poorly exposed, calcareous siltstone (identified by excavating to outcrop) with very rare graptolites and a thin green-grey tuff interval near the base. Unit 13 (56 m thick) is a pale grey-yellow-weathering interval of 30–50 cm thick

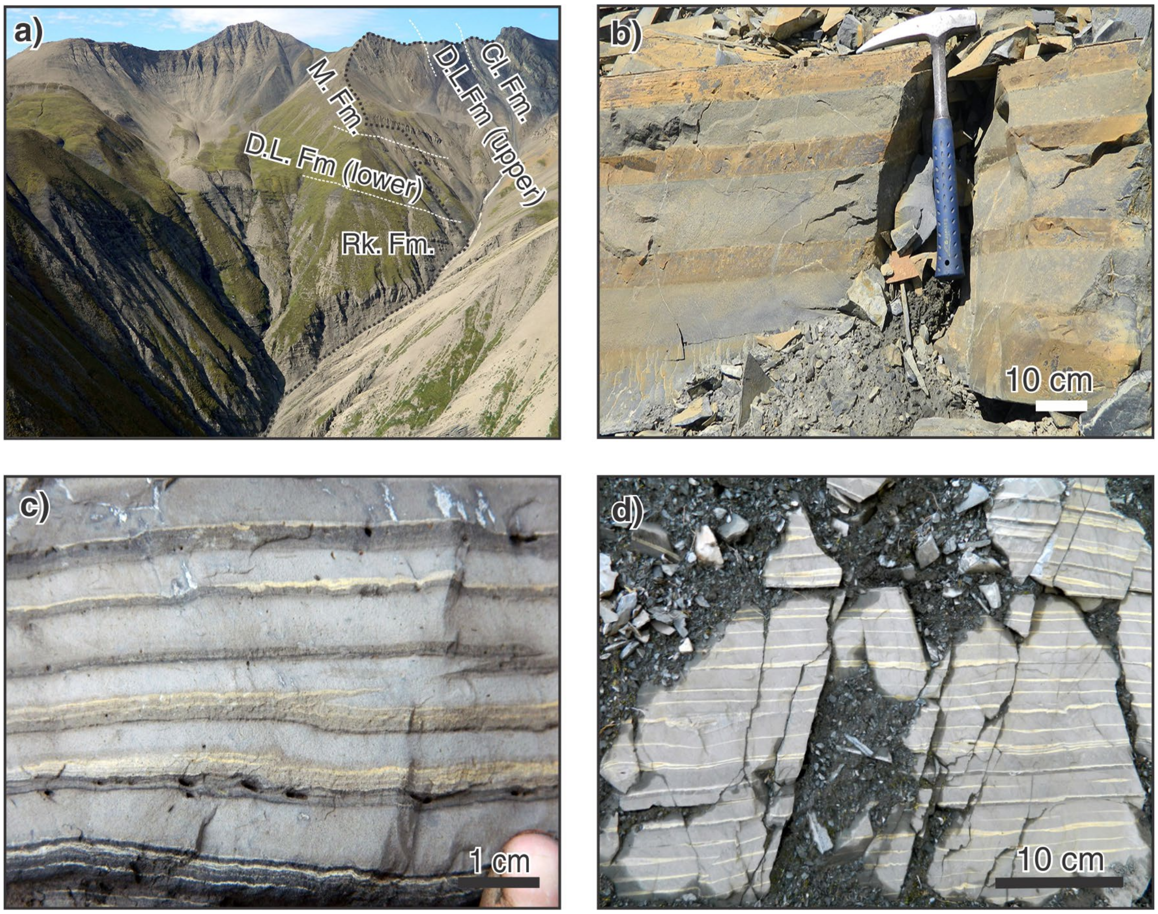


Figure 7. Features of Rabbitkettle Formation in section 2. **a)** Outcrop photograph of section 2 with a dotted line depicting the traverse of the measured section; topographic differential between creek at base of photograph and skyline in upper right is approximately 500 m; Rk. Fm. = Rabbitkettle Formation, M. Fm. = Marmot Formation, D.L. Fm. = Duo Lake Formation, and Cl. Fm. = Cloudy Formation; 2013-119; **b)** layers of alternating medium grey-brown-weathering lime mudstone and orange-brown-weathering calcareous quartz sandstone (100 m above base of section); 2013-144; **c)**, **d)** centimetre-sized graded beds of lime mudstone, calcareous siltstone, and calcareous quartzose to calcareous sandstone (335 m and 531 m above section base, respectively); c) 2013-149; d) 2013-142. All photographs by T. Chevrier.

Figure 7. (cont.) Features of Rabbitkettle Formation in section 2. **e)** undulatory bed contacts are probably the result of semilithified beds sliding down a topographic gradient (427 m above section base); 2013-137; **f)** orange-weathering, calcareous, wavy-laminated sandstone, with organic-rich lime mudstone clasts (353 m above section base); 2013-152; **g)** creep fold reflects intrastratal deformation of semi-indurated carbonate layers (381 m above section base); 2013-139; **h)** metre-scale slump fold (outlined by dashed line; 161 m above section base); 2013-146. All photographs by T. Chevrier.

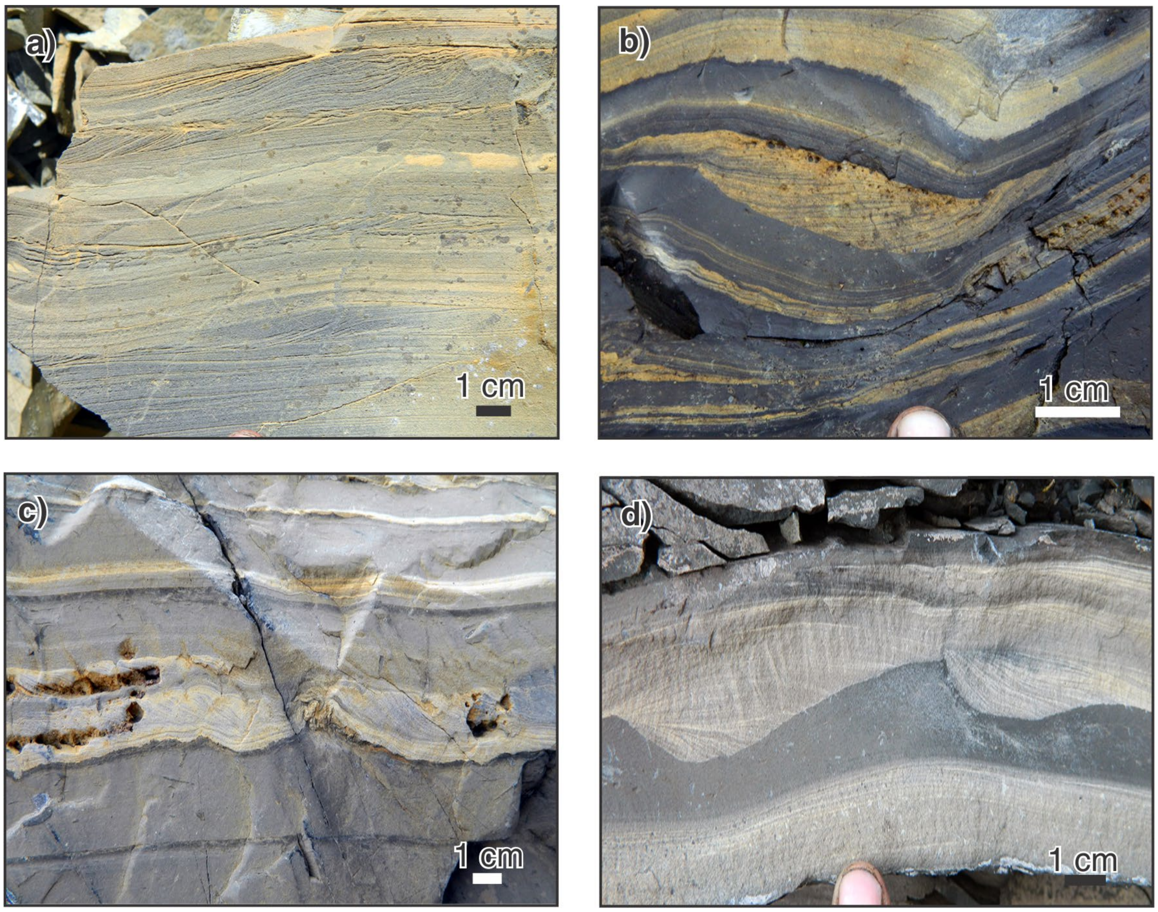


Figure 8. Features of Rabbitkettle Formation in section 2. **a)** Crossripple lamination (112 m above section base); 2013-121; **b)** crosslamination and laminated calcareous sandstone in lime mudstone (394 m above section base); 2013-118; **c)** climbing-ripple crosslamination and pyrite-filled vugs (478 m above section base); 2013-130; **d)** interbedded fine-grained, crosslaminated sandstone and thinly bedded silty limestone with sandstone-filled scours (498 m above section base); 2013-114. All photographs by T. Chevrier.

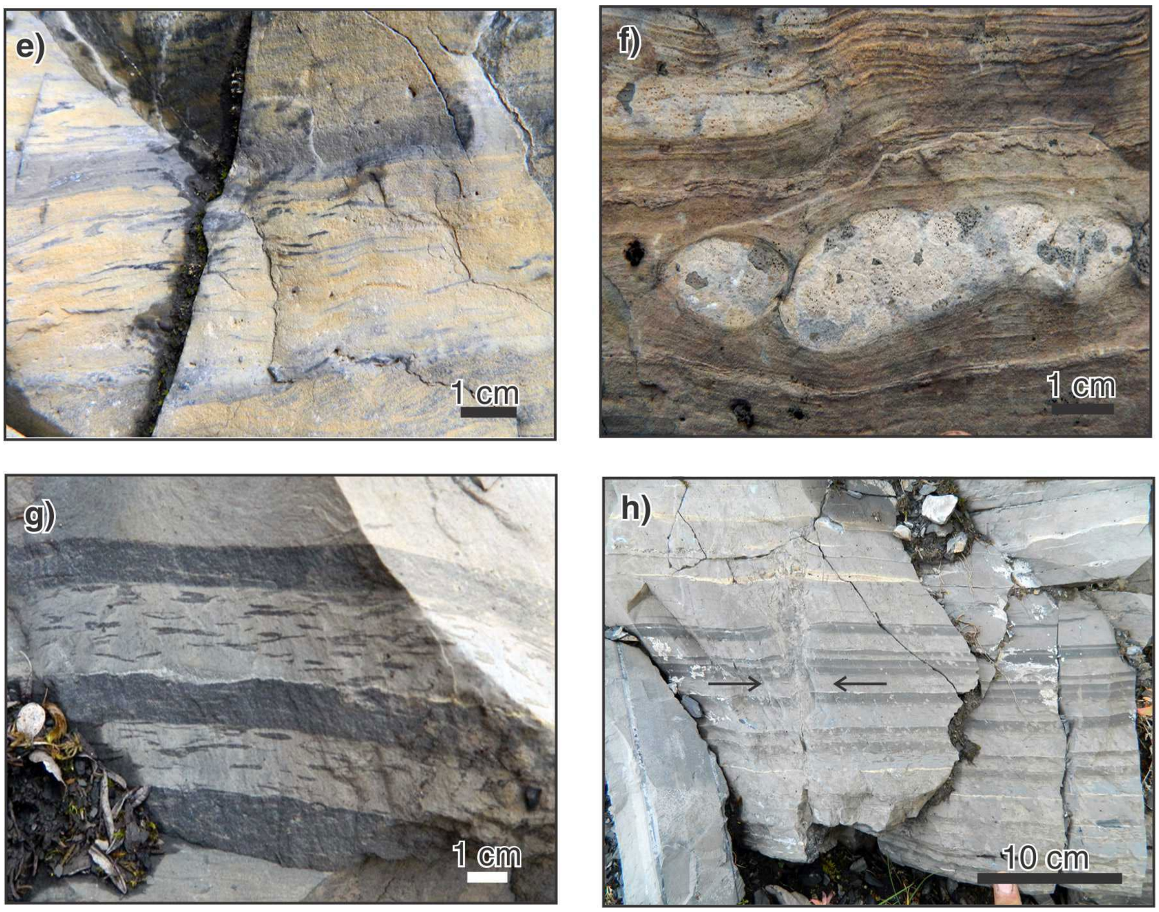


Figure 8. (cont.) Features of Rabbitkettle Formation in section 2. **e)** Black chert laminae (162 m above section base); 2013-126; **f)** lime mudstone nodules (322 m above section base); 2013-135; **g)** millimetre-sized organic-rich lime mudstone intraclasts in a lime mudstone interval (474 m above section base); 2013-150; **h)** dewatering structure (526 m above section base); 2013-124. All photographs by T. Chevrier.

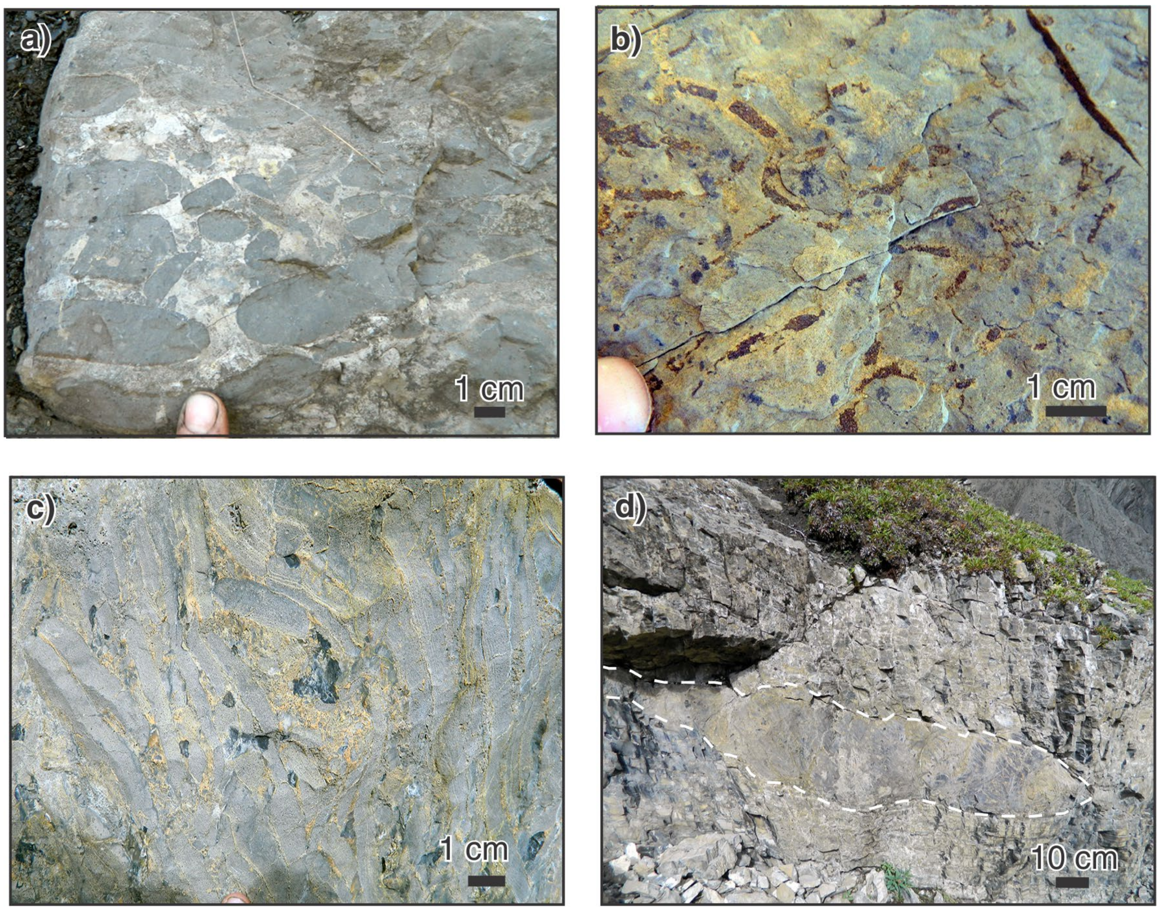


Figure 9. Features of Rabbitkettle Formation in section 2. **a)** Centimetre-sized subrounded lime mudstone intraclasts (675 m above section base); 2013-112; **b)** bedding-plane burrows (113 m above section base); 2013-145; **c)** centimetre-thick and decimetre-long, subangular to subrounded lime mudstone intraclasts in channel outlined in Figure 9d; 2013-123; **d)** a 2 m wide, approximately 1 m thick channel with a sharp basal contact filled with lime mudstone intraclasts and a calcareous sandstone matrix; 2013-115. All photographs by T. Chevrier.

Figure 10. Features of Marmot and Duo Lake formations in section 2. **a)** Vesicular flow of the Marmot Formation; 2013-125; **b)** lapilli tuff and planar-laminated siltstone of the Marmot Formation; 2013-148; **c)** the Duo Lake Formation is distinguished by its dark grey-weathering, variably calcareous quartzose siltstone with very faint lamination, and an abundance of graptolites (824 m above section base); 2013-122; **d)** thinly bedded, medium grey- and rust-weathering, variably calcareous siltstone, with an approximately 30 cm thick interval of pale grey-weathering lime mudstone (859 m above section base); 2013-147; **e)** graptolites in unit 8 (880 m above section base); 2013-134; **f)** an approximately 2 m thick interval of medium grey-weathering quartz-sandy lime mudstone (936 m above section base); 2013-133. All photographs by T. Chevrier.

beds of lime mudstone with abundant graptolites and rare brachiopods, followed by another poorly exposed interval of calcareous siltstone with abundant graptolites.

Cloudy Formation

Approximately 200 m of the Cloudy Formation (Fig. 2, 11), measured as section, was described mostly in a gully (Fig. 12a) at this study location (UTM zone 9, NAD83, 402250E, 7152679N, ±6 m); it is not well exposed. The basal contact of the Cloudy Formation was placed by Cecile (1982) where interbedded lime mudstone (unit 2 of Fig. 11: 14 m thick) and laterally discontinuous crinoid wackestone (unit 14 of Fig. 6; 20 m thick; and Fig. 12b) overlie graptolite-bearing calcareous siltstone and quartz-silty lime mudstone of the underlying Duo Lake Formation. This interval is overlain by medium grey-weathering 60–80 cm thick beds of lime mudstone (unit 3; 175 m thick), with dark grey to black centimetre-thick chert beds (Fig. 12c) that are highly contorted at scale of tens of metres (Fig. 12d). Cloudy Formation strata above this interval of folded strata (unit 4; 38 m thick) consist of thinly bedded quartz siltstone, chert, and sparse lime mudstone layers. This upper part of the Cloudy Formation contains sparse graptolites.

INTERPRETATIONS

Hess River Formation

The Hess River Formation is distinguished from the other deep-water lower Paleozoic units in the study area by the following attributes: its medium to dark grey weathering colour, the presence of alternating recessive and resistant packages, and the dearth and monotony of the sedimentary structures (weak grading; mechanical lamination, rare cross-lamination) as compared to superficially similar strata of the Rabbitkettle Formation. Another conspicuous characteristic is the ubiquity of centimetric to decimetric, subtly graded, sharp-based beds of quartz-silty lime mudstone. The

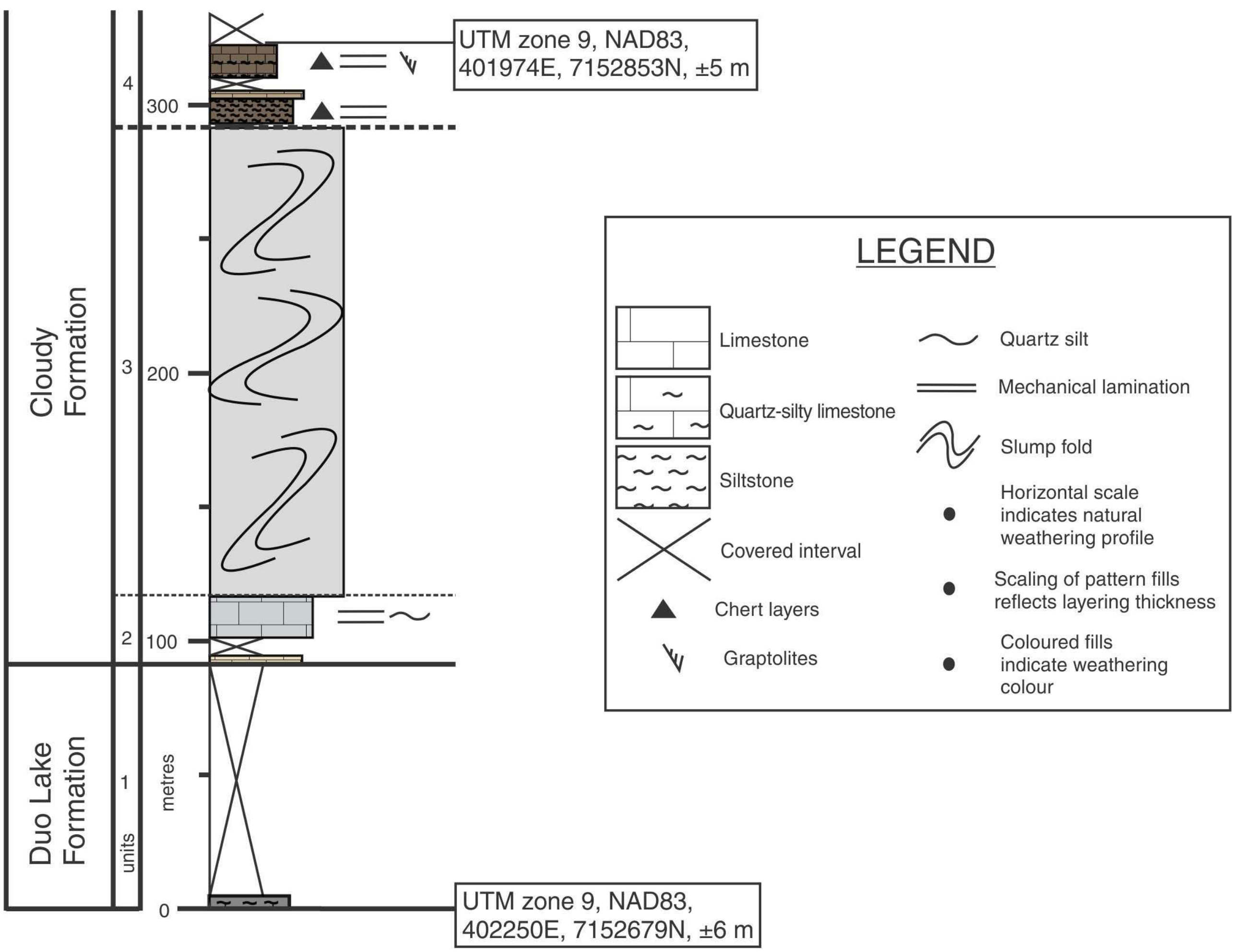


Figure 11. Lithostratigraphic section 3: Cloudy Formation. This section includes the lower contact with the Duo Lake Formation. The thickness of the olistostrome was measured using the last measured structural orientation of underlying strata.

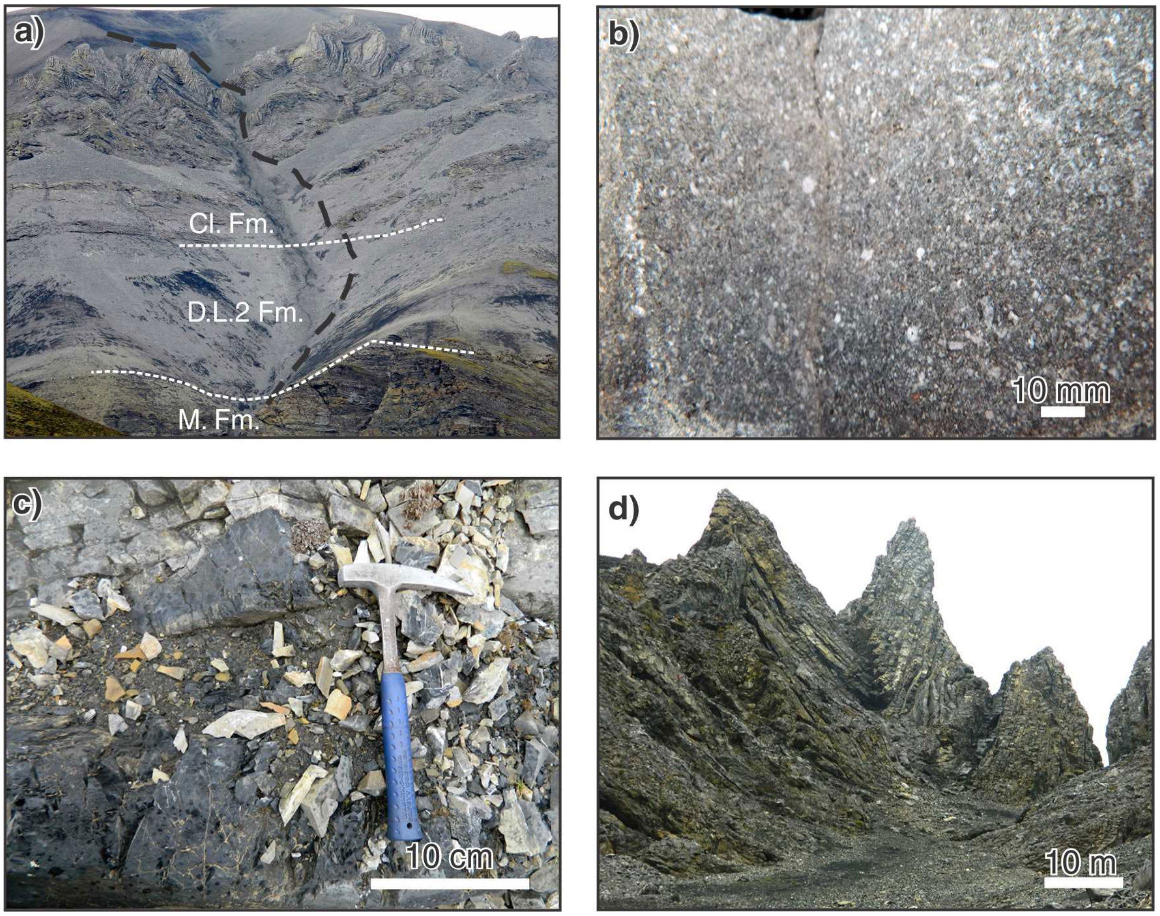


Figure 12. Features of Cloudy Formation in section 3. **a)** Outcrop photograph of section 3 with a dotted line depicting the traverse of the measured section; topographic differential between creek at base of photograph and skyline in upper right is approximately 500 m; M. Fm. = Marmot Formation, D.L.2 Fm. = upper Duo Lake Formation, Cl. Fm. = Cloudy Formation; 2013-143; **b)** laterally discontinuous crinoid wackestone in the Cloudy Formation above the Duo Lake Formation in Figure 6 (section 2), but absent at the contact in Figure 11 (section 3). 2013-128; **c)** black chert bed and lime mudstone bed in the folded unit of the Cloudy Formation (225 m above section base); 2013-136; **d)** part of the olistostrome (unit 3), showing the folded and overturned beds of the Cloudy Formation; the exposure of the olistostrome is approximately 15 km in areal extent; 2013-127. All photographs by T. Chevrier.

formation is in general quite consistent in its compositional and textural characteristics, with the exception of the black shale interval and the calcareous quartzose sandstone marker beds.

These alternating recessive and resistant beds, along with sedimentary structures such as grading, crosslamination, and rare groove casts, indicate that the Hess River Formation is a succession of fine-grained carbonate turbidite units (Playton et al., 2010). The absence of coarse, redeposited carbonate clasts indicates that the sediment was not lithified on the seafloor. The dearth of thicker turbidite beds suggests that the slope had a very low angle (Playton et al., 2010), such that the turbidite beds, once deposited, were stable. The presence of quartzose sandstone laminae in the faintly graded carbonate mudstone is compatible with proximity to the quartz sandstone-dominated “flysch” unit in the “axial” depositional zone of the Hess River Formation (Cecile, 1982). The shallow-water equivalent of the Hess River Formation that must have supplied the carbonate material to the deep-water basin is no longer preserved, and other lower Paleozoic shallow-water strata surrounding the embayment are not known to contain significant quartzose material. The source of the quartz-sandy component of the Hess River Formation remains unclear, although Cecile (1982) suggested that it was derived from a source to the present-day northwest.

Rabbitkettle Formation

The Rabbitkettle Formation is distinguishable from a distance from other formations by its thick bedding (layers typically 1 m thick) as well as its metre-scale slump folds. It consists of pale grey- to buff-weathering, graded, laminated to thinly bedded calcareous siltstone, quartzose sandstone, and lime mudstone. Sedimentary structures such as cross-lamination, creep folds, scours, nodules, and organic-rich mudstone clasts are common in the Rabbitkettle Formation, and distinguish it from the superficially similar Hess River Formation.

The abundance of slump folds and creep folds in the Rabbitkettle Formation indicate that, at section 2 of this study location, strata were deposited on a semiconsolidated slope (Playton et al., 2010), but the presence of hummocky cross-stratification indicates that storm-wave oscillation episodically reached the seafloor. Scour marks and graded carbonate packages lacking shallow-water indicators indicate deposition from turbidity currents (Playton et al., 2010). The seafloor setting for the Rabbitkettle Formation appears to have been both shallower (at least episodically above storm wave base) and more steeply inclined than that of the underlying Hess River Formation.

Duo Lake Formation

The Duo Lake Formation is dominated by thinly bedded, variably calcareous graptolitic siltstone that makes it easy to distinguish from underlying formations. The formation is not well exposed at this location and a significant proportion of it could not be described because of the presence of thick scree cover.

The variably calcareous siltstone, scarcity of limestone and sandstone, lack of sedimentary structures such as subtle grading, crosslamination, or bioturbation, and presence of graptolites indicate deposition in a level-bottom, deep-water area that was probably poorly oxygenated. The gradational change (unit 13) between the Duo Lake Formation and the Cloudy Formation, marked by an increase in carbonate toward a unit consisting of abundant crinoid ossicles and other skeletal fragments in the Cloudy Formation (unit 14) may record a transition into a relatively shallower environment.

Cloudy Formation

The chaotically folded and overturned beds (Fig. 12d) in unit 3 of section 3, sandwiched between similar units that are completely unaffected by folding indicate that unit 3 was syndepositionally folded; it was interpreted as an olistostrome by Cecile (1982). The sediment layers are not brecciated or cracked, and so were not fully lithified when they failed gravitationally and came to rest at a location with a lower slope angle. The olistostrome in the Cloudy Formation at the study location indicates deposition on or near a slope with a significant gradient. The carbonate-dominated composition of the olistostromal strata implies that the area upslope of the study location was probably closer to the contemporaneous shelf environment, but no structural features in the olistostrome or elsewhere in the formation clearly indicate the orientation of this slope. The uppermost 30 m of the Cloudy Formation at this study location (section 3, unit 4; nonolistostromal strata), resemble the Duo Lake Formation; it consists predominantly of noncalcareous quartzose siltstone with rare lime mudstone beds and graptolites, and is interpreted as a level basin-floor facies that may have been situated below the carbonate compensation depth.

CONCLUSIONS

Lower Paleozoic strata at the study location are deep-water carbonate facies that were deposited in a basin that exhibited a succession of subtly distinct environments and sediment types, and conspicuously different seafloor configurations. Based on the lithostratigraphic data collected in this study and the results of previous research (Cecile, 1982), the Misty Creek embayment at the study location was at some time (during late Cambrian to Ordovician) a slope and at another time a deep-water (during Ordovician to Silurian), level-bottom environment. The four Misty Creek embayment deep-water formations can be summarized as follows. 1) The Hess River Formation was deposited on a subtle slope and contains fine-grained calcareous turbidite units. Laminae of quartzose, calcareous sand may be related to the fringes of the axial zone of quartzose “flysch” of the embayment, as reported in Cecile (1982). 2) The Rabbitkettle Formation was deposited on a slope, as indicated by the presence of metre-scale slump folds and centimetre-scale creep folds. There is also evidence suggesting storm activity (hummocky cross-stratification), which indicates that this formation was deposited at least intermittently above storm wave base. 3) The Duo Lake Formation appears to have been deposited onto a seafloor with no significant topographic gradient that may have been anoxic and below the carbonate compensation depth. 4) The Cloudy Formation contains both level-bottom indicators (noncalcareous siltstone with no sedimentary structures) and evidence of a nearby slope (olistostrome). The basinal environment of the Misty Creek embayment was clearly tectonically unstable during the lower Paleozoic.

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