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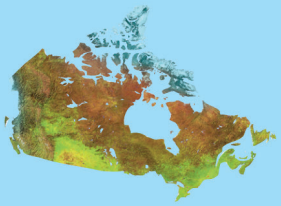

New data from Late Ordovician–Early Silurian Mount Kindle Formation measured sections, Franklin Mountains and eastern Mackenzie Mountains, Northwest Territories

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Geological Survey of Canada
Current Research 2013-8

2013

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ISSN 1701-4387
Catalogue No. M44-2013/8E-PDF
ISBN 978-1-100-21943-1
doi:10.4095/292389

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Recommended citation

Pope, M.C. and Leslie, S.A., 2013. New data from Late Ordovician–Early Silurian Mount Kindle Formation measured sections, Franklin Mountains and eastern Mackenzie Mountains, Northwest Territories; Geological Survey of Canada, Current Research 2013-8, 11 p. doi:10.4095/292389

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Correction date:

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Abstract : Four measured sections of the Late Ordovician–Early Silurian Mount Kindle Formation near Norman Wells, Northwest Territories indicate this unit was deposited on a shallowly dipping carbonate ramp that was subsequently dolomitized. The most shoreward facies are tidal flats that pass basinward into skeletal packstone-grainstone deposited on the ramp crest. Basinward of the ramp crest are burrowed skeletal wackestone-packstone passing downramp into skeletal wackestone or mudstone with nodular chert. The abundance of macrofauna (corals, stromatoporoids, brachiopods, bryozoans, sponges, and crinoids) in this unit indicates that it formed in warm water. The majority of the macrofauna was silicified postdepositionally. Preliminary conodont analysis indicates the base of the Mount Kindle Formation is Late Ordovician (Katian). There is a marked faunal change at a lithological break between shallow-water open-marine skeletal packstone and overlying cherty skeletal mudstone interpreted to be the Ordovician–Silurian unconformity that subdivides the Mount Kindle Formation into two separate sequences.

Résumé : Quatre coupes mesurées de la Formation de Mount Kindle de l'Ordovicien tardif-Silurien précoce, à proximité de Norman Wells dans les Territoires du Nord-Ouest, indiquent que cette unité s'est formée sur une rampe carbonatée faiblement inclinée et a ensuite été dolomitisée. Les faciès les plus proches du rivage correspondent à des dépôts d'estran tidal qui passent, vers l'intérieur du bassin, à des packstones/grainstones à bioclastes formés sur la crête de la rampe. Côté bassin de la crête de la rampe, on trouve des wackestones/packstones à bioclastes criblés de terriers, qui passent vers le bas de la rampe à des wackestones ou mudstones à bioclastes et à nodules de chert. L'abondance de la macrofaune (coraux, stromatopores, brachiopodes, bryozoaires, spongiaires et crinoïdes) dans cette unité indique qu'elle s'est formée dans des eaux chaudes. La majeure partie de la macrofaune a été silicifiée après la sédimentation. Une analyse préliminaire des conodontes indique que la base de la Formation de Mount Kindle est de l'Ordovicien tardif (Katien). On observe un changement marqué de la faune au niveau d'une discontinuité lithologique entre les packstones bioclastiques de milieu marin peu profond à circulation libre et les mudstones bioclastiques cherteux sus-jacents, que nous interprétons être la discordance de l'Ordovicien–Silurien qui divise la Formation de Mount Kindle en deux séquences distinctes.

INTRODUCTION

The Late Ordovician–Early Silurian Mount Kindle Formation was deposited across a broad area of the Northwest Territories and neighbouring Mackenzie Mountains. Though this unit commonly is relatively thin, it is an important mapping unit because of its abundant macrofauna, and its occurrence between commonly unfossiliferous Cambrian and Devonian rocks. During the 2011 field season four stratigraphic sections of the Late Ordovician–Early Silurian Mount Kindle Formation were measured from Norman Wells, Northwest Territories (Fig. 1) as part of the Mackenzie Delta Corridor Project (Geo-mapping for Energy and Minerals (GEM) Program). The sections were measured at Donnelly River, Dodo Canyon, near the Keele River, and along the Little Bear River. This report describes the first three sections briefly and focuses on the Little Bear River measured section, as it was the most thoroughly documented section, being collected for both conodont biostratigraphy, at 5–10 m intervals, and for stable isotope (C, O) chemostratigraphy at 1 m intervals. The additional three sections were measured, described, and sampled for conodont biostratigraphy. The section at Dodo Canyon is unique in that a thin bed of quartz arenite occurs disconformably between the underlying Franklin Mountain Formation and the basal Mount Kindle Formation.

REGIONAL TECTONOSTRATIGRAPHIC CONTEXT

The Late Ordovician–Early Silurian rocks of the Mackenzie and Franklin Mountains, Northwest Territories were deposited on a passive continental margin during the basal portion of the Sauk megasequence (Sloss, 1963). The biostratigraphic framework for these strata is provided by numerous workers utilizing primarily brachiopods and conodonts (Ludvigsen, 1975, 1982; Barnes et al., 1976; Tipnis et al., 1978; Lenz and McCracken, 1982; Lenz and Chen, 1985; Mitchell and Sweet, 1989). These studies indicate the Late Ordovician rocks in this area were deposited during the Katian, (Chatfieldian to Cincinnatian stages) and that the very latest Ordovician (Hirnantian stage) locally is missing (Lenz, 1982). Silurian rocks were deposited during the Llandoverian stage of the Early Silurian based on brachiopods and corals (Norford and Macqueen, 1975). Paleomagnetic reconstructions suggest the passive margin in this area was positioned between 0–10°N latitude and aligned approximately north-south (Witzke, 1990; Scotese and McKerrow, 1990; Mac Niocaill et al., 1997).

The Mount Kindle Formation unconformably overlies the Late Cambrian–Early Ordovician Franklin Mountain Formation and commonly is unconformably overlain by the

Figure 1. Google Earth™ map of Franklin Mountains, Northwest Territories. Mount Kindle measured sections (Donnelly River, Dodo Canyon, Little Bear River, and Keele River) are indicated by white balloons.

Devonian Bear Lake Formation. Locally, toward the west, the Middle–Late Silurian Tsetzo Formation overlies the Mount Kindle Formation. Coeval Ordovician-Silurian units are deposited discontinuously along the Lower Paleozoic continental margin that stretches from Alaska and northern Canada into the southern Great Basin (e.g. Sloss, 1988; Cecile and Norford, 1993; Harris et al., 1995).

The unconformity between the Late Ordovician strata and underlying Late Cambrian–Early Ordovician strata commonly is a pronounced sharp surface in outcrops throughout the area (Cecile et al., 1997) that may locally host solution-collapse caves (e.g. Roots et al., 2011). The Late Ordovician–Early Silurian boundary occurs within the Mount Kindle Formation and commonly it is a disconformity that is very difficult to determine in the field (Lenz, 1976). The disconformity is marked by a change in rock type with deeper water facies overlying shallower water facies, and a distinctive change in conodont faunas.

CORRELATION OF THE MOUNT KINDLE FORMATION

Late Ordovician–Silurian strata in the Mackenzie Mountains (Fig. 2) are about 150–300 m thick and formed a gently sloping ramp on the passive margin that locally passed westward into the Misty Creek embayment, an intraramp extensional basin (Cecile, 1982; Cecile et al., 1997). The Late Ordovician strata in the area are subdivided into three distinct geographically separate units. The easternmost unit, the Late Ordovician to Silurian Mount Kindle Formation, is pervasively dolomitized and contains both subtidal and peritidal facies deposited unconformably on the Late Cambrian–Early Ordovician Franklin Mountain Formation (Lenz, 1982). The typical lower part (Late Ordovician) of the Mount Kindle Formation is a dark weathering, thick-bedded to massive, bioturbated subtidal skeletal dolowacke-packstone with rare chert beds or nodules (Cecile et al., 1997). The upper part of consists of light coloured, thinly bedded, cryptalgally laminated dolomudstone. The Late Ordovician to Silurian Mount Kindle Formation interfingers with the Whittaker Formation in the Mackenzie Mountains. The lower portion of the Whittaker Formation in its easterly outcrops consists of subtidal to intertidal dark grey-weathering bioturbated skeletal dolowacke-packstone that passes westward into intercalated dark brown-grey, thin-bedded limestone and chert of the Road River Group. Within the Misty Creek embayment the Late Ordovician portion of the Mount Kindle or Whittaker formations pass basinward into interbedded shale and limestone of the Duo Lake or Cloudy formations (Cecile, 1982). Mafic-felsic volcanic rocks of the Marmot Formation are interbedded with the basinal facies within the Misty Creek embayment (Cecile, 1982).

Measured sections

Four sections of the Mount Kindle Formation (Fig. 3) were measured bed-by-bed (<10 cm resolution) along a roughly north to south transect using a Jacob's staff and level. GPS co-ordinates of the top and bottom of each section are provided in Appendix A. The Little Bear River section is described first because it was studied in the greatest detail.

Little Bear River section

The Little Bear River section (Fig. 4) was measured in cliff exposures on either side of the river. The base of the Little Bear River section is marked by a change from the laminated, coarse-crystalline Franklin Mountain Formation to bioturbated skeletal dolowackstone-packstone of the Mount Kindle Formation (Fig. 5a). The basal unit consists of a thin (<1 cm) light brown clay horizon conformably overlain by a 10 cm thick dolomudstone (sample 2 for conodonts), grading upward into 10 cm of red clay, overlain by the typical skeletal dolowackstone-packstone of the Mount Kindle Formation, the lower approximate 10 cm of which is stained red. X-ray diffraction of the red clay indicates that it is dominantly illite, with strong well spaced peaks at 10 Å, 5 Å, and 3.3 Å that remain stable with glycolation. There is a small amount of montmorillonite (smectite group) present as indicated by a 17 Å peak in the glycollated sample. The red clay horizon is interpreted as hematite-stained terrestrial residuum.

Above the basal unit is approximately 22 m of thick-bedded, cherty, bioturbated skeletal dolopackstone, that is overlain by 7 m of thin-bedded cherty, skeletal dolowackstone (Fig. 5b). Conformably overlying the skeletal dolowackestone is approximately 34 m of thick-bedded, bioturbated skeletal dolopackstone. At 63 m and extending for approximately 3.5 m is cherty, bioturbated dolomudstone that grades upward into 15 m of thick-bedded, bioturbated, skeletal dolopackstone. From 83–84 m is an interval of thin-bedded bioturbated skeletal dolowackestone that is overlain by 8 m of thick-bedded skeletal dolopackstone with abundant, but poorly preserved, stromatoporoids. Directly overlying the skeletal dolopackstone is 1 m of cherty cryptalgally laminated dolomudstone with a sharp upper surface. A 2 m thick bed of bioturbated skeletal dolowackestone-dolopackstone overlies the dolomudstone and is in turn overlain by up to 7 m of cryptalgally laminated dolomudstone (Fig. 5c). The upper surface of the dolomudstone is an irregular surface with up to 3 m of erosional relief. This surface was picked in the field as the most likely boundary between the Ordovician and Silurian portions of the Mount Kindle Formation as it was the most prominent disconformity of few disconformities marked by flooding surfaces. The upper approximately 27 m of the Mount Kindle Formation consists of thick bedded bioturbated skeletal dolopackstone whose upper part was inaccessible due to high water levels of the Little Bear River in July 2011. The contact between the

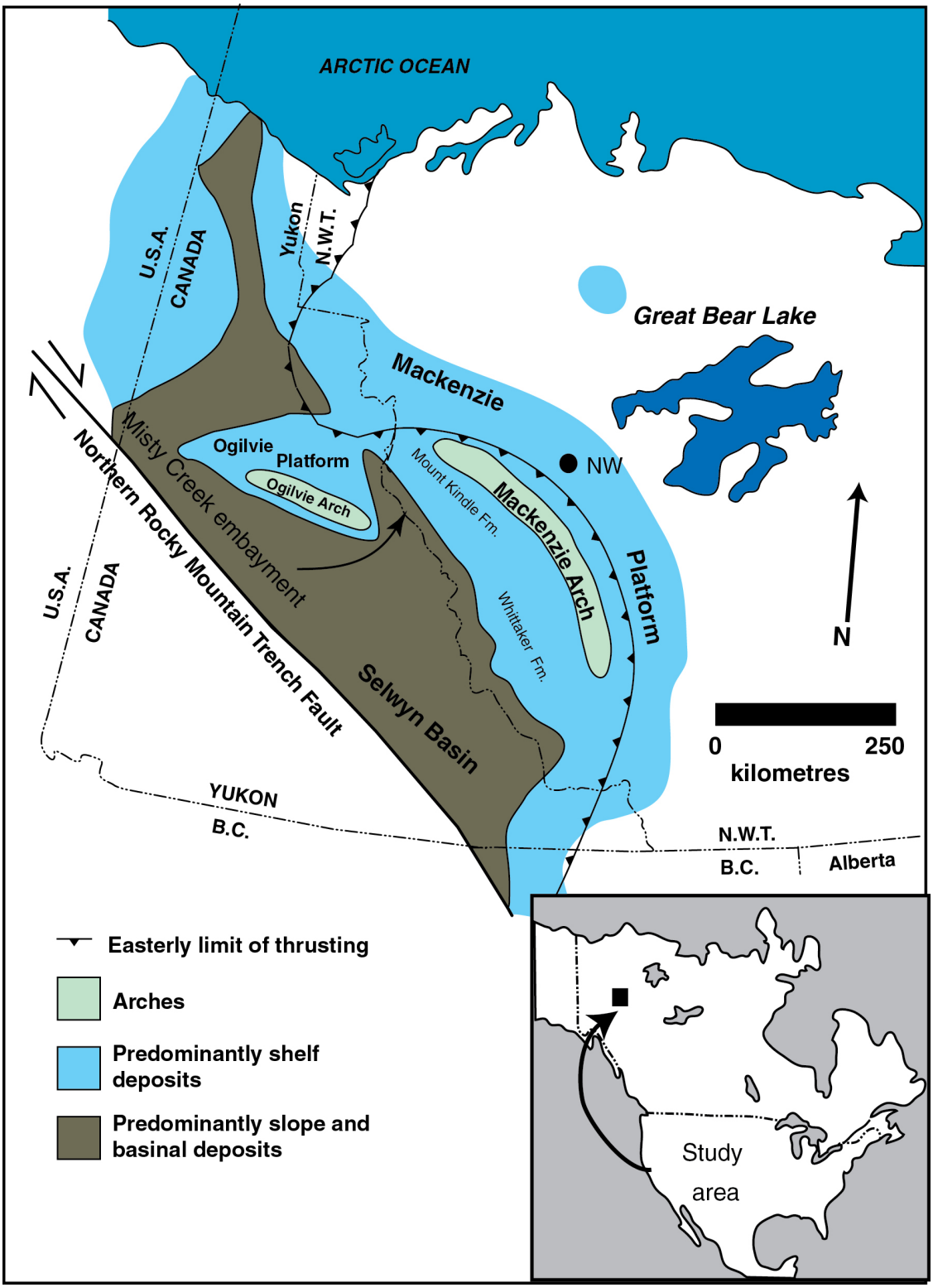

Figure 2. Map of the distribution of Mount Kindle Formation and coeval Whittaker Formation and basinal facies in northwestern Canada (*modified from* Cecile et al., 1997). NM is the location of Norman Wells, Northwest Territories.

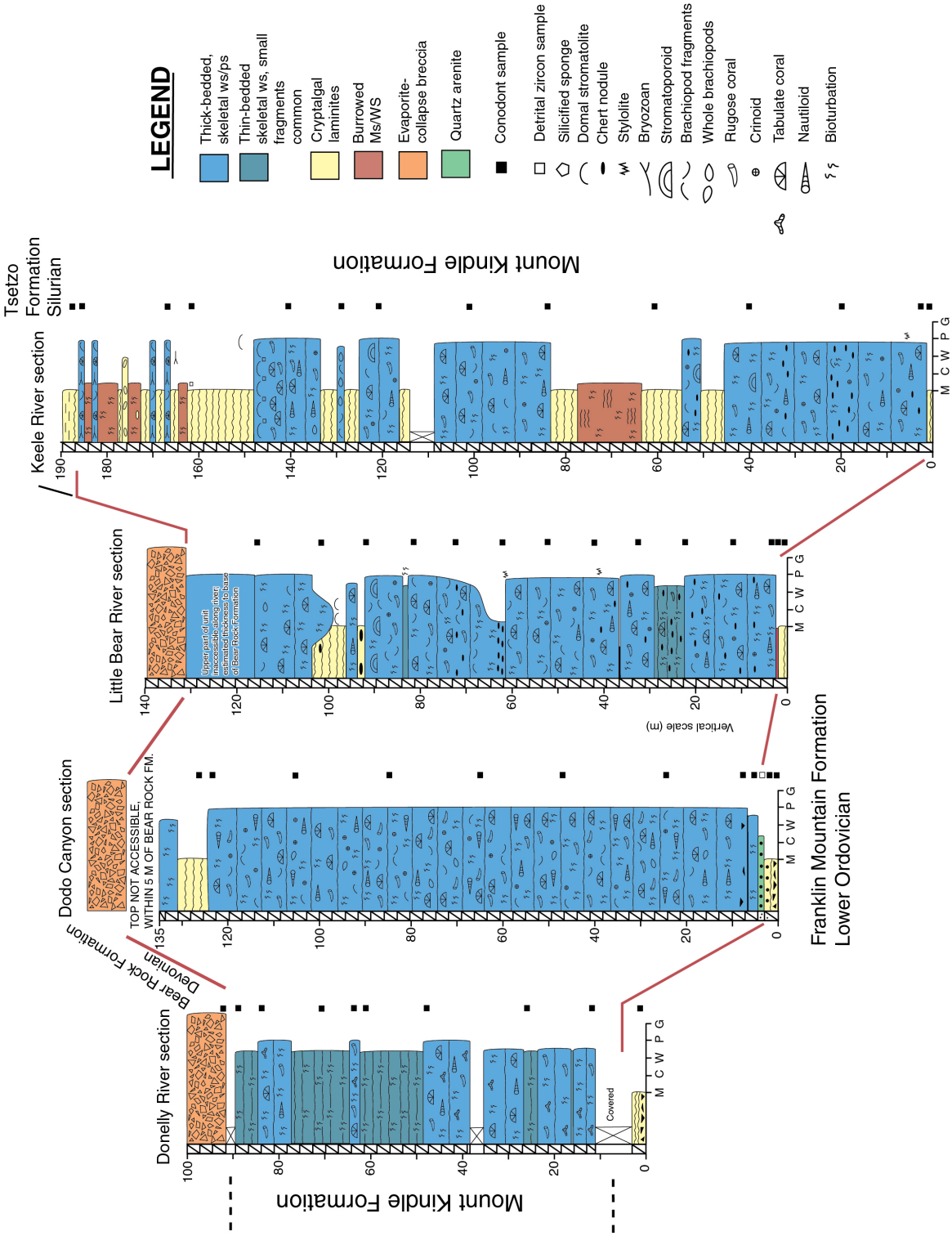

Figure 3. Regional cross-section of the four Mount Kindle sections measured during this study. Symbols at base of each section are Dunham Classification (M = mudstone; C = calcisiltite; W = wackestone; P = packstone; G = grainstone).

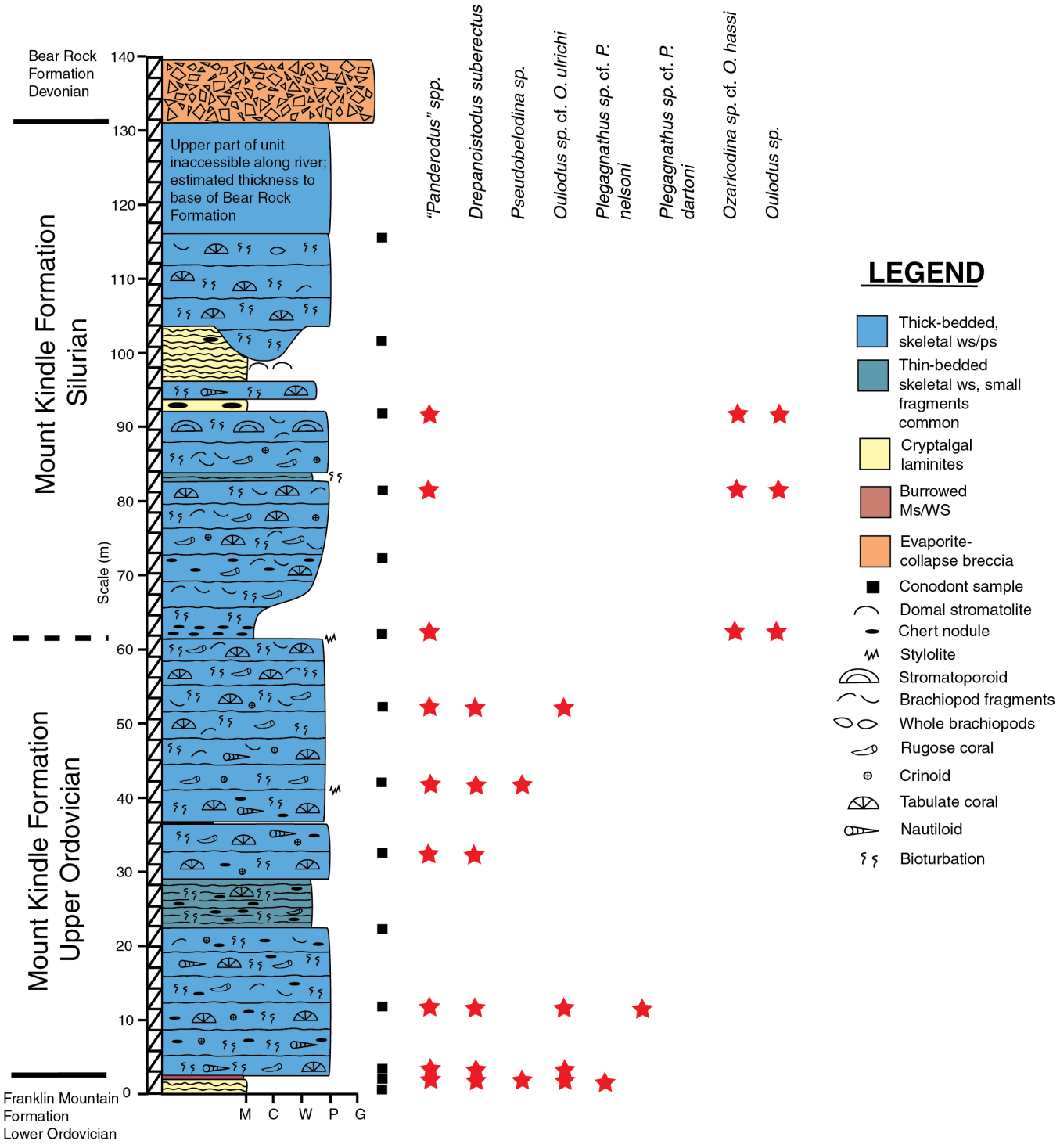

Figure 4. Little Bear River measured section plotted with conodont species identifications (red stars).

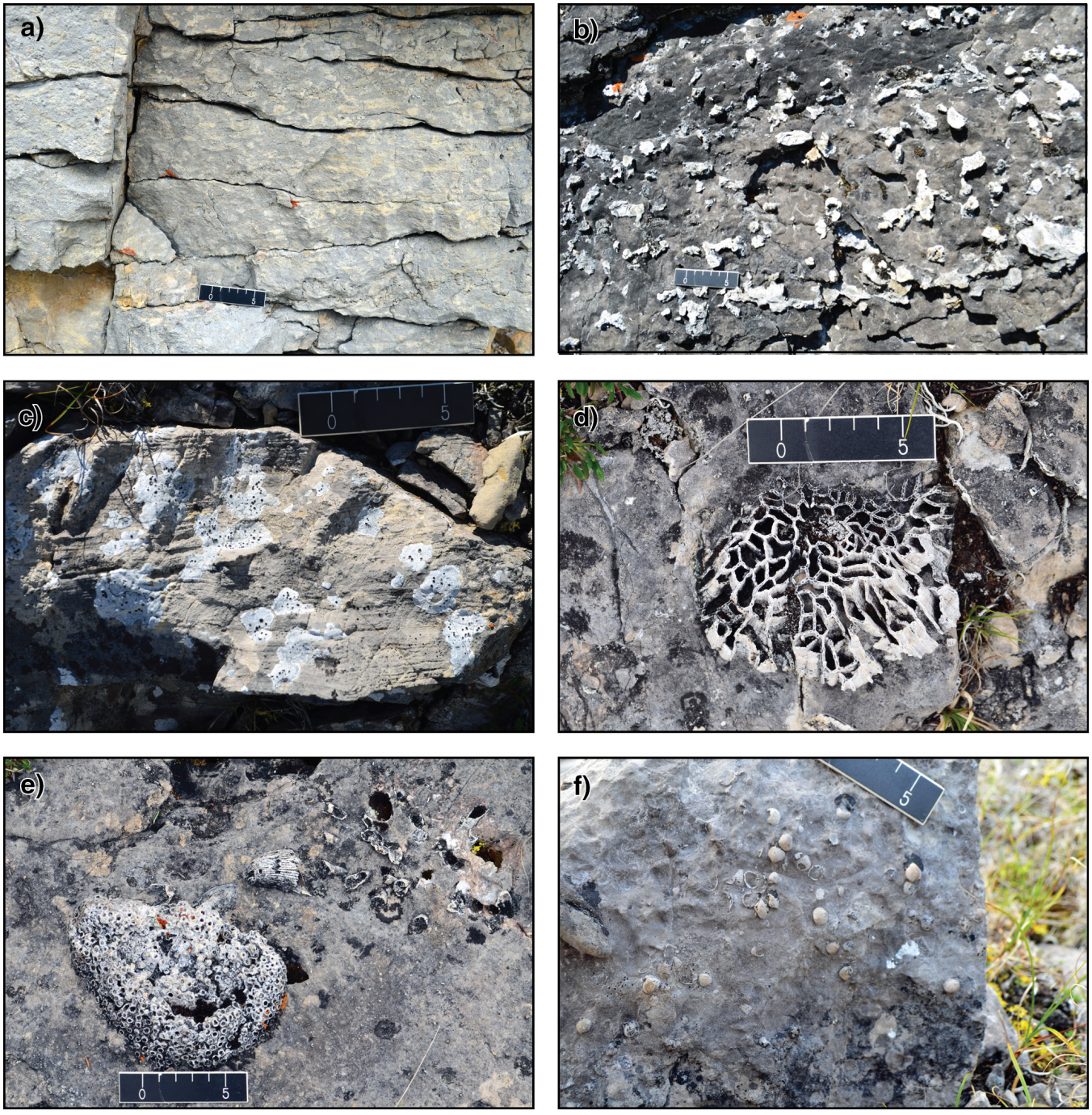

Figure 5. Photographs of Mount Kindle Formation facies and fossils. The measurment in meters indicate height of picture above base of section. Scale on photographs is in centimetres. **a)** Bioturbated skeletal dolowackestone-packstone, Donnelly River, 15 m; 2013-021. **b)** Cherty bioturbated skeletal dolowackestone-packstone, Keele River, 21 m; 2013-019. **c)** Cryptalgal laminites, Keele River, 81 m; 2013-020. **d)** Silicified chain coral, most likely *Catenipora*, Donnelly River, 46 m; 2013-016. **e)** Silicified colonial and rugose corals, Donnelly River, 41 m; 2013-017. **f)** Silicified brachiopods (approximately 1 cm across), Keele River, 147 m; 2013-018. All photographs are by M.C. Pope.

Mount Kindle and Devonian Bear Rock formations was estimated and is placed at the lowest occurrence of partially silicified dolomitic evaporite-collapse breccia.

Preliminary conodont information from the Little Bear River section (Fig. 4) indicates that the base of the Mount Kindle Formation is no older than middle Katian (Ka2) and is most likely late Katian (Ka3; Bergström et al. (2009)). This interpretation is based on a conodont fauna consisting of *Panderodus* spp., *Drepanoistodus suberectus*, *Pseudobelodina* sp., *Oulodus* sp. cf. *O. ulrichi*, *Plegagnathus* cf. *P. nelson*, and *Plegagnathus* cf. *P. dartoni* that occurs in the lower 50 m of the section (samples 1–8, *see* Fig. 4). The key genus in the age determination is *Plegagnathus*, a genus restricted to the Katian. The presence of *P.* cf. *P. dartoni* in sample 4, 10 m above the base of the section, indicates that this level in the section it is late Katian (Ka3) and in the *A. ordovicicus* Conodont Zone (Sweet, 1979, 1984, 1995; Bergström et al., 2009).

The conodont fauna changes at the sample collected 60 m to a fauna dominated by *Panderodus*? sp., *Oulodus* sp. and *Ozarkodina* sp. cf. *O. hassi*. This fauna is of Silurian aspect and suggests that the lithological change just below 60 m in the measured section may represent the disconformity at the Ordovician–Silurian boundary. The faunal change in the Mount Kindle Formation at this level is similar to the faunal change in the Whittaker Formation at Avalanche Lake (Nowlan et al., 1988). Interestingly, this marked faunal change to a Silurian aspect fauna is substantially lower in the section (60 m) than the prominent erosional surface at 105 m where the authors thought the boundary most likely occurred based on field evidence.

Donnelly River section

The Donnelly River measured section (Fig. 3) is well exposed on a cliff east of the Donnelly River and southeast of a lake shaped like a half moon. The base of the Donnelly River section consists of partially silicified, yellow cryptalgally laminated dolomudstone containing intraclasts of dolomudstone, evaporite moulds, and evaporite-collapse breccia of the Lower Ordovician Franklin Mountain Formation. The boundary between the Franklin Mountain Formation and the Mount Kindle Formation occurs in an approximately 7 m thick covered interval. The Mount Kindle Formation is approximately 80 m thick and consists of alternating units of thick-bedded, bioturbated skeletal dolowackestone-dolopackstone with abundant large whole fossils, and thin-bedded bioturbated skeletal wackestone composed primarily of skeletal fragments. The most prominent fossils within the thick-bedded dolowackestone-dolopackstone are crinoid ossicles, nautiloids, and rugose and tabulate corals (Fig. 5d, e); many of these fossils are silicified, standing out in relief above the carbonate surface. The upper contact of the Mount Kindle Formation and Devonian Bear Rock Formation occurs in an approximately 2 m thick covered interval. The Bear Rock Formation here consists of greater than 8 m of dolomitic, massively bedded, matrix-supported evaporite-collapse breccia.

Dodo Canyon section

The Dodo Canyon section (Fig. 3) is well exposed on the north side of the Dodo Canyon in the easternmost Mackenzie Mountains. The uppermost Lower Ordovician Franklin Mountain Formation is composed of cryptalgally laminated dolomudstone with rare sand grains and silicified evaporite collapse breccia. The top of the Franklin Mountain Formation is an irregular, disconformable surface with up to 10 cm relief that is overlain by a white quartz arenite, the thickness of which varies from 10 cm to 60 cm. The upper surface of the quartz arenite grades into the basal few metres of the Mount Kindle Formation that consists of sandy, bioturbated skeletal dolowackestone with abundant small, angular chert fragments. The overlying 110 m is comprised of dark grey, thick-bedded, bioturbated skeletal dolopackstone including crinoid ossicles, bryozoans, sponges, stromatoporoids, brachiopods, corals, and nautiloids; most of the macrofossils in this section are silicified. From 124–131 m is yellow cryptalgally laminated dolomudstone that is overlain by 4–5 m of bioturbated, thick-bedded skeletal dolowackestone. The uppermost part of the Mount Kindle Formation was not accessible along a steep cliff face, but the base of the Devonian Bear Rock Formation was less than 5 m above the last Mount Kindle Formation outcrop of skeletal dolowackestone. The total thickness of the Mount Kindle Formation in Dodo Canyon is estimated to be approximately 135 m.

Keele River section

The Mount Kindle Formation was measured on a large cliff face west of the Keele River (Fig. 3), on the east side of a north-south oriented syncline; this section is very near the section that was measured by Macqueen (1970). The uppermost Lower Ordovician Franklin Mountain Formation consists of thin beds of cryptalgally laminated dolomudstone with occasional silicified evaporite units. The contact between the Franklin Mountain Formation and the Mount Kindle Formation is a sharp surface with a few centimetres of relief. The lower 45 m of the Mount Kindle Formation consists of thick-bedded, dark grey, bioturbated, skeletal dolowackestone-dolopackstone containing corals, nautiloids, crinoid ossicles, brachiopods (Fig. 5f), and rare stromatoporoids near its top; many of the macrofossils in this section are silicified. The skeletal dolowackestone-dolopackstone contains a number of dark grey to black chert nodules arranged in horizontal bands. Directly overlying the skeletal dolowackstone-dolopackstone is 5 m of light coloured, cryptalgally laminated dolomudstone, that is overlain by 5 m of dark grey, thick-bedded, bioturbated, skeletal dolopackstone containing corals, crinoid ossicles, stromatoporoids,

and brachiopods. Overlying the dolopackstone is almost 30 m of yellow-light brown cryptalgally laminated dolomudstone. Part of this unit is slightly bioturbated, more coarsely crystalline, and darker in colour; it contains no macrofauna and cryptalgal laminations are still visible. From 83 m to 148 m the section is comprised primarily of thick-bedded bioturbated skeletal dolopackstone alternating with thinner intervals of light coloured, cryptally laminated dolomudstone. Fossils in the dolopackstone include crinoid ossicles, nautiloids, rugose and tabulate corals, stromatoporoids, and brachiopods. In the uppermost dolopackstone bed there are many brachiopods and silicified evaporite casts and moulds. Light coloured, cryptalgally laminated dolomudstone overlies the uppermost dolopackstone and continues up to 162 m. The upper 26 m of the Mount Kindle Formation consists of interbedded light brown burrowed dolomudstone, yellow-tan cryptalgally laminated dolomudstone, and dark grey skeletal packstone. Additionally, there are a number of intraclasts between 173 m and 175 m. the skeletal dolopackstone contains corals, bryozoans, and brachiopods. The contact between the Mount Kindle Formation and the overlying Late Silurian Tsetzo Formation is tentatively picked at the top of the uppermost skeletal dolopackstone bed where it is immediately overlain by cryptalgally laminated dolomudstone and shale interpreted to be within the Tsetzo Formation.

DEPOSITIONAL ENVIRONMENTS

The abundance and diversity of macrofauna (crinoids, corals, stromatoporoids, brachiopods, nautiloids, sponges, and bryozoans) in the skeletal dolowackestone-packstone indicates that most of the Mount Kindle Formation was deposited on a warm-water, subtidal carbonate ramp. Most of these fossils are replaced by silica, suggesting an early source of silica on the ramp. The light coloured, cryptally laminated dolomudstone in the Mount Kindle Formation records peritidal deposition. The silicified evaporite moulds in this facies indicates climate was arid during deposition of these peritidal rocks. An increase of peritidal rocks toward the west suggest the Franklin Arch may have been an active shallow-water feature affecting Late Ordovician–Silurian deposition (e.g. Cecile et al., 1997).

IMPLICATIONS FOR CORRELATION

The Mount Kindle type section (63° 21′N, 123° 12′W) is 262 m thick and was subdivided into three informal members, lower, middle, and upper, respectively (Norford and Macqueen, 1975). The lower member (21 m thick) consists of recessive skeletal dolowacke-packstone with many corals, brachiopods, gastropods, and crinoid ossicles. The middle member (65 m thick) is more resistant, consisting of thin- to thick-bedded, dark coloured skeletal dolopackstone-grainstone with abundant corals, stromatoporoids, crinoid ossicles, and other skeletal fragments. The middle member also contains rare chert nodules in thin horizons. The upper member (176 m thick) consists primarily of dolomudstone with thin interbeds of skeletal dolopackstone containing some corals, stromatoporoids, and pentamerid brachiopods. The present authors' studies indicate this tripartite subdivision is not traceable regionally since a lower recessive interval is not usually discernible. In the Ogilvie Mountains the Mount Kindle Formation is approximately 600 m thick (Morrow, 1999). In the Sekwi Mountain mapping area the Mount Kindle Formation–Whittaker Formation varies from 270–400 m thick (Roots et al., 2011).

Since the Mount Kindle Formation contains both Late Ordovician and Silurian strata it might be suggested that this unit be elevated to group status and that the lower (Late Ordovician) part of this group be designated a formation, and the upper (Silurian) portion be designated a separate formation; however, since it is difficult to separate these units in the field (e.g. Lenz, 1982) it is suggested that this unit continues to be mapped as a single unit and individual biostratigraphic units are more appropriate and it seems premature to attempt subdividing this unit at this time. It is imperative that the sequence stratigraphy and biostratigraphy of each unit be studied separately to more fully understand the depositional and diagenetic history of each unit in this area.

FUTURE STUDIES

During 2012 the authors will complete the identification of the conodont samples of the remaining sections collected during the 2011 field season, thus establishing a high-resolution biostratigraphic framework for this unit. A sequence stratigraphic framework for the Mount Kindle Formation will be constructed based on the high-resolution conodont biostratigraphy. The authors will also measure the stable isotope ratios (C, O) of samples collected from the Little Bear River section. The results of these analyses will be plotted against stratigraphic position to determine if its stable isotope fluctuations can be correlated with the global stratotype (Bergström et al., 2009) to further refine regional and possibly global correlations (e.g. Brenchley et al., 1994, 2003). The U-Pb ages of the detrital zircon grains from the quartz arenite at the base of the Dodo Canyon section will be determined to possibly provide a minimum depositional age for these strata and further elucidate the provenance of these unique sedimentary units.

CONCLUSIONS

The Late Ordovician–Silurian Mount Kindle Formation is well exposed around Norman Wells, Northwest Territories and records primarily shallow, subtidal carbonate deposition on a gently sloping ramp. Abundant macrofossils throughout this unit indicate waters on the ramp were warm. Peritidal

facies in the upper part of the unit indicate shallowing events on the ramp. The increasing abundance of peritidal facies to the west may indicate the Mackenzie Arch was a topographic high during deposition of the Mount Kindle Formation. The threefold subdivision of the Mount Kindle Formation at its type section is not traceable regionally. The authors suggest the Mount Kindle Formation continue to be mapped as a single unit, but that the lower (Late Ordovician) and upper (Silurian) parts be recognized as individual units to further clarify their depositional and diagenetic history in this area.

ACKNOWLEDGMENTS

Field support for this project was provided by the Mackenzie Delta Corridor Project (Geo-mapping for Energy and Minerals (GEM) Program). Helicopter support by Sahtu Helicopters was excellent. K. Fallas, R. MacNaughton, B. Pratt, and T. Hadlari provided stimulating discussions about the stratigraphic and tectonic evolution of the Mackenzie Mountains and Franklin Mountains. T. Proks and L. Kung provided excellent field assistance measuring the Little Bear River and Dodo Canyon sections, respectively. L. Kearns (James Madison University) assisted with X-ray diffraction analysis.

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Appendix

Table A1. UTM co-ordinates and latitude and longitude co-ordinates for the base and top of each of the Mount Kindle measured sections. Horizontal map datum for co-ordinates is NAD83.

Section	UTM			Latitude	Longitude
	Zone number and letter	Easting	Northing		
Donnelly River					
Top of section	09 W	567790	7298602	65°48'05.9548"	127°31'04.0026"
Base of section	09 W	567919	7298264	65°47'54.9755"	127°30'54.4799"
Dodo Canyon					
Top of section, north canyon rim	09 W	582423	7204867	64°57'27.3715"	127°15'17.0546"
Base of section, north canyon rim	09 W	581853	7204407	64°57'13.0259"	127°16'01.4408"
Little Bear River					
Top of section	09 W	620118	7151646	64°28'08.5505"	126°30'06.3338"
Base of section	09 W	619900	7151282	64°27'57.0794"	126°30'23.7071"
Keele River					
Top of section	09 W	574184	7120139	64°11'58.3040"	127°28'20.3070"
Base of section	09 W	574155	7120411	64°12'07.1104"	127°28'21.9724"