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Early Neoproterozoic Basin Formation in Yukon, Canada: Implications for the make-up and break-up of Rodinia

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SUMMARY

Geological mapping and stratigraphic analysis of the early Neoproterozoic Fifteenmile Group in the western Ogilvie Mountains of Yukon, Canada, have revealed large lateral facies changes in both carbonate and siliciclastic strata. Syn-sedimentary NNW-side-down normal faulting, during deposition of the lower Fifteenmile Group, generated local topographic relief and wedge-shaped stratal geometries. These strata were eventually capped by platformal carbonate after the establishment of a NNW-facing stromatolitic reef complex that formed at the same time as reefs in the Little Dal Group of the Mackenzie Mountains, Northwest Territories. Correlations between specific formations within these groups and with equivalent strata in the Shaler Supergroup on Victoria Island are tested with carbon isotope chemostratigraphy. The basin-forming event that accommodated these strata was restricted to northwestern Laurentia (present day coordinates) and does not represent widespread rifting of the entire western margin. Instead we propose that these strata were accommodated by extension and localized subsidence associated with the passing of Rodinia over a plume and the emplacement of the coeval Guibei (China) and Gairdner (Australia) large igneous provinces. Deposition culminated with the intrusion of the Gunbarrel dykes. The northern margin of Laurentia was reactivated by renewed extension at ca. 720 Ma associated with the emplacement of the Franklin large igneous province. Significant crustal thinning and generation of a thermally subsiding passive margin on the western margin of Laurentia may not have occurred until the late Ediacaran.

RÉSUMÉ

Le cartographiage géologique et l'analyse stratigraphique du groupe néoprotézoïque Fifteenmile situé à l'ouest des montagnes Ogilvie du Yukon, Canada, ont révélé de grands changements latéraux de faciès à la fois pour les strates carbonatées et silicoclastiques. La mise en place des failles normales syn-sédimentaires inclinées vers le NNW au cours du dépôt du groupe Fifteenmile inférieur, a entrainé la formation locale d'un relief topographique et une prisme des strates. Ces dernières ont finalement été recouvertes de carbonates de plateforme issus de la mise en place d'un complexe récifal stromatolitique exposé NNW contigu à la formation de même âge du groupe Little Dal des montagnes Ogilvie, en Territoires du Nord-Ouest. Les corrélations existant entre des formations spécifiques de chacun de ces groupes, sont testées grâce à la chimiostratigraphie des isotopes du carbone. De ce fait, cet événement ne correspond pas au large rifting s'étendant sur l'entière bordure ouest de la Laurentie et nous proposons à la place, que ces strates ont été localisées au cours d'un rift avorté généré par la mise en place simultanée des larges provinces ignées Guibei (Chine) et Gairdner (Australie). La bordure nord de la Laurentie a été réactivée par une nouvelle phase d'extension à ca. 720 Ma associée à l'emplacement de la province ignée Franklin. L'amincissement crustal et la formation d'une marge passive thermiquement subsidente le long de la bordure ouest de la Laurentie ne se sont certainement pas produits avant l'Édiacarien supérieur.

INTRODUCTION

The supercontinent Rodinia was originally conceived on the basis of 1.2–1.0 Ga orogenesis on several continents and Neoproterozoic–Cambrian-age rifting and development of passive margins surrounding Laurentia (Bond and Kominz 1984; Dalziel 1991; Hoffman 1991; Moores 1991). However, the exact arrangement of cratons, the timing and geometry of break-up, the number of rifting events, and the relationship to large igneous provinces (LIPs) have remained controversial (e.g. Hoffman 1991; Moores 1991; Dalziel 1997; Sears and Price 2003; Goodge et al. 2008; Li et al. 2008b; Evans 2009). The construction of an accurate Rodinian paleogeography and understanding the chronology of breakup is essential for testing proposed links between Neoproterozoic tectonics, climate, and biogeochemistry. For example, enhanced weatherability and CO_2 consumption during the break-up of Rodinia has been proposed as the background condition for the cooling trend that culminated in Cryogenian glaciation and Snowball Earth (Kirschvink 1992; Hoffman et al. 1998; Hoffman and Schrag 2002; Schrag et al. 2002; Godderis et al. 2003; Donnadieu et al. 2004).

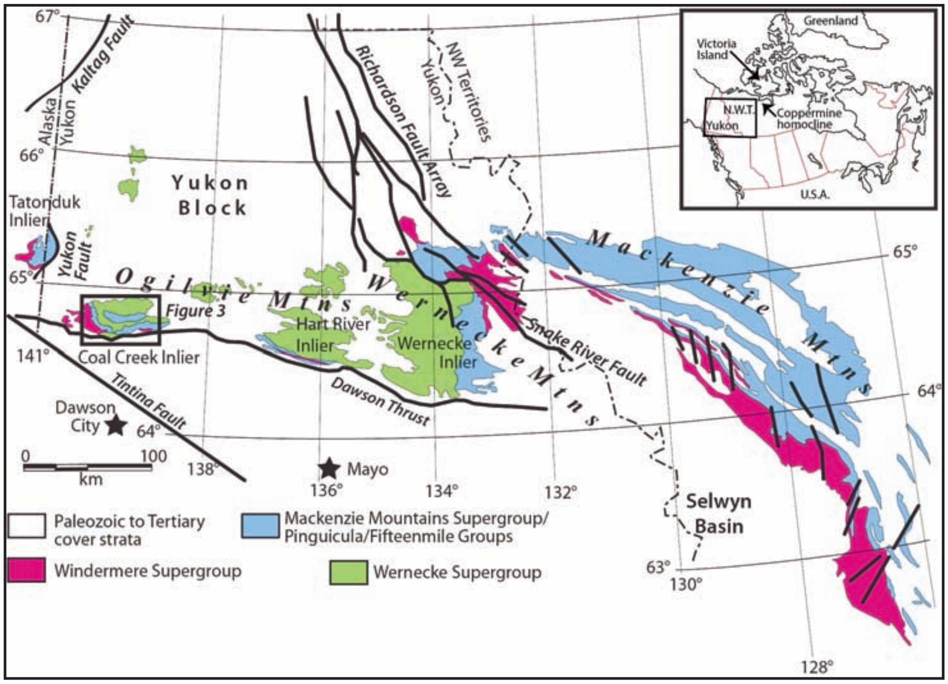

Figure 1. Distribution of Proterozoic strata in the Ogilvie, Wernecke, and Mackenzie mountains of NW Canada, modified from Abbott (1997).

Paleogeographic reconstructions place Laurentia in the core of Rodinia (e.g. Li et al. 2008b). Multiple extensional events attributed to rifting of the western margin of Laurentia (present coordinates) have been previously identified in the Windermere Supergroup (~0.78–0.54 Ga, Sequence C of Young et al. 1979), including at least one in the ca. 780–660 Ma Coates Lake and Rapitan groups in the northern Cordillera (Jefferson and Parrish 1989; Mustard 1991; Lund et al. 2003; Macdonald et al. 2010b), and another in the ca. 580–560 Ma Hamill-Gog Group in the southern Cordillera (Colpron et al. 2002). However, earlier and poorly understood early Neoproterozoic basin forming events (Sequence B of Young et al. 1979) are also required to accommodate the Pinguicula and Fifteenmile groups of the Yukon and the equivalent Mackenzie Mountains Supergroup (MMSG) in the Mackenzie Mountains and Shaler Supergroup on Victoria Island (Figs. 1 and 2). Aitken (1981) documented facies patterns in the Little Dal Group of the MMSG that suggested a NNW-facing margin, including a stromatolitic buttress in the Platform Assemblage that faces the Basinal Assemblage to the NNW. Citing the lack of syn-sedimentary faulting, obvious syn-rift deposits and the continuity of early Neoproterozoic sequences between the Mackenzie Mountains and Victoria Island, Rainbird et al. (1996) proposed that Sequence B strata were deposited in an intracratonic sag basin. Alternatively, Turner and Long (2008) inferred a suite of NE–SW oriented transfer faults in the Katherine and Little Dal groups based on abrupt lithofacies and thickness variations and suggested that the MMSG was accommodated by SW–NE extension on the western margin of Laurentia. This model invoked a simple shear, upper plate–lower plate detachment geometry (Lister et al. 1986) previously developed for the early Paleozoic passive margin, where margin-orthogonal transfer faults were proposed (Cecile et al. 1997). Although strong lineaments are present in the Ediacaran to early Paleozoic Selwyn Basin (Cecile et al. 1997), their involvement in an earlier extension is speculative. None of the proposed early Neoproterozoic transfer faults were identified in surface exposures in the Mackenzie Mountains (Turner and Long 2008).

Early Neoproterozoic strata in the Yukon and Alaska have been largely overlooked in tectonic models of basin development. Here we present the first detailed stratigraphic description of the Fifteenmile Group in the Coal Creek inlier of Yukon, Canada. We further complement these stratigraphic descriptions with new geological mapping (Fig. 3), and detailed carbon isotope chemostratigraphy through large lateral facies changes. Based on these data, we propose new correlations for Sequence B strata between Yukon and Northwest Territories and a new model for the tectonic evolution of northwestern Laurentia from the formation to the break-up of the supercontinent Rodinia.

GEOLOGICAL BACKGROUND

Tectonic Setting

Proterozoic strata in the northwestern Canadian Cordillera are preserved in erosional windows separated by 40–80 km of Phanerozoic cover (termed 'inliers'; Fig. 1). The inliers of the Ogilvie Mountains are situated on the 'Yukon block' (Jeletsky 1962), which is an isostatically independent crustal block separated on its eastern margin from the North American autochthon by the Cretaceous to Paleogene Richardson Fault Array (Norris 1997; Hall and Cook 1998). This NNW–SSE zone of crustal weakness roughly outlines large Paleozoic facies changes that define the Richardson Trough (Cecile 1982, 2000; Cecile et al. 1997), large Neoproterozoic facies changes in the Windermere and Mackenzie Mountains Supergroups (Eisbacher 1981; Norris 1997), and the easternmost extent of exposure of the Pinguicula Group and Wernecke Supergroup (Delaney 1981; Eisbacher

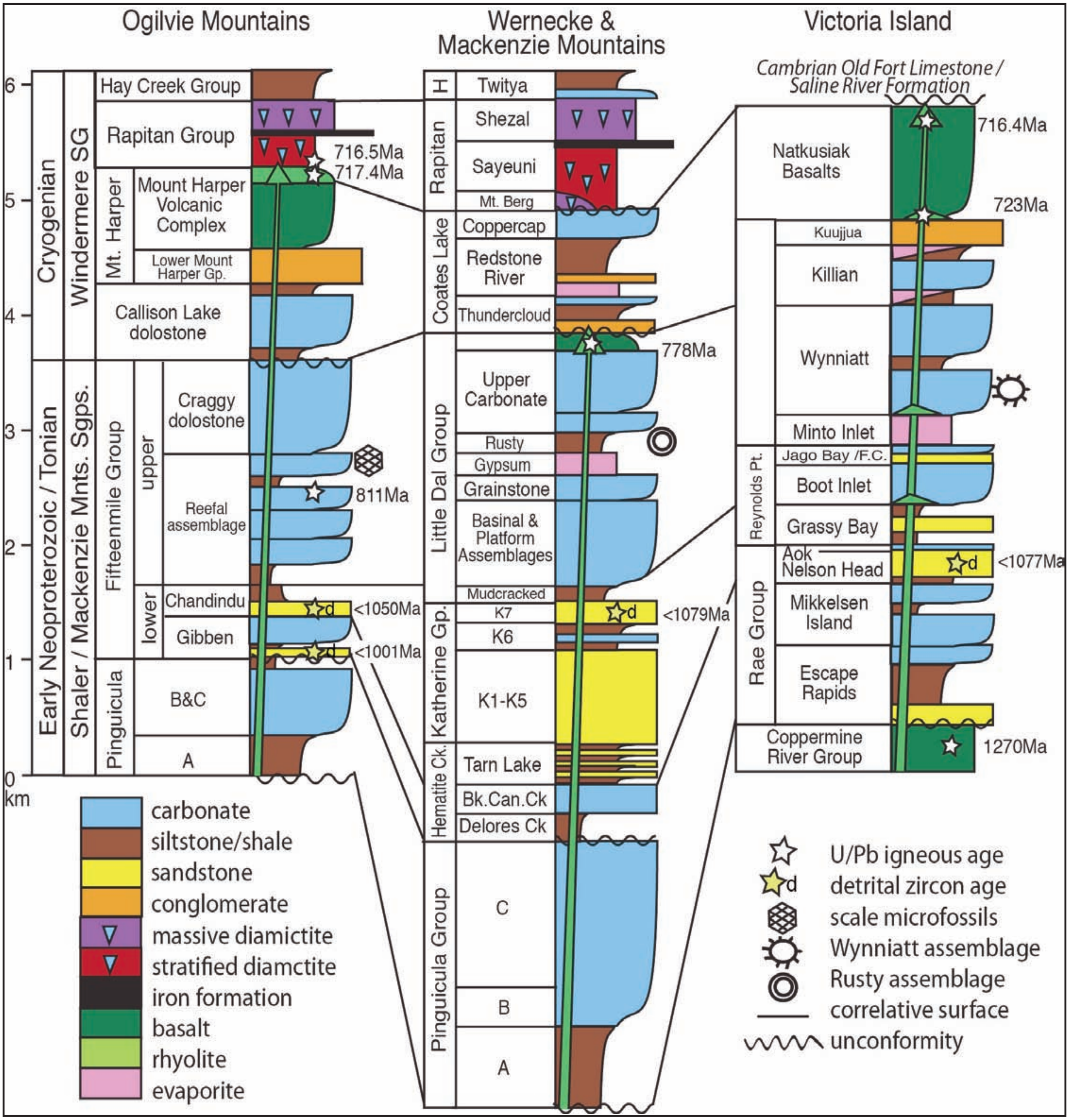

Figure 2. Proposed lithostratigraphic correlation of Neoproterozoic strata between the different Proterozoic inliers of the Ogilvie Mountains, the Wernecke/Mackenzie Mountains, and Victoria Island. Stratigraphy of the Wernecke and Mackenzie Mountains adapted from Turner (2010) and stratigraphy of Victoria Island adapted from Long et al. (2009). Microfossil assemblages of the lower Wynniatt Formation (Wynniatt assemblage) and Rusty Shale formation (Rusty assemblage) are described by Butterfield (2005a, b) and Butterfield and Rainbird (1998). Scale microfossils from the Fifteenmile Group (formerly assigned to the Tindir Group) are described by Cohen et al. (2011) and Cohen and Knoll (2012). Age constraints are discussed in text.

1981). To the east of the Richardson Fault Array, Neoproterozoic rocks outcrop in the arcuate Mackenzie Mountains fold belt (Aitken and Long 1978; Park et al. 1989). The Yukon block is bound to the south by the Cretaceous to Paleogene Dawson Fault, which separates it from the Selwyn Basin (Gordey and Anderson 1993), and to

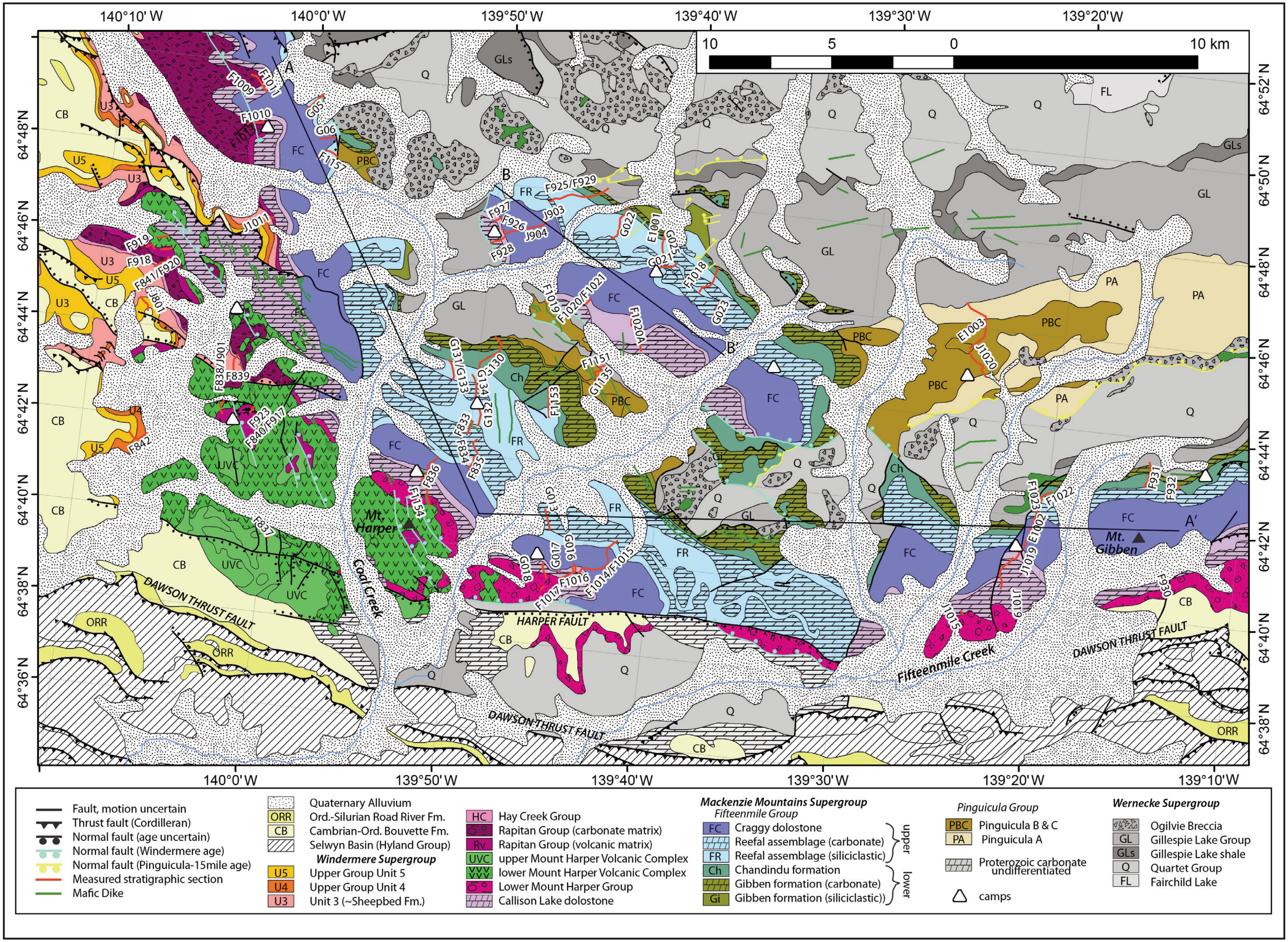

Figure 3. Geology of the Coal Creek inlier of the southwest Ogilvie Mountains, mapped by the authors with contributions from the 1:50 000 map of Thompson et al. (1994).

the north and west by the Cenozoic Kaltag Fault (Fig. 1). Early Neoproterozoic strata equivalent to the platformal rocks exposed in the inliers have not been identified south of the Dawson Fault (Abbott 1997). Abrupt facies changes occur across the Dawson Fault in late Neoproterozoic and Paleozoic strata, suggesting that it was also a long-lived basement structure that originated during the Proterozoic and was sporadically reactivated in the Phanerozoic (Thompson et al. 1987; Abbott 1997; Norris 1997).

Stratigraphic Setting

Since the early recognition that similar stratigraphic sequences were exposed throughout NW Canada (Fig. 2; Gabrielse 1972; Young 1977, 1981; Young et al. 1979), correlation of units between the Tatonduk (Young 1982), Coal Creek (Thompson et al.,1987), Hart River (Abbott 1997), and Wernecke (Eisbacher 1981; Delaney 1981) inliers of the Ogilvie and Wernecke Mountains of Yukon (Eisbacher 1981; Thorkelson 2000; Thorkelson et al. 2005), the Mackenzie Mountains fold belt of the Northwest Territories (NWT) (Aitken 1981), and the Amundsen Basin of Nunavut and NWT (Young 1981; Rainbird et al. 1996) has been a principal goal in geological mapping and stratigraphic analysis. Recent mapping and stratigraphic, geochemical, and geochronological analyses (Turner and Long 2008; Furlanetto et al. 2009; Jones et al. 2010; Macdonald and Roots 2010; Macdonald et al. 2010b, 2011; Medig et al. 2010; Martell et al 2011; Turner 2011; Halverson et al. 2012) have resulted in important new constraints on these successions. However, a comprehensive regional synthesis of Proterozoic stratigraphy has remained elusive due to the scarcity of isotopically dateable rock types, significant along-strike facies changes, poorly understood structural complications between inliers, and the lack of detailed descriptions of Proterozoic stratigraphy exposed in Yukon.

No crystalline basement is exposed in the Ogilvie, Wernecke, or Mackenzie mountains. The oldest exposed rocks belong to the Paleoproterozoic Wernecke Supergroup, which is only present on the Yukon block. The Wernecke Supergroup corresponds to Sequence A of Young et al. (1979, 1981) and consists of over 10 km of polydeformed carbonate and siliciclastic rocks (Delaney 1981). The Wernecke Supergroup was previously considered to be pre-1.71 Ga (Thorkelson et al. 2005); however, this constraint has become ambiguous following the new geochronological data of Furlanetto et al. (2009) which include ca. 1.65 Ga zircons in the Fairchild Lake, Quartet, and Gillespie Lake groups. Thus, it appears that the Wernecke Supergroup was deposited in a syn-tectonic basin immediately prior to the ca. 1.60 Ga Racklan orogeny and emplacement of the mineralized Wernecke breccia (Thorkelson et al. 2001a, 2005). Mafic intrusions cutting the Wernecke Supergroup are likely correlative with the ~1380 Ma Hart River sills in the Hart River inlier (Abbott 1997) or the ~1270 Ma Bear River dykes (Thorkelson 2000; Schwab et al. 2004).

The Wernecke Supergroup is unconformably overlain by the Pinguicula Group, which was originally included with Sequence B strata of northwest Canada and thought to be equivalent with part of the lower MMSG (Young et al. 1979; Aitken and McMechan 1991; Rainbird et al. 1996). The Pinguicula Group was originally defined in the Wernecke Mountains near Pinguicula Lake and separated into units A–F (Eisbacher 1981). Abbott (1997) later described early Neoproterozoic strata in the Hart River inlier of the eastern Ogilvie Mountains that rested with an angular unconformity on the Gillespie Lake Group and Hart River sills and were overlain by the Callison Lake dolostone. He correlated these strata with units A–D of the Pinguicula Group in the Wernecke Mountains, but recognized an angular unconformity between units C and D. Refining earlier work in the Wernecke Mountains, Thorkelson (2000) upheld units A–C in the Pinguicula Group, but reassigned units D–F to the Hematite Creek Group. Turner (2011) subdivided the Hematite Creek Group and reassigned the uppermost units to the Katherine and Little Dal groups of the MMSG. The more restricted definition of units A–C of the Pinguicula Group permits correlation with the pre-1270 Ma Dismal Lake Group in the Coppermine homocline (Kerans et al. 1981; Thorkelson et al. 2005). This correlation stemmed from the identification of a dyke assigned to the ca. 1380 Ma Hart River Sills that cuts fine-grained clastic strata assigned to Pinguicula A in the Wernecke Mountains (Thorkelson 2000). However, the intruded strata were later reassigned to the Wernecke Supergroup (Medig et al. 2010), which raised the possibility that Pinguicula A–C is younger than 1270 Ma.

The Pinguicula Group is unconformably overlain by the MMSG. The MMSG correlates with the Shaler Supergroup on Victoria Island at a formation resolution (Rainbird et al. 1996; Jones et al. 2010), and as mentioned above, a portion of the of the MMSG can be correlated across the Richardson Fault Array into eastern Yukon (Turner 2011), however, how these strata extend to inliers in the Ogilvie Mountains has remained uncertain. Age constraints on the lower MMSG and its equivalents (Fig. 2) are provided by 1050±5 and 1059±3 Ma detrital zircons from unit PD1 and 1001±2 Ma detrital zircons from unit PD3 of the Hart River inlier (both units are assigned to the lower Fifteenmile Group), a 1079 ±2 Ma detrital zircon in unit K7 of the Katherine Group of the Mackenzie Mountains, and a 1077±2 Ma detrital zircon from the Nelson Head Formation of Victoria Island (Rainbird et al. 1997). An additional upper age constraint is given by the ca. 780 Ma mafic intrusions (assigned to the Gunbarrel igneous event) that cut the Little Dal Group up to the Gypsum Formation (Jefferson and Parrish 1989; Harlan et al. 2003). These intrusions have been correlated geochemically with the Little Dal Basalt (Dudás and Lustwerk 1997), which separate the upper MMSG from the unconformably overlying Coates Lake Group and the Cryogenian–Ediacaran Windermere Supergroup (Sequence C of Young et al. 1979).

STRATIGRAPHY OF THE COAL CREEK INLIER

Previous Studies

Neoproterozoic strata in the Coal Creek inlier were originally separated from the Wernecke Supergroup by

Norris (1978) and later mapped and described as the Fifteenmile Group (named after the headwaters of Fifteenmile River; Thompson et al. 1987, 1994) and the Mount Harper Group (Mustard and Roots 1997). The Fifteenmile Group was a provisional term used to distinguish older Neoproterozoic strata in the Coal Creek inlier from the Lower Tindir Group of the Tatonduk inlier and the Pinguicula Group in the Wernecke Mountains (Thompson et al. 1994). The Fifteenmile Group was originally subdivided into upper and lower subgroups, containing three (PF1–PF3) and five (PR1–PR5) informally defined map units, respectively (these units are shown on the regional map of Thompson et al. (1994); see Figure 11 of Macdonald et al. (2011) for a chart comparing the old and new stratigraphic nomenclature). Previous workers suggested that the lower Fifteenmile Group was intruded by breccia (referred to as the 'Ogilvie breccia') equivalent to the ca. 1600 Ma Wernecke breccia (Thorkelson et al. 2001b) and hence was partly equivalent to the Pinguicula Group and Wernecke Supergroup of the Wernecke inlier (Thompson et al., 1987, 1994). However, Medig et al. (2010) demonstrated that map unit PR1 overlies a regolith formed on top of the Ogilvie breccia and that all of the lower Fifteenmile Group is younger. Moreover, a tuff recovered within strata previously mapped as PR4 (revised to PF1a to reconcile inconsistencies of previous mapping) was dated at 811.51 ± 0.25 Ma (U/Pb ID-TIMS; Macdonald and Roots 2010; Macdonald et al. 2010a). We follow Medig et al.'s (2010) suggestion that units PR1–PR3 are largely correlative with units A–C of the Pinguicula Group, which provides a distinct separation of the remaining Fifteenmile Group from the underlying Pinguicula Group.

Major revisions to the mapping in the Coal Creek inlier, including elimination of many inferred thrust faults in the lower Fifteenmile Group, led Macdonald et al. (2011) to propose a new subdivision of the Fifteenmile Group into an informal 'lower assemblage' of mixed shale and dolostone, overlain by the informal Craggy dolostone. Halverson et al. (2012) subsequently subdivided the lower assemblage into the informal Gibben and Chandindu formations and the overlying Reefal assemblage. Macdonald et al. (2011) also revised the stratigraphic nomenclature by removing the Callison Lake dolostone (Abbott 1997; Macdonald and Roots 2010) from the Fifteenmile Group. The Callison Lake dolostone is overlain by the Mount Harper Group, which includes the lower Mount Harper Group (LMHG) and the Mount Harper volcanic complex (MHVC; Macdonald et al. 2011; Fig. 2). A minimum age constraint on the Fifteenmile Group comes from rhyolite flows in the upper MHVC, which were dated at 717.43 ± 0.14 Ma (U/Pb ID-TIMS; Macdonald et al. 2010a). The MHVC is interbedded with and conformably succeeded by 716.47 ± 0.24 Ma glacial deposits of the Rapitan Group (U/Pb ID-TIMS; Macdonald et al. 2010a). In the Coal Creek inlier, the Rapitan Group is overlain by the Cryogenian Hay Creek Group and the Ediacaran to Early Cambrian 'Upper' Group (Macdonald et al. 2011; Chapter 3.3.4 in Martel et al. 2011), which are in turn unconformably overlain by the Cambrian to Devonian Bouvette Formation.

Methods

We measured 54 stratigraphic sections through the Pinguicula, Fifteenmile, Mount Harper, Rapitan, Hay Creek, and 'Upper' groups in the Coal Creek inlier. Carbonate lithofacies are defined (Table 1) and used in the lithostratigraphic descriptions below along with siliciclastic lithofacies differentiated by grain size and composition. These lithofacies are then grouped into facies assemblages (Table 2), which are used to track the evolving depositional environments and sequence architecture of the Fifteenmile Group. Sequences described are composed of parasequence sets that define systems tracts (Mitchum and Van Wagoner 1991), but without further age constraints, the order of these sequences remains uncertain. In the descriptions below we focus on the Fifteenmile Group, but to provide broader tectonostratigraphic context we also discuss the bounding stratigraphy in the Pinguicula Group, Callison Lake dolostone, and Mount Harper Group in the Coal Creek inlier.

Pinguicula Group

In the Coal Creek inlier, the Pinguicula Group is exposed in a syncline to the NW of Mt. Gibben (Fig. 3, section E1003) and along ridges north of Mount Harper, where it unconformably overlies the Wernecke Supergroup. The Pinguicula Group has been divided into a siliciclastic-dominated unit and a carbonate-dominated unit, referred to as Pinguicula A and Pinguicula B/C, respectively (Macdonald et al. 2011). On the north limb of the syncline near Mt. Gibben, Pinguicula A is composed of a lower ~320 m-thick unit of weakly foliated, brown to grey-coloured siltstone and shale with irregularly dispersed large dolostone blocks and conglomerates interpreted as olistostromes (Fig. 4a) and debris flows, respectively (Macdonald et al. 2011). On the south limb of the syncline, the distinct orange-coloured dolostone blocks are over 10 m in diameter and their internal bedding is discordant with the surrounding siliciclastic matrix. The olistostrome-bearing siliciclastic rocks are overlain by >500 m of yellow to blue-grey weathering dolostone of Pinguicula B/C. On the north side of the syncline, the carbonate rocks consist predominantly of grainstone and stromatolites (a facies characteristic of Pinguicula C in the Hart River and Wernecke inliers), whereas on the south side of the syncline the dolostones are characterized by laminated dolomicrite and dolosparite with rare lime mudstone (a facies characteristic of Pinguicula B in the Hart River and Wernecke inliers). These facies are gradational in the Coal Creek inlier; hence we mapped them together and refer to this sequence as Pinguicula B/C because they represent one depositional package with distinct lateral facies changes. At the top of Pinguicula B/C, stromatolites with high synoptic relief are overlain with black shale and minor dolomicrite, and green-weathering flat-laminated siltstone, which we include with Pinguicula B/C.

North of Mount Harper (Fig. 3; section G135), the Pinguicula Group is represented by a thick dolostone capped by a spectacular assemblage of *Minjaria, Tungussia*, and *Conophyton* stro-

Table 1. Carbonate lithofacies and descriptions of lithology, bedding, and sedimentary structures that distinguish these facies.

Carbonate Lithofacies	Lithology	Bedding	Comments
Rhythmite	"Micrite, mostly limestone, minor dolostone"	"Flat-bedded, parallel-laminated, <10 cm-thick, commonly graded"	"Commonly associated with shale, marl, and debris flows"
Ribbonite	Micrite to grainstone	Wavy laminated with or without wave or current ripples or low-angle cross-lamination; commonly nodular; 20 cm-thick	"Molar tooth structure common in fetid, organic-rich facies"
Stromatolite	Undulose and crinkly to fenestral laminated dolostone	"Discrete columnar to rounded microbialite with >1 cm of synoptic relief, massive weathering bioherms (m-scale) and reefs (100 m-scale)"	Commonly associated with edgewise conglomerate and grainstone
Grainstone	"Well-sorted sand to packestone, oolitic or intraclastic dolostone"	"With or without large-scale cross-bedding, massively bedded >0.2 m thick, coarsely recrystalized"	Recrystallization commonly limits confident determination of original grainsize
Microbialaminite	Undulose and crinkly to fenestral laminated dolostone or limestone	Thin to massive beds	"Commonly associated with shale and rhythmite, or with itraclast breccia and rip-up clasts"
Intraclast breccia	"Poorly sorted gravel to boulder clasts with void-fill cement, angular to subrounded; silicified dolostone"	"Massive, resistant, upward buckling teepee structures and karstic dissolution surfaces are common"	Associated with microbialminite and grainstone
Debris flow breccia	"Gravel to boulder, angular to subrounded, tabular clasts in micrite to grainstone matrix"	Graded and imbricated	Commonly associated with rhythmite or shale; includes massive olistoliths

matolites (Halverson et al. 2012). The stromatolitic dolostone in this section is overlain by green siltstone. The Pinguicula Group tapers out to the NW of section G135 by a combination of onlap onto the unconformably underlying Gillespie Lake Group (upper Wernecke Supergroup) and truncation beneath an erosional unconformity at the base of the Fifteenmile Group (section G130, Fig. 3).

Fifteenmile Group

The Fifteenmile Group is exposed in the Tatonduk, Coal Creek, and Hart River inliers. We recently proposed a revised subdivision of the Fifteenmile Group into four informally defined formations: the Gibben and Chandindu formations, which constitute the lower Fifteenmile Group, and the Reefal assemblage and Craggy dolostone, which constitute the upper Fifteenmile Group (Macdonald et al. 2011; Halverson et al. 2012). Because of large lateral facies change within the Fifteenmile Group, we use a sequence stratigraphic approach to attempt the correlation of time-equivalent surfaces across the basin and help interpret the basin fill. Where subaerial unconformities are apparent, depositional sequences are defined. Elsewhere, particularly in more distal environments, the maximum regressive surface (MRS) is used as the correlative sequence boundary.

Gibben Formation Lithostratigraphy

North of Mt. Harper (section G130; Figs. 3 and 5), the Gibben formation unconformably overlies a westward-thinning wedge of the Pinguicula Group. Locally, the basal Gibben formation includes a thin medium-grained sandstone unit with abundant carbonate and slate lithic clasts. It is succeeded by a shoaling-upward interval of grey dolomitic ribbonite and wackestone that grade into oolitic grainstone and eventually into microbialaminite with tepee structures (see Table 1 for descriptions of lithofacies). Here the top of the formation is interpreted to be a subaerial exposure surface with evidence of minor karsting. It is overlain by maroon, mud-cracked shale and siltstone of the basal Chandindu formation.

Near Mt. Gibben (E1002; Figs. 3 and 5), the basal sandstone is missing and the lowermost Gibben formation consists of a basal ~100 m interval of blue-grey oolitic and stro-

Table 2. Facies assemblages and descriptions of lithofacies associations, sedimentary structures, and their potential depositional environments.

Assemblage	Lithofacies Associations	Sedimentary Structures	Depositional environments
FA1: Carbonate Platform / Tidal Flats	"Microbialaminite, grainstone, intraclast breccia"	"Teepee structures, beach-rock, pervasive void-fill cements, ooils, edgewise conglomerate"	Periodically restricted and exposed intertidal to supratidal lagoon
FA2: Back Reef Lagoon	"Microbialaminite, grainstone, ribbonite, rhythmite, shale"	"Pin-stripe laminated microbialite and mudstone with no scours, red, terestrial siltstone"	Restricted lagoon adjascent to stromatolite reef
FA3: Rim / Reef Core	"Stromatolite, talus breccia"	Massively recrystalized	Protective stromatolite reef
FA4: Upper Foreslope	"Ribbonite, rhythmite, siltstone, shale, stromatolite bioherms"	"Hummocky cross-lamination, slumps, graded beds, olistoliths, molar tooth structure common in fetid lime mudstone"	Upper foreslope with longshore flow outboard of a carbonate reef or platform
FA5: Lower Foreslope	"Shale, siltstone"	"Graded beds, flat lamination, occasional channelization"	Lower foreslope outboard of significant carbonate deposition
FA6: Pro-delta	"Shale, siltstone, sandstone, rounded to sub-rounded conglomerate"	"Mudcracks, channels, large cross-bed sets"	River delta with continental source or alluvial fan adjacent to active fault

matolitic dolostone that is faulted against sheared and chloritized sills. In the northernmost exposures of the Coal Creek inlier (section E1001), the Gibben formation thickens dramatically, with up to several hundred metres of grey to black shale that transitions up-section into muddy pink limestone ribbonite. This pink limestone is followed by oolitic and microbialaminite facies of dolostone, typical of the upper Gibben formation in other sections. The thick lower shale and pink limestones decrease in thickness laterally (Fig. 6), disappearing altogether in many sections where the Gibben formation is represented by only a relatively thin interval of dolomitic microbialaminites (Fig. 6). The result is that the total thickness of the Gibben formation varies from <20 to >600 m as a result of expansion of the section into fault-bound graben and condensation on topographic highs.

Sequence Stratigraphy

In the Coal Creek inlier, the Gibben formation contains a thin, basal quartzlithic arenite. The sandstone correlates with the PD1 map unit in the Hart River inlier defined by Abbott (1997) that was subsequently revised to the Fifteenmile Group based on the conformable contact at the top of the sandstone (Medig et al. 2010; Halverson et al. 2012). In the Hart River inlier, PD1 comprises a series of shale to sandstone cycles that broadly make up a single depositional sequence (S1, not shown here; see Halverson et al. 2012). Above the sandstone, the remainder of the Gibben formation spans a second depositional sequence (S2; Fig. 5 and 6), which consists of a shale to carbonate highstand (regressive) systems tract bound by a subaerial unconformity that marks the contact with the overlying Chandindu formation.

Chandindu Formation

Lithostratigraphy

The top of the Gibben formation marks an abrupt transition from nearly pure carbonate sediment into an interval of maroon shale and siltstone with abundant mud-cracks, characteristic of the basal Chandindu formation. The Gibben formation thins laterally and is in places absent under this distinctive mud-cracked interval, suggesting that an additional unconformity is present at this level. Up-section, the mud-cracked interval transitions into cyclic packages of shale, siltstone, and dolostone that are typically capped by grainstone, stromatolites, or microbialaminite. However, the upper Chandindu formation is overall quite variable between sections, which we attribute to differential subsidence associated with protracted tectonic extension. This syn-Chandindu faulting is apparent from map relations (Fig. 3) and the presence of large olistoliths within the upper part of the formation (Fig 4b). In some stratigraphic sections, stromatolitic bioherms are relatively abundant, as are poorly sorted and massive coarse-grained sandstone beds. The upper boundary of the Chandindu formation is marked by a major flooding surface, which effectively separates this heterogeneous sequence from the overlying shale- and dolomite-dominated Reefal assemblage.

Sequence Stratigraphy

The basal mud-cracked interval of the Chandindu formation records one of few, well-developed lowstand systems

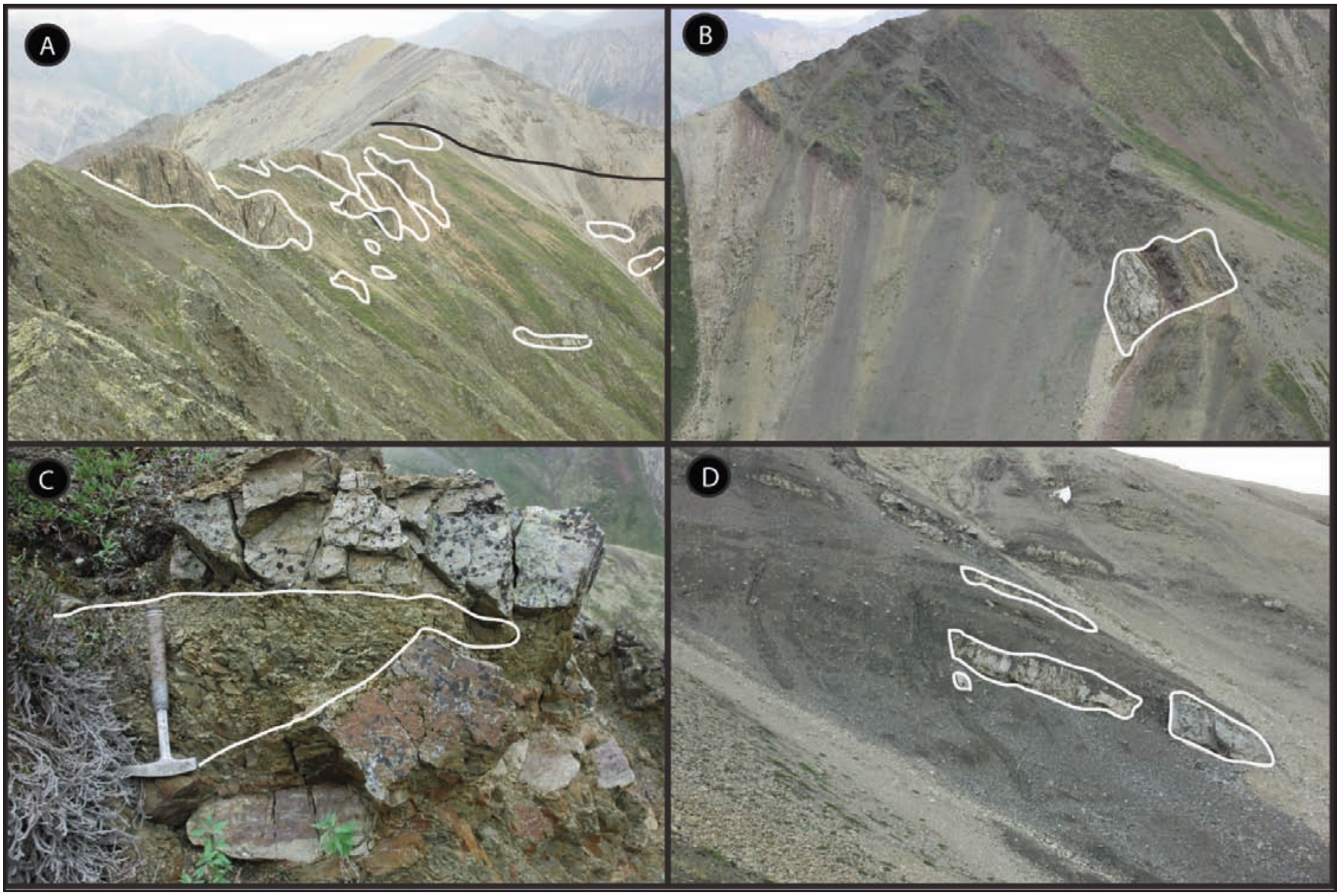

Figure 4. Olistoliths and slumps in Neoproterozoic strata of the Coal Creek inlier. A) Large carbonate olistostromes of the Gillespie Lake Group (outlined in white) in siltstone of unit A of the Pinguicula Group, looking north, just west of J1020 (Fig. 3). B) Olistostrome containing the contact between the Gibben and Chandindu formations (outlined in white) within the lower Chandindu formation near F1018 (Fig. 3). Note that this olistolith is near the large normal fault shown in Figure 7a that was active during deposition. C) Slump fold (outlined in white) on the hanging-wall of the syn-Chandindu fault shown in Figure 7a, just west of section F1018. This fold is verging to the NW, into the axis of the basin and away from the footwall. D) Olistolith within sequence S3a of the Reefal assemblage (outlined in white), just west of section G022 (Fig. 3).

tracts (LST) in the lower Fifteenmile Group, marked by aggradational stacks of sandstone and conglomerate with abundant exposure surfaces, and is interpreted to represent tidal-flat deposition as base level began to rise. The overlying mud, silt, and wackes as well as the shale–carbonate cycles are interpreted to record a gradual increase in base level in sequence S3 (Figs. 5 and 6) and possibly represent the development of a deltaic system, through which the gritty sands were delivered to the centre of the basin, and adjacent to which, the tidally influenced shale–carbonate cycles formed. Normal faulting continued or resumed in the Chandindu formation, resulting in local uplift and shedding of olistoliths into the basin and flooding that culminated at the contact with the overlying Reefal assemblage.

Reefal Assemblage
Lithostratigraphy

The Reefal assemblage consists of ~500 m of shale, siltstone, minor coarse-grained sandstone, carbonate mudstone, grainstone, and massive stromatolitic boundstone (Figs. 5 and 6), and is characterized by large lateral facies change. The NNW-side down normal faults cut the Gibben and Chandindu formations, and are capped by shale that marks the base of the Reefal assemblage (Figs. 3, 6 and 7a). Stromatolitic buildups were preferentially established on inferred paleohighs along the footwalls of the faults, marking the rim of the carbonate platform. Carbonate olistoliths and slump folding in the adjacent shale (Fig. 4d) suggests that significant relief existed on the flanks of stromatolitic buildups. We interpret large lateral facies changes in the Reefal assemblage to represent proximal platform and stromatolite reef facies in the SE to more distal foreslope and basin facies to the NW (Tables 1 and 2). Sections from within the carbonate platform are dominated by stromatolitic bioherms and intertidal to supratidal carbonate facies, including dark grey limestone microbialaminites (lagoonal), dolomitic microbialaminites (supratidal), and abundant grainstone (supratidal and proximal to the reef). To the NW, the succession is dominated by shale and gravitationally redeposited dolostone.

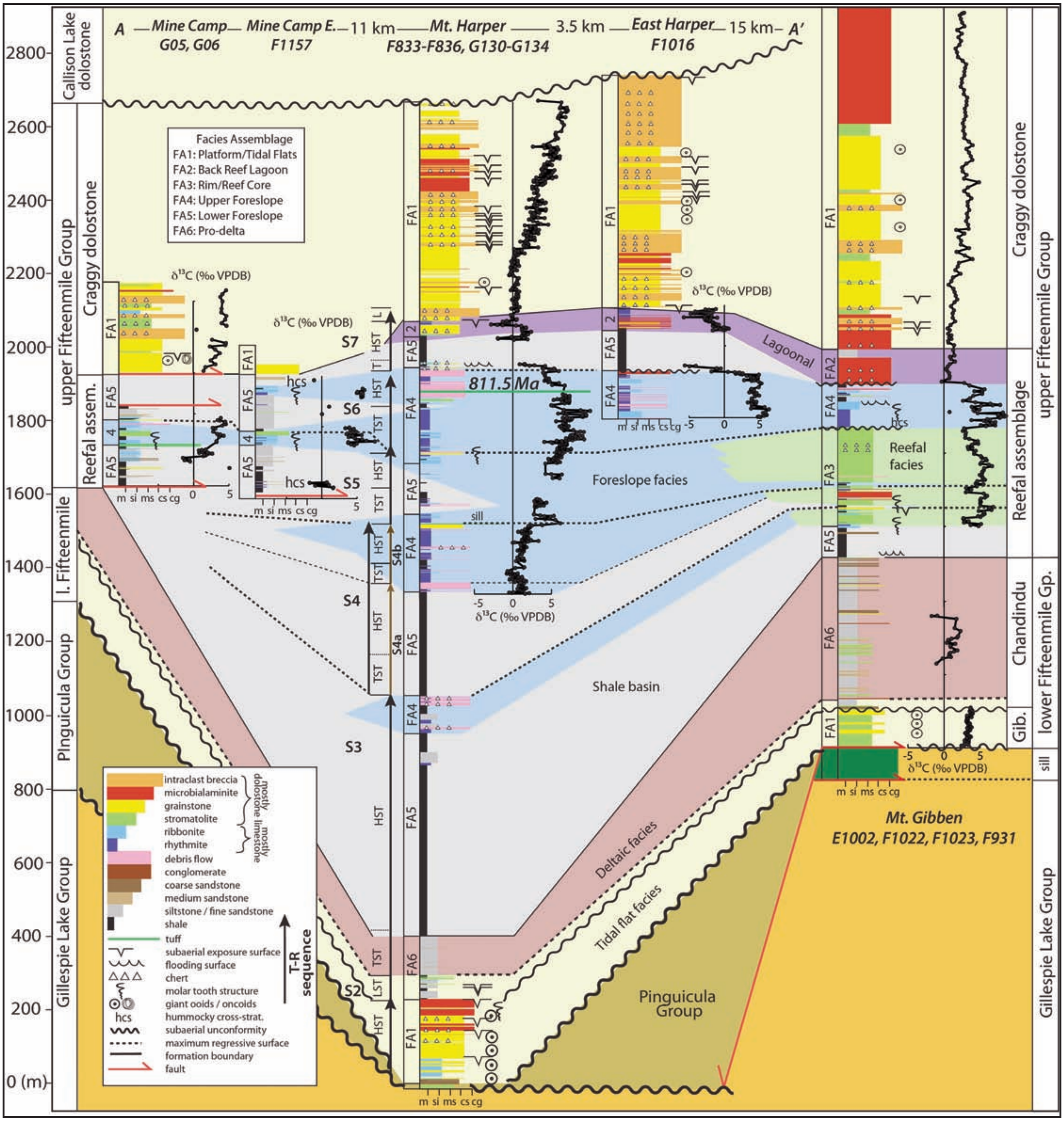

Figure 5. Lithostratigraphy, sequence stratigraphy, and carbon isotope chemostratigraphy of the Fifteenmile Group along an ESE–WNW transect of the southern belt of exposures, shown as A-A' in Figure 3, which includes locations of the individual stratigraphic sections. Sequences S2-S7 are described in text.

Upper foreslope facies are dominated by carbonate mudstone, which commonly contain molar tooth structure and massive talus breccias that shed material from the adjacent reefs. Basinal facies include shale, sandstone, and re-sedimented carbonate. The complex geometry of these facies assemblages results in significant variability between measured sections and abundant stratigraphic repetition of lithologically similar shale-to-carbonate sequences (Figs. 5 and 6) that was previously interpreted as the product of thrust faults (e.g. Thompson and Roots 1994).

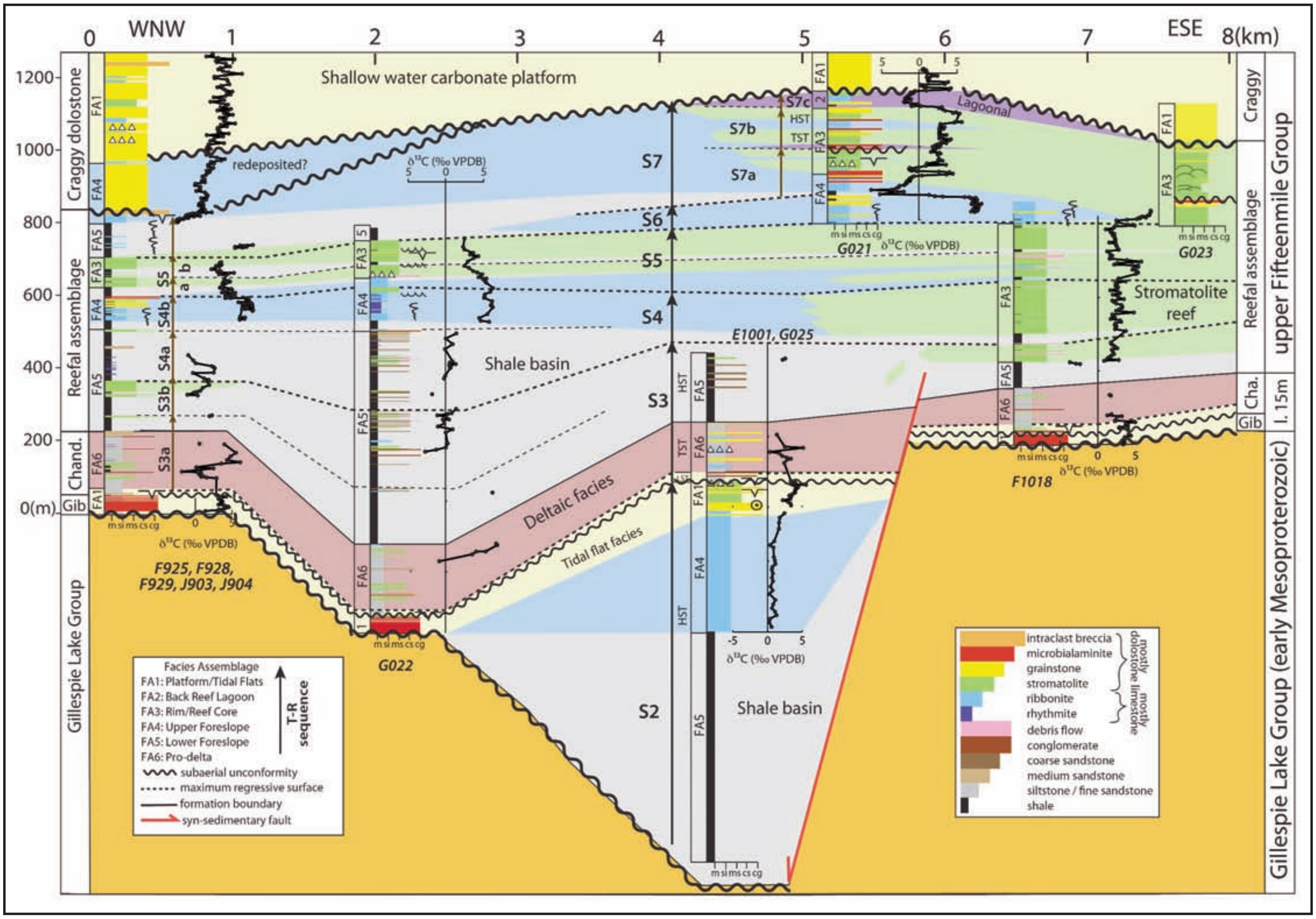

Figure 6. Lithostratigraphy, sequence stratigraphy, and carbon isotope chemostratigraphy of the Fifteenmile Group along an ESE–WNW transect of northern belt of exposures near Reefer Camp, shown as B-B' in Figure 3, which includes locations of the individual stratigraphic sections. Sequences S2-S7 are described in text.

Sequence Stratigraphy

At the northwest end of the Coal Creek inlier, measured sections of the Reefal assemblage reveal symmetric transgressive–regressive sequences capped by highstand stromatolitic buildups (Fig. 7b). This architecture reflects a series of NNW-prograding stromatolite-cored reef tracts that grade distally into grey and black shale-dominated basinal deposits. The Reefal assemblage begins with the HST of sequence S3 and contains four additional sequences (S4–S7) that can be correlated across the Coal Creek inlier. Several of these are composite sequence sets, which in some sections comprise 2 to 6 parasequences that are correlated with less confidence across the basin (Figs. 5 and 6). The S3 HST records the nucleation and growth of the first prominent reef system of the Reefal assemblage on relict basement highs, most prominently in sections F1018, G021, and G023 ('Reefer Camp'). During the upper S3 HST and subsequent HSTs, the reef system prograded to the NNW, shedding carbonate debris into and eventually overriding the adjacent shale sub-basin. These episodes of progradation are interrupted by abrupt flooding events marking condensed transgressive systems tracts (TSTs), the most prominent of which (base S6) flooded most of the basin following progradation of the stromatolite platform over much of the basin at the top of S5. Only at the core of the reef system, in section G023, are carbonates nearly continuous. However, it is possible that deposition may have been interrupted during intermittent exposure of the platform. In the axes of the original fault-controlled sub-basins, carbonates are found in the form of talus breccia, slump breccia, grain flows, ribbonite, turbidite, and rhythmite (Tables 1 and 2). The ~811 Ma ash bed occurs between two carbonate sediment gravity flows at the top of S6 (Fig. 5).

Throughout the Reefal assemblage, sequences comprise coupled TSTs and HSTs, with little or no clear evidence of a significant base level fall. A superb example of a well-preserved TST–HST couplet occurs in sequence S7b of section G021 (Fig. 6), in which the entire carbonate platform retrogrades over a minor subaerial disconformity developed in suptratidal microbialaminites (Fig 8). The maximum flooding surface (MFS) lies in red shale just above a minor flooding unconformity, which is superseded by red marly ribbonite, followed by stromatolites

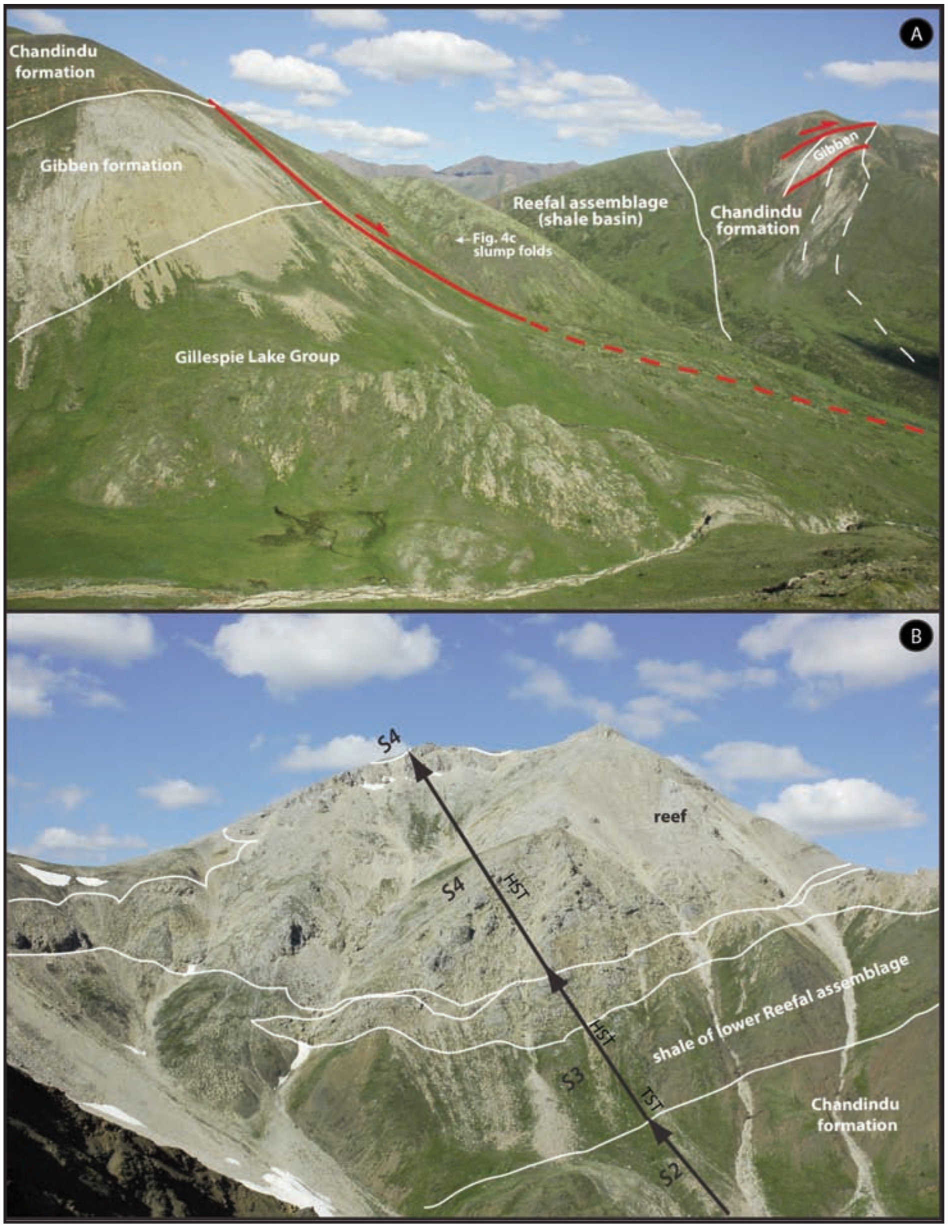

Figure 7. A) Annotated photo looking west towards syn-Chandindu normal faults (in red) west of section F1018. Slump folding in Figure 4c and basinal facies of the Reefal assemblage are shown on hanging-wall. B) Annotated photo of reef core (outlined in white) of the Reefal assemblage, looking west from section F1018 to the exposure directly below section G021. This photo is looking directly above the footwall shown in Figure 7a. Sequence stratigraphic systems tracts shown that are depicted in Figure 6.

and grainstone as the reef edge migrated back across the platform. The absence of falling stage and lowstand systems tracts in the Reefal assemblage is likely a result of broad and relatively rapid subsidence rates across the basin that far outpaced any eustatic sea level fluctuations (Mitchum and Van Wagoner 1991).

Craggy Dolostone

The uppermost sequence of the Reefal assemblage is capped by a distinct subaerial exposure surface overlain by the heavily silicified and informally named Craggy dolostone. The Craggy dolostone forms a conspicuous, ridge-forming, >500-m-thick white dolostone and consists predominantly of thick bedded and massively recrystallized and silicified sucrosic dolostone. Microbialaminite and low-relief stromatolites (up to 10 cm of relief) are variably preserved through the pervasive and multigenerational silicification and recrystallization. Ooids, coated grains, brecciated teepee structures, tabular clast conglomerates, intraclast breccia, and low-angle crossbeds have also been observed. Silicification is particularly intense near the upper unconformity that separates the Craggy dolostone from the overlying Callison Lake dolostone. Although the pervasive silicification and recrystallization challenge any comprehensive facies and sequence stratigraphic analyses of the Craggy dolostone, it is evident that it records the development of a broad and stable carbonate platform following the filling of residual sub-basin bathymetry in the Reefal assemblage.

Callison Lake Dolostone

The Craggy dolostone is succeeded by the Callison Lake dolostone (Abbott 1997), which was recently separated from the Fifteenmile Group (Macdonald et al. 2011) because it unconformably overlies the Fifteenmile Group (Macdonald and Roots 2010). Halverson et al. (2012) suggested placement in the Mt. Harper Group, but we leave it as an orphaned unit here awaiting formal formation and group designation. Near Mt. Gibben, the Callison Lake dolostone is ~500 m thick and consists of a basal siltstone and shale sequence with laterally discontinuous stromatolitic bioherms. This is overlain by medium-bedded dolostone interbedded with black shale that consists almost exclusively of sedimentary talc (Tosca et al. 2011). These strata (previously mapped as unit PF2; Thompson et al. 1994) are overlain by ~200 m of a silicified dolostone characterized by domal stromatolites (previously mapped as unit PF3). An additional ~25 m interval of interbedded black shale and dolostone occurs just below the contact with the lower Mount Harper Group. We map the entire shale–carbonate sequence as the Callison Lake dolostone because this succession appears to form a genetically continuous unit, minimizes new terminology and allows for straightforward stratigraphic correlation between the Coal Creek and Hart River inliers.

Mount Harper Group

Lower Mount Harper Group

Conglomerate and breccia of the lower Mount Harper Group overlie the Callison Lake dolostone north of the Harper Fault and overlie the Wernecke Supergroup and an undifferentiated carbonate unit to the south (Fig. 3). Near Mount Harper, the lower Mount Harper Group is exposed on the north side of a syn-depositional fault scarp where it consists of up to 1100 m of talus breccia and debris flow conglomerate interpreted as coalescing alluvial fans (Mustard and Donaldson 1990; Mustard 1991). To the east, in the Mt. Gibben area, the Lower Mount Harper Group is up to 300-m thick and consists predominantly of alluvial deposits commonly containing mud-cracks and conglomerate interbedded with minor marl that were deposited in a distal fan environment (Mustard 1991). The lower Mount Harper Group thins abruptly to the north away from the Harper Fault (Fig. 3).

Mount Harper Volcanic Complex

The Mount Harper Volcanic Complex (MHVC) is divided into six informal units that are defined both stratigraphically and compositionally (Roots 1987; Mustard and Roots 1997). A lower basaltic suite, composed of members A–C, comprises several hundreds of metres of pillowed and massive flows erupted into both subaqueous and subaerial settings. The lower flows overlie sandstone, siltstone, and cobble conglomerate north of the Harper Fault (Mustard and Roots 1997). Soft-sediment deformation, dolostone rip-ups, and spiracles attest to the soft, damp substrate encountered by the initial lava flow (Mustard and Roots 1997). The basal flows on the south side of the Harper fault disconformably overlie thick bedded undifferentiated carbonates and quartzite of the Pinguicula Group or Wernecke Supergroup, attesting to uplift and erosion of the fault block prior to volcanism. Volcanic members A and B form an edifice up to 1200 m thick. Some of the later eruptions were subaerial, producing agglutinated spatter cones and hematitic, autobrecciated massive flows (Mustard and Roots 1997). Holocene erosion has provided cross-sectional views of the edifice in which paleoslopes and tapering flows dip away from the volcanic edifice. Other steep exposures reveal that the edifice was unevenly dissected during, or shortly after, members A and B were extruded, resulting in overlaps by tuff-breccia, lapilli tuff, and block-and-ash breccia deposits of member C. The clasts are either primary basaltic or derived from erosion (Mustard and Roots 1997).

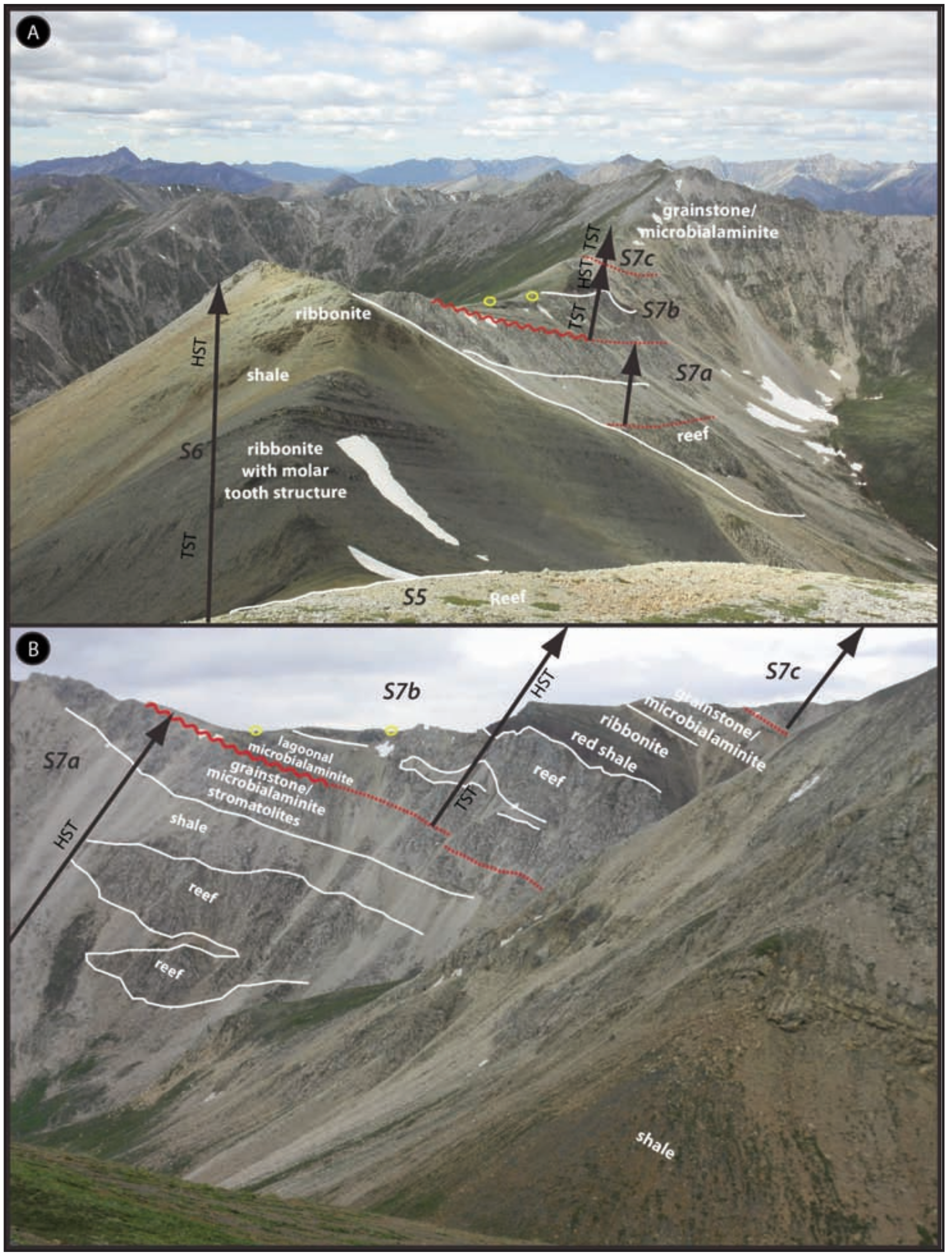

Figure 8. Sequence stratigraphic systems tracts outlined in red and reefs outlined in white; these are depicted in Figure 6 and described in text. A) Annotated photo of section G021, looking from the top peak shown in Figure 7b down the ridge to the south. Tents are circled in yellow for scale. B) Same exposure of section G021 as shown in Figure 8A, but looking east to show geometry of facies and systems tracts.

The upper suite consists of three members: D (rhyolite), E (andesite), and F (andesite). The relative timing of eruption and original distribution of these distinct units remain unclear. In different localities, each unit unconformably overlies members A–C. Rhyolite of member D forms thick flows and probable domes, and was dated at 717.43 ± 0.14 Ma (U/Pb CA-ID-TIMS zircon; Macdonald et al. 2010b). The age of the lower members of the MHVC are unknown so the temporal and spatial relationship between the eruption of the lower and upper suites remains unconstrained (Mustard and Roots 1997). Member E forms cliff exposures of columnar-jointed and shattered massive flows; these prograde over an apron of angular flow shards ('hydroclastic breccia') that extend over an older edifice. Member F andesites form pillowed flows, breccias, tuffs, and invasive flows that interfinger with and intrude into diamictites of the Rapitan Group, which includes a ~1-m thick, green to pink, brecciated tuff that was dated at 716.47 ± 0.24 Ma (U/Pb CA-ID-TIMS zircon; Macdonald et al. 2010b).

Mafic Dykes

Two sets of mafic dykes are present in the Coal Creek inlier. One set is oriented WSW–ENE and predominantly intrudes the Wernecke Supergroup (Fig. 3). These dykes are likely correlative with the sheared mafic rocks that are in fault contact with the Fifteenmile Group near Mt. Gibben in section E1002 (Fig. 3) and multiple intrusions associated with the WSW–ENE oriented Ogilvie breccias. In section E1003 (Fig. 3), an ESE–WNW oriented dyke also intrudes Pinguicula A.

A second set of dykes is oriented NNW–SSE and intrudes strata up through the lower MHVC. These dykes are associated with chaotic deformation in the Lower Mount Harper Group, indicating that these rocks were still soft sediments when the second suite was emplaced. No dykes have been observed to intrude the Rapitan Group. Thus, the NNW–SSE dykes appear to be associated with the ca. 717 Ma upper MHVC and predate the ca. 716 Ma Rapitan Group.

STRUCTURE

Our geological mapping has revealed two distinct sets of Precambrian structures within the Coal Creek inlier (Fig. 3). The oldest structures, predominantly NNW-side down normal faults oriented ~070°, cut the Chandindu formation and all of the underlying stratigraphy and were active during deposition of the Pinguicula Group and the Chandindu and Gibben formations of the Fifteenmile Group (yellow faults, Fig. 3). These structures have the same orientation as the Ogilvie breccias (Thompson et al. 1987, 1994) and one of the two major mafic dyke sets, suggesting either a genetic relationship or reactivation of earlier structures that generated the Ogilvie breccias. It is also unclear if the faulting in the lower stratigraphy of the Fifteenmile Group represents a continuum of activity or the reactivation of older syn-Pinguicula structures. These faults control the sedimentation patterns and stratal geometries between, and within, the Pinguicula Group and lower units of the Fifteenmile Group, forming two separate WSW–ENE oriented troughs (Figs. 3, 6 and 7). The Pinguicula Group stratigraphy appears to thicken to the southwest into the bounding WSW–ENE faults and these strata do not appear farther to the south. The faults are truncated and capped by the lowermost sequence of the Reefal assemblage of the Fifteenmile Group, but the fault-generated topography was preserved through deposition of the remaining Reefal assemblage and is highlighted by the distribution of stromatolite reef development.

A second set of WNW–ESE oriented, NNE-side down normal faults cuts the entire Fifteenmile Group and underlying strata (Fig. 3). These faults were active during deposition of the Mount Harper Group and are subparallel to the dykes that intrude all of the Fifteenmile and Mount Harper Group stratigraphy. Syn-extensional emplacement of the dykes is further demonstrated by soft-sediment deformation around many of the intrusions in the fault-controlled Lower Mount Harper Group. A third set of normal faults, oriented ~E–W, cut the overlying Windermere Supergroup and, in places, were reactivated as structures that offset the Cambrian–Devonian Bouvette Formation; the age and tectonic significance of these faults are unclear.

Cordilleran (Cretaceous) N- and NW-vergent thrust faults are common south of the Dawson Thrust and on the western margin of the Coal Creek inlier, but largely absent within the core of the inlier. Early attempts at mapping the Proterozoic stratigraphy in the Coal Creek inlier were confounded by large lateral facies change in the Fifteenmile Group, in particular within the Reefal assemblage. Consequently, these earlier maps include many inferred thrust faults (Thompson et al. 1994), which we have reinterpreted as predominantly conformable contacts along abrupt lithological changes.

CHEMOSTRATIGRAPHY

Methods

We report 1386 new carbonate carbon and oxygen isotope measurements (see data repository). Samples were cut perpendicular to lamination, revealing internal textures and between 5 and 20 mg of powder were micro-drilled from the individual laminations (where visible), avoiding veining, fractures, and siliciclastic components. Subsequent $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ analyses were performed on aliquots of this powder, acquired simultaneously on a VG Optima dual inlet mass spectrometer attached to a VG Isocarb preparation device (Micromass, Milford, MA), in the Harvard University Laboratory for Geochemical Oceanography. Micro-drilled samples were reacted in a common, purified H_3PO_4 bath at 90°C where evolved CO_2 was collected cryogenically and analyzed using an in-house reference gas. External error (1σ) from standards was better than ± 0.1‰ for both $\delta^{13}C$ and $\delta^{18}O$. Samples were calibrated to VPDB (Vienna Pee-Dee Belemnite) using the Carrara Marble standard. Increasing the reaction times (~7 minutes) minimizes any potential memory effect resulting from the common acid-bath system, which is included in the precision estimates noted above. Carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotopic results are reported in per mil notation of $^{13}C/^{12}C$ and $^{18}O/^{16}O$, respectively, relative to the standard VPDB.

Results

Carbon isotope chemostratigraphy of the Fifteenmile Group was performed to test local, regional, and global correlations through large facies changes. In the basal Gibben formation of the Fifteenmile Group, $\delta^{13}C$ values rise from ~0 to +4‰, and is a consistent trend throughout the inlier (Figs. 5 and 6). Carbon isotope values in thin carbonate interbeds, within siliciclastic-dominated strata of the overlying Chandindu formation and lower portion of the Reefal assemblage, are highly variable. This is likely due, in part, to local re-mineralization of organic matter and proportionately greater contribution of ^{13}C-depleted authigenic cements to the whole-rock carbonate content. Nonetheless, more carbonate-rich facies at the top of sequence 4b in the Mount Harper composite section (Fig. 5), show consistent values around 0‰ that rise steadily up-section to very heavy values (~+4‰).

The stromatolite reefs of sequence 5 of the Reefal assemblage have δ^{13}C values that average ~+4‰. However, lateral gradients are present in coeval strata. Above the basal flooding surface of sequence 6, δ^{13}C values increase further to ~+8‰. This sequence contains the 811.5 ± 0.1 Ma ash bed (Macdonald et al. 2010b). Above the ash bed, ´^{13}C values decrease smoothly to values as low as -6‰ (Figs. 5 and 6). However, the full ~14‰ isotope excursion is not present in some sections because the interval is shale-dominated (e.g., in the Mount Harper composite section, Fig. 5). In other sections, the excursion is cut out by erosional surfaces (e.g., in the Mt. Gibben composite section, Fig. 5). The most complete section of the excursion is exposed at Reefer Camp (section G021), which was measured from a paleo-high developed above a reef core (Fig. 6). There, the S7a transgression is carbonate dominated, so the whole excursion is preserved along with two additional smaller excursions in the S7a highstand and S7c (Fig. 6). Although a weak covariance between δ^{13}C and δ^{18}O can be observed through these excursions (see data repository), lateral reproducibility through different facies precludes large-scale diagenetic alteration.

In the Craggy dolostone, δ^{13}C values increase steadily up-section and plateau at ~4‰. Although these dolomites are dominated by cement and full of exposure surfaces, the δ^{13}C trends are consistent along strike and show no covariance with oxygen isotopes (see data repository).

DISCUSSION

Regional Correlations

Tatonduk Inlier

Young (1982) broadly divided Proterozoic strata discontinuously exposed in the Tatonduk inlier, a faulted anticline near the Yukon–Alaska border (~85 km NW of Mount Harper), into the upper and lower Tindir Group. The stratigraphically lowest exposed outcrop consists of ~150 m of grey to dark brown shale, siltstone and sandstone ('mudstone' unit of Young, 1982). These strata are succeeded by ~100 m of thin-bedded orange to light blue dolomicrite, followed by ~275 m of shallow-water dolostone dominated by stromatolitic buildups that are correlative with either Pinguicula B/C or the Gibben formation (Macdonald et al. 2011). The carbonates are overlain by black shale and an additional 500 m or more of poorly exposed interbedded sandstone and shale.

At Mt. Slipper, near the northernmost exposures in the Tatonduk inlier, carbonate strata previously mapped as the Cambrian–Ordovician Jones Ridge Limestone (Norris 1982; Young 1982; Morrow 1999), were reinterpreted based upon new mapping and carbon and strontium chemostratigraphy to be part of the Fifteenmile Group (Macdonald et al., 2010a, b, 2011). The exposures of the Fifteenmile Group at Mount Slipper consist of >350 m of predominantly stromatolitic dolostone and an additional ~500 m of black shale with interbedded quartz sandstone and minor carbonate that are assigned to the Reefal assemblage. Scale microfossils were located within the top 10 m of the Reefal assemblage at Mt. Slipper (Macdonald et al. 2010a; Cohen et al. 2011; Cohen and Knoll, 2012). These strata are succeeded by a yellow-weathering dolostone with common intraclast breccia, black chert nodules, and green siltstone and shale interbeds that are assigned to the Craggy dolostone. The remaining stratigraphy on Mt. Slipper and the youngest exposed strata in this part of the inlier consists of heavily silicified dolostone, and it is unclear if this dolostone is temporally equivalent to the Craggy dolostone or Callison Lake dolostone.

In the southern part of the inlier, the Fifteenmile Group is overlain by the Pleasant Creek Volcanics, which may be correlative with the ca. 717 Ma Mount Harper Volcanic Complex (Macdonald et al. 2011). Glacial diamictite with iron formation (Young 1982) is correlative with the Rapitan Group in the Coal Creek inlier and the Mackenzie Mountains (Macdonald et al 2010b; Macdonald and Cohen 2011). Numerous mafic dykes intrude the pre-Rapitan Group strata, including the exposures at Mt. Slipper, whereas the Rapitan Group and overlying stratigraphy do not host these intrusions (Macdonald et al. 2010a).

Hart River Inlier

Abbott (1997) defined six Pinguicula-correlative units beneath the Callison Lake dolostone in the Hart River inlier. The Pinguicula units include: A, B and C, and three discontinuous members of unit D. Unit PD1 consists of a series of shale to sandstone cycles that broadly make up a single depositional sequence. Unit PD1 is conformably overlain by a carbonate sequence capped by a thick, shoaling-upward, medium-bedded, bluish-grey dolostone with abundant ooids and microbialaminite (PD2), which is, in turn, succeeded by mud-cracked siltstone and shale of PD3 (Halverson et al. 2012). The basal siltstone–sandstone sequence of PD1 is regarded as the basal sequence of the Fifteenmile Group (S1), which is equivalent to the thin sandstone unit at the base of the Gibben formation in the Coal Creek inlier. Unit PD2 is equivalent to the carbonates of the Gibben formation in the Coal Creek inlier. Unit PD3 is composed of brown sandstone with minor orange dolostone, which we correlate with the Chandindu formation (Halverson et al. 2012). Correlation between the Coal Creek and Hart River inliers indicates that all of the upper Fifteenmile Group is missing in the Hart River inlier at the angular unconformity beneath the Callison Lake dolostone (Abbott 1997; Macdonald and Roots 2010).

Wernecke and Mackenzie Mountains

Recent stratigraphic studies in the Wernecke Mountains (Thorkelson et al. 2005; Medig et al. 2010; Turner 2011) have assigned various portions of units D–F of the Pinguicula Group of Eis-

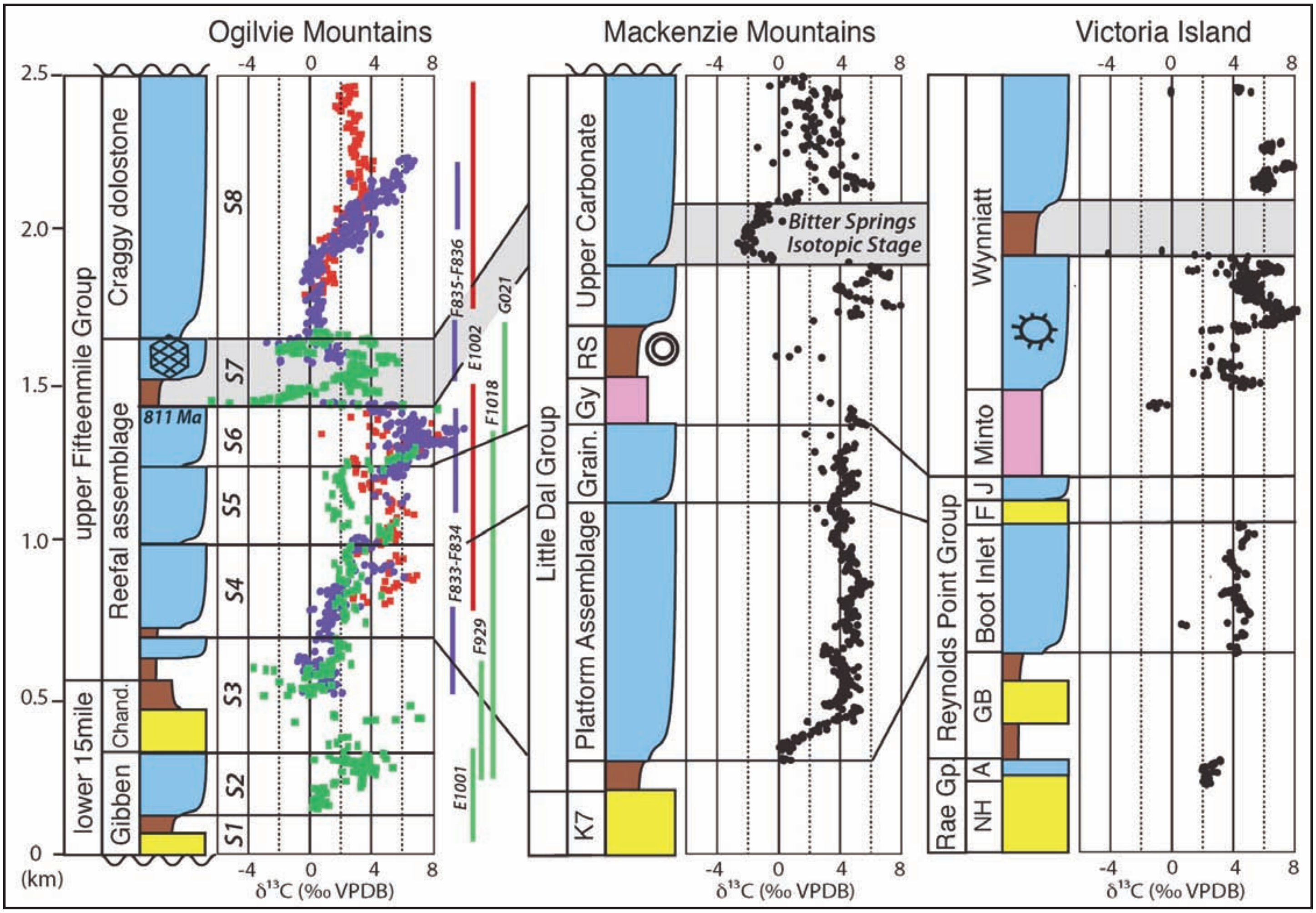

Figure 9. Correlation of sequences between the Fifteenmile Group, Little Dal Group, and Shaler Supergroup as indicated by carbon isotope chemostratigraphy. Schematic stratigraphy and symbology follows Figure 2. Red squares are from stratigraphic sections located near Mt. Gibben, green squares are from sections located near Reefer camp, and blue dots are from sections near Mount Harper (see Figure 3). Particular sections are noted with coloured bars and detailed in Figures 5 and 6. Carbon isotope data from the Mackenzie Mountains is after Halverson (2006) and data from Victoria Island is after Jones et al. (2010). Refer to Figure 2 for abbreviations of formations.

bacher (1981) to the Hematite Creek, Katherine, and Little Dal groups. Moreover, Turner (2011) formally divided the Hematite Creek Group into the Dolores Creek, Black Canyon Creek, and Tarn Lake formations. This work facilitates correlation of the Coal Creek strata with particular formations in the Mackenzie Mountains and Shaler supergoups. Extension of our proposed correlation scheme for the Pinguicula and Fifteenmile groups in the Tatonduk, Coal Creek and Hart River inliers to the Wernecke Mountains suggests that the Dolores Creek Formation is equivalent to unit PD1 in the Hart River inlier, that the Black Canyon Creek Formation is equivalent to PD2 in the Hart River inlier and the Gibben formation in the Coal Creek inlier, and that the Tarn Lake Formation and Katherine Group are equivalent to PD3 in the Hart River inlier and the Chandindu formation in the Coal Creek inlier (Figs 2 and 9).

Halverson (2006) presented ´^{13}C data for the Little Dal Group in the Mackenzie Mountains that we can use to test proposed lithostratigraphic correlations (Fig. 9). In regards to this chemostratigraphic correlation, the Reefal assemblage displays a rise in δ^{13}C from 0 to +5‰ that mirrors the δ^{13}C profile of the Platform Assemblage of the Little Dal Group. Extremely positive δ^{13}C values (>+8‰) at the base of sequence 6 in the Fifteenmile Group are correlative with similar values in the lower portion of the Upper Carbonate formation of the Little Dal Group. These correlations suggest that the Gypsum formation and the Rusty Shale formation were deposited during the S6 LST (Fig. 9). Negative δ^{13}C values within a transgressive sequence tract in the middle Upper Carbonate formation (Halverson 2006) can be correlated with the negative values in S7 of the Fifteenmile Group (Fig. 9). Exact correlations between the upper portion of the Upper Carbonate formation and the Craggy dolostone remain unclear.

Victoria Island

A composite carbon isotope curve through the upper Shaler Supergroup was recently published by Jones et al. (2010), who suggested that the Aok Formation could be correlative with the basal Little Dal Group. Here we follow previous lithostratigraphic correlation schemes (e.g. Rainbird et al. 1996), which correlate unit K6 of the Katherine Group with the Aok Formation and, in turn, the Chandindu formation; however, these correlations are limited by the lack of data in unit K6 of the Katherine Group. Sequence S4 of the Reefal assemblage is broadly correlative with the Platform Assemblage in the Mackenzie Mountains and Boot Inlet Formation on Victoria Island. Sequence S5 can be correlated with the Grainstone formation and the Fort Collinson and Jago formations on Victoria Island. Like the Gypsum Formation, evaporites of the Minto Inlet Formation appear to record a period of lowstand represented by progradation of giant reef complexes in the LST of S3B. Extremely positive $\delta^{13}C$ values (>+8‰) in the lower portion of the Wynniatt Formation can be correlated with those at the base of S6 in the Fifteenmile Group (Fig. 9). We follow Jones et al. (2010) and correlate the $\delta^{13}C$ downturn in the middle Wynniatt transgression with the Bitter Springs isotopic stage. These correlations (Fig. 9) suggest that rich microfossil assemblages in the lower Wynniatt Formation (Butterfield and Rainbird 1998; Butterfield, 2005a, b) and less diverse assemblages in the Rusty Shale (Butterfield and Rainbird, 1998) are stratigraphically below scale microfossils from the Fifteenmile Group (Cohen et al. 2011; Cohen and Knoll, 2012).

Implications for Neoproterozoic Carbon Isotope Chemostratigraphy

Halverson et al. (2006) suggested that the rise in $\delta^{13}C$ values from 0‰ to +5‰ in the Platformal Assemblage of the Little Dal Group represents a global rise from a carbon cycle that averaged 0‰ in the Mesoproterozoic to one that averaged +5‰ in the Neoproterozoic. With no direct age constraints on the base of these isotopic profiles, the thickness of the strata up to the ~811 Ma ash bed is dependent on accumulation rates. It is likely that platformal and stromatolite dominated facies have higher sedimentation rates than basinal facies, and consequently the duration of the early Neoproterozoic +5‰ plateau (Halverson et al. 2010), which is based on the Platformal Assemblage of the Little Dal Group, may be exaggerated. Moreover, isotopically heavy intervals in the Gibben formation (Figs. 6 and 10) indicate that this rise was not steady and that there is probably significant variability in late Mesoproterozoic and early Neoproterozoic carbon isotope records that remains to be fully elucidated.

Macdonald et al. (2010) suggested that the 811.5 ± 0.1 Ma ash bed dates the onset of the Bitter Springs isotopic stage. This interpretation is further supported by additional high-resolution chemostratigraphic sections through carbonate-rich strata of the upper Reefal assemblage; however, this work has revealed three carbon isotopic excursions that do not have obvious counterparts elsewhere (Fig. 6). The Bitter Springs anomaly in Svalbard and Australia has a double peak, with slightly positive values between the major negative excursions (Halverson et al. 2007; Swanson-Hysell et al. 2010). In this correlation scheme, the first downturn in the TST of S7a of the Reefal assemblage, which begins at ca. 811.5 Ma, is equivalent to the G1 surface in Svalbard, and the return to positive values in the HST of S7C at the top of the Reefal assemblage is equivalent to the S1 surface.

Another interesting feature of the $\delta^{13}C$ curve from the Fifteenmile Group is that the major negative downturn at the base of the Reefal assemblage corresponds with the maximum flooding surface of sequence S7. This can be interpreted in at least three ways: 1) there was a global decrease in the percent of carbon buried as organic carbon; 2) the transgression was eustatic and corresponded to the addition and remineralization of isotopically light carbon to the ocean/atmosphere, which drove both a negative carbon isotope excursion, warming, and transgression; or 3) isotopically light authigenic carbonate was preferentially formed locally during transgressive sequences. The data presented here demonstrates that not all of the transgressive sequences in the succession host negative isotope excursions, and that the negative $\delta^{13}C$ excursion at the base of S7 is broadly reproducible in the basin where the sequence is preserved. Thus, if authigenesis is responsible, it must have been widespread but episodic in the basin.

Basin Formation in the Coal Creek Inlier

Basin Event 1: The Pinguicula prelude

Active tectonism during deposition of the Pinguicula Group is demonstrated by: 1) olistostromes of the Gillespie Lake Group within Pinguicula Group strata that increase in abundance towards the south; 2) lateral facies changes in Pinguicula B/C with stromatolitic reefs built on paleo-highs that grade to the SSE into laminated dolomicrite; 3) lateral thickness variations in all of the units of the Pinguicula Group. These thickness variations do not merely represent erosion associated with the sub-Gibben unconformity, but instead record internal thinning and truncation due to depositional onlap of topographic relief.

The extent to which the overlying Fifteenmile Group follows the syn-tectonic depositional patterns of the Pinguicula Group in the Coal Creek inlier is remarkable. This could be interpreted in one of two ways: 1) the Pinguicula Group is an older basin and the Fifteenmile Group extension and depositional patterns followed preexisting crustal weaknesses; 2) the Pinguicula Group was deposited in half graben along NNW-side down normal faults and represents an early phase of early Neoproterozoic extension that culminated in the deposition of the Fifteenmile Group.

Basin Event 2: Lower Fifteenmile extension

The lowermost Fifteenmile Group is highly variable in thickness with depositional patterns defined by small fault-bounded sub-basins, resulting in wedge-shaped stratal geometries and inferred onlapping patterns (Figs. 5 and 6). Northeast of Mount Harper, these faults cut through the Gibben and Chandindu formations as NNW-side down normal faults (Fig. 3) that are capped by the overlying Reefal assemblage.

The interpretation of the geometry of these structures depends on the degree to which the Yukon block has been affected by post-811

Ma vertical axis tectonic rotations. A large Neoproterozoic counterclockwise (CCW) rotation and dextral displacement between the Yukon block and Laurentia was first proposed by Eisbacher (1981) and developed further by Aitken and McMechan (1991) and Abbott (1996) who incorporated paleomagnetic evidence (Park and Jefferson 1991; Park et al. 1992). The dextral displacement hypothesis originated as a response to abrupt facies changes in the MMSG across the Snake River Fault (Fig. 1) and paleocurrent directions in the Wernecke Supergroup (Eisbacher 1981; Aitken and McMechan 1991). Right-lateral displacement occurred in the late Neoproterozoic along the Richardson Fault Array (Fig. 1) and these faults were reactivated during the Cretaceous (Norris 1997). A post-Cryogenian CCW rotation was further suggested by paleomagnetic studies on the Mount Harper Volcanic Complex (Park et al. 1992). Park et al. (1992) proposed an 80° CCW rotation, however, he used earlier dates with large error on the Mount Harper Volcanic Complex and correlated the virtual pole with that of the Little Dal Basalt. The new ages on the Mt. Harper Volcanic Complex and the Franklin LIP (Macdonald et al. 2010) suggest this pole should be correlated with the grand mean pole on the Franklin LIP (Denyszyn et al. 2009) to refine this rotation. This would reduce the rotation to 66° CCW. If the paleomagnetic pole on the Mount Harper Volcanic Complex (Park et al. 1992) stands further scrutiny, then the pre-811 Ma WSW–ENE structures in the Coal Creek inlier would rotate roughly parallel with the strike of the Mackenzie Arc and the Fifteenmile Group would represent the conjugate margin of a graben formed opposite of the MMSG. If the paleomagnetic pole cannot be reproduced and the Yukon block has not moved substantially relative to the autochthon, then the WSW–ENE structures would represent extension on the NW margin of Laurentia.

Basin Event 3: Mount Harper extension

As discussed above, the Craggy dolostone is unconformably overlain by the Callison Lake dolostone in the Coal Creek inlier and this unconformity places the Callison Lake dolostone on the lower Fifteenmile Group in the Hart River inlier (Abbott 1997; Macdonald and Roots 2010; Halverson et al. 2012). Silicification typically extends 100s of metres below this unconformity surface, which also displays evidence of localized paleokarstification (Mustard and Donaldson, 1990). Depositional patterns of the Callison Lake dolostone and the Mount Harper Group are completely divorced from those of the underlying Fifteenmile Group suggesting the commencement of an additional basin-forming episode. Locally, the lower Mount Harper Group paraconformably overlies shale in the uppermost Callison Lake dolostone and unconformably overlies the Quartet Group (Fig. 3), which suggests pronounced synsedimentary fault activity (Mustard, 1991). Clasts within the conglomerate display an inverted stratigraphy, with clasts of the youngest units on the footwall dominating the lowest conglomerates on the hanging-wall, and clasts of older units becoming more common upwards in the congolomerate, demonstrating that it formed while progressively eroding strata on the footwall. Much of the overlying Mount Harper Volcanic Complex formed via subaerial eruptions, suggesting that the volcanics filled much of the graben (Fig. 9). Where the volcanics taper to the north, the overlying glacial diamictite of the Rapitan Group thickens significantly.

The Callison Lake dolostone and Mount Harper Group occupy an equivalent stratigraphic position with the Coates Lake Group of the Mackenzie Mountains (Macdonald and Roots, 2010). In the Mackenzie Mountains, the Coates Lake Group and Little Dal Basalt unconformably overlie the MMSG in NNW-oriented grabens that formed in response to right-lateral transtension (Jefferson 1978). Coates Lake- to Rapitan-age folding is also present in the Mackenzie Mountains and is responsible for paleohighs that formed along transpressional segments of transfer zones (Jefferson 1978).

The Make-Up and Break-Up of Rodinia

The exact timing and geometry for both the formation and the breakup of Rodinia has remained elusive. Situated at the NW corner of Laurentia, and in the centre of Rodinia (Li et al. 2008b), the Yukon occupies an important position for distinguishing between tectonic events occurring on the northern and western margins of Laurentia. Recent paleomagnetic studies provide a Rodinia reconstruction that is "longer-lasting and tighter-fitting" (Li and Evans 2011), and these data require that Australia and Laurentia came together after 1070 Ma with a 'missing link' presiding in-between, and subsequently separated between ca. 750 and 650 Ma. Paleomagnetic and geochronologic data indicate that South China may be the 'missing link' (Li et al., 1995, 2008b). South China is a composite Neoproterozoic continent consisting of the Cathaysia and Yangtze blocks, which converged during the ca. 835 Ma Sibao orogeny (Wang et al. 2012). In the 'missing link' model, the Cathaysia Block was a fragment of Mesoproterozoic Laurentia and the Yangtze Block provided westerly-derived 1600–1490 Ma zircons to the Belt Supergroup (Ross et al. 1992; Ross and Villeneuve 2003). The Sibao Orogeny may have also provided a more local source of Grenville-age 1.2–1.0 Ma zircons to the western margin of Laurentia (Li et al. 2008a) that have previously been attributed to a transcontinental river system (Rainbird et al. 1997). However, no early Neoproterozoic foreland basin or orogen has been identified on the western margin of Laurentia to suggest a link to this orogenic event. Possible exceptions occur in the Coppermine homocline (Fig. 1), where two sets of structures deform the ca. 1270 Ma Coppermine River Group and predate the Shaler Supergroup (Hildebrand and Baragar 1991), and in the Wernecke Mountains, where NW-vergent folds in the Hematite Creek and Katherine groups have been assigned to the Corn Creek Orogeny (Eisbacher 1981; Thorkelson 2000; Thorkelson et al. 2005). Neoproterozoic folding has also been described in the Coates Lake and Rapitan groups in the Mackenzie Mountains (Helmstaedt et al.1979; Eisbacher 1981), and in the Shaler Supergroup on Victoria Island (Heaman et al. 1992; Bedard et al. 2012), but these structures appear to be too young to be correlative with the Sibao orogeny.

The Fifteenmile Group and equivalent strata in the Mackenzie Mountains and Victoria Island, can be broadly correlated to the Shihuiding Formation of the Cathaysia Block, and the Ziajiang, Danzhou and Banxi groups of the Yangtzee Block (Wang et al. 2011), the lower Callana Group in South Australia, the Bitter Springs Formation and equivalents in central Australia (Walter et al. 1995). Like the Fifteenmile Group, these Chinese basins also contain ca. 810 Ma tuff horizons (Wang et al. 2012). The 'missing link' model predicts that more ca. 800 Ma grains from the Sibao orogeny will be discovered in the uppermost Fifteenmile Group or overlying strata. Interestingly, significant ca. 800 Ma populations have been discovered in the Uinta Mountains Group of Utah (Dehler et al. 2010), which may have been sourced from South China. Additionally, new age constraints on successions in the western US indicate that there are no known basins that formed between 1.0 and 0.8 Ga between 62° N and Mexico (Dehler et al., 2010, 2011), such that the basin forming event that accommodated the Fifteenmile Group and equivalents in the Shaler Supergroup and MMSG is a phenomenon of the NW margin of Laurentia and cannot represent rifting on the whole of the western margin, contrary to the simple-shear rift model proposed to accommodate the MMSG (Turner and Long 2008). We suggest instead that the inferred NE–SW oriented faults in the MMSG of Turner and Long (2008) are coeval with the faults in the basal Fifteenmile Group and also represent normal faults rather than transfer faults. This is consistent with Aitken's (1981) previous interpretation of the Little Dal Group, which suggested deepening to the NNW.

Based on the assumption that the early Neoproterozoic conjugate margin to Laurentia was South China, we propose a new model for the early Neoproterozoic tectonic evolution of northwest Canada. The coincidence between basin formation in South China, Australia, and NW Canada at ca. 830 Ma, and the emplacement of the Gubei and Gairdner LIPs in South China and Australia between 830 and 810 (Wingate et al. 1998; Li et al. 1999; Wang et al., 2008) suggests a mechanistic link. We propose that these strata were accommodated by extension and the subsequent thermal decay associated with the passing of Rodinia over a plume. In this model, the Reefal assemblage and Craggy dolostone are associated with the thermal decay of this plume. Deposition culminated with the intrusion of the 780 Ma Gunbarrel dykes—the nature of this igneous event remains poorly understood. This model is further consistent with the inference of Rainbird et al. (1996) that Sequence B formed in an intracratonic basin.

The ca. 717 Ma NNE-side down normal faults in the Coal Creek inlier represent a reactivation of the NW margin of Laurentia. Geological and geochronological data suggest that Siberia occupied a position north of the Yukon during the Neoproterozoic (Rainbird et al. 1998). Moreover, dykes of approximately Franklin age are present in southwestern Siberia (Gladkochub et al. 2006; Bedard et al. 2012;). Rainbird (1993) further documented fault-bounded graben with coarse terrestrial fill in the upper Shaler Supergroup, immediately beneath the ca. 723 Ma Natkusiak basalts. Although a record of later Cryogenian thermal subsidence is not present in Victoria Island where there is no section present above the Natkusiak basalts (Rainbird 1993), a Cryogenian passive margin succession on the northern margin of Laurentia may be recorded in the subsurface west of Melville Island (Helwig et al. 2011) and in the Katakturuk Dolomite on the parautochthonous North Slope subterrane (Macdonald et al. 2009). Thus, a scenario consistent with all of these data is that extension occurred in the early Neoproterozoic between Siberia and northwest Laurentia, creating space between the two cratons and separating their respective APW paths (Rainbird et al. 1998; Khudoley et al. 2001; Evans 2009); however this extension may not have manifested itself in full rifting with the development of oceanic crust, such that both margins were later affected by additional extension and the emplacement of the ca. 720 Ma Franklin LIP.

The nature of Cryogenian basin formation on the western margin of Laurentia remains enigmatic. As discussed above, the presence of both Cryogenian normal faults and folding implies a transtensional–transpressional setting for Windermere-age rifting (Jefferson and Parrish 1989). Transtension may further account for the irregular distribution of Cryogenian strata in Yukon (Macdonald et al. 2011) and the lack of significant crustal thinning until the latest Ediacaran (Colpron et al. 2002), consistent with thermal subsidence models that indicate final rifting in the earliest Cambrian (Bond and Kominz 1984). Full description of Cryogenian and Ediacaran basins is beyond the scope of this paper and the later Neoproterozoic tectonic evolution of NW Laurentia remains to be elucidated with future work.

CONCLUSIONS

Geological mapping, chemostratigraphy and sequence stratigraphic analysis of Neoproterozoic strata in Yukon motivate revised correlation of the early Neoproterozoic deposits of northwest Canada. These results demonstrate that at least three and possibly four basin-forming events are recorded in Neoproterozoic strata of Yukon. The Pinguicula Group constitutes the oldest succession and its age and accommodation history remain poorly constrained. Subsidence and deposition of the Fifteenmile Group initiated prior to ~811 Ma as a result of NNW-side down normal faulting (present coordinates). The extension that accommodated the Fifteenmile Group is coincident with the passing of a plume under Rodinia and the emplacement of large igneous provinces and the formation of failed intracontinental rift basins in South China and Australia. Large stromatolite-cored reef systems of the Reefal assemblage developed on these paleohighs and prograded to the NNW in a series of highstand systems tracts, shedding reworked carbonate into and gradually filling deep-water, shale subbasins. The basin was reactivated with ca. 717 Ma NNE-side down normal faulting in the Yukon and the emplacement of the Franklin large igneous province on the northern margin of Laurentia.

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