The Proterozoic Pinguicula Group, Wernecke Mountains, Yukon: A siliciclastic and carbonate slope to basin succession with local and exotic sediment provenance

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ABSTRACT

The late Meso or early Neoproterozoic Pinguicula Group, Wernecke Mountains, Yukon, is a siliciclastic and carbonate succession deposited on an angular unconformity developed on the Wernecke Supergroup. The group consists of three units. Unit A consists of a fining-upward conglomerate and sandstone unit overlain by a monotonous siltstone succession. Unit B is a dolostone and limestone succession in which shallower-water facies, deposited above storm wave-base, grade up-section into slope facies with intraclast rudstones and turbidites. Unit C is a deep-water dolostone and limestone succession that has been pervasively altered by carbonate veins, zebra dolomite, and coarsely crystalline dolostone.

Detrital zircon geochronology from the Pinguicula Group provides information on provenance and age of the sediment deposited in the Pinguicula basin. A distinctive population from the Mesoproterozoic, between 1610 and 1490 Ma (North American Magmatic Gap), suggests that sediment may have been derived from Australia. In addition, detrital zircon ^{207}Pb/^{206}Pb ages from the Wernecke inlier are as young as 1144±25 Ma (one grain), which raises the possibility that the Pinguicula Group is younger than *ca.* 1150 Ma. The reliability of this finding will be addressed by additional geochronology.

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INTRODUCTION

The Meso or early Neoproterozoic Pinguicula Group is a siliciclastic and carbonate bearing succession in the Wernecke Mountains, Northern Yukon (Fig. 1a,b,c, herein referred to as the study area). Beyond this area it has poorly known distribution, but has been mapped in the Hart River inlier (Abbott, 1997). The group comprises three units (A, B, and C), which have not previously been described in detail.

Possible correlatives of the Pinguicula Group have been identified in the Hart River (also referred to as the Pinguicula Group) and Coal Creek (lower Fifteenmile Group) inliers in the Ogilvie Mountains (Thompson *et al.*, 1992; Abbott, 1997; Medig *et al.*, 2010). More distant correlatives have also been proposed, such as the Dismal Lakes Group in the Coppermine Homocline (Cook and MacLean, 1995; Thorkelson, 2000; Long *et al.*, 2008) and the lower Tindir Group in Alaska (Abbott, 1997; Macdonald *et al.*, 2011). The lack of detailed stratigraphic work in the type area combined with the lack of refined ages for the group have made definitive correlations difficult.

Between 2009 and 2011, detailed sections were measured in units A, B, and C of the Pinguicula Group. Samples were collected from a sandstone bed at the base of unit A and detrital zircon grains were extracted for U-Pb geochronologic analysis. Results of the analysis and the implications for proposed correlations, as well as the stratigraphy of the Pinguicula Group, are discussed in detail below.

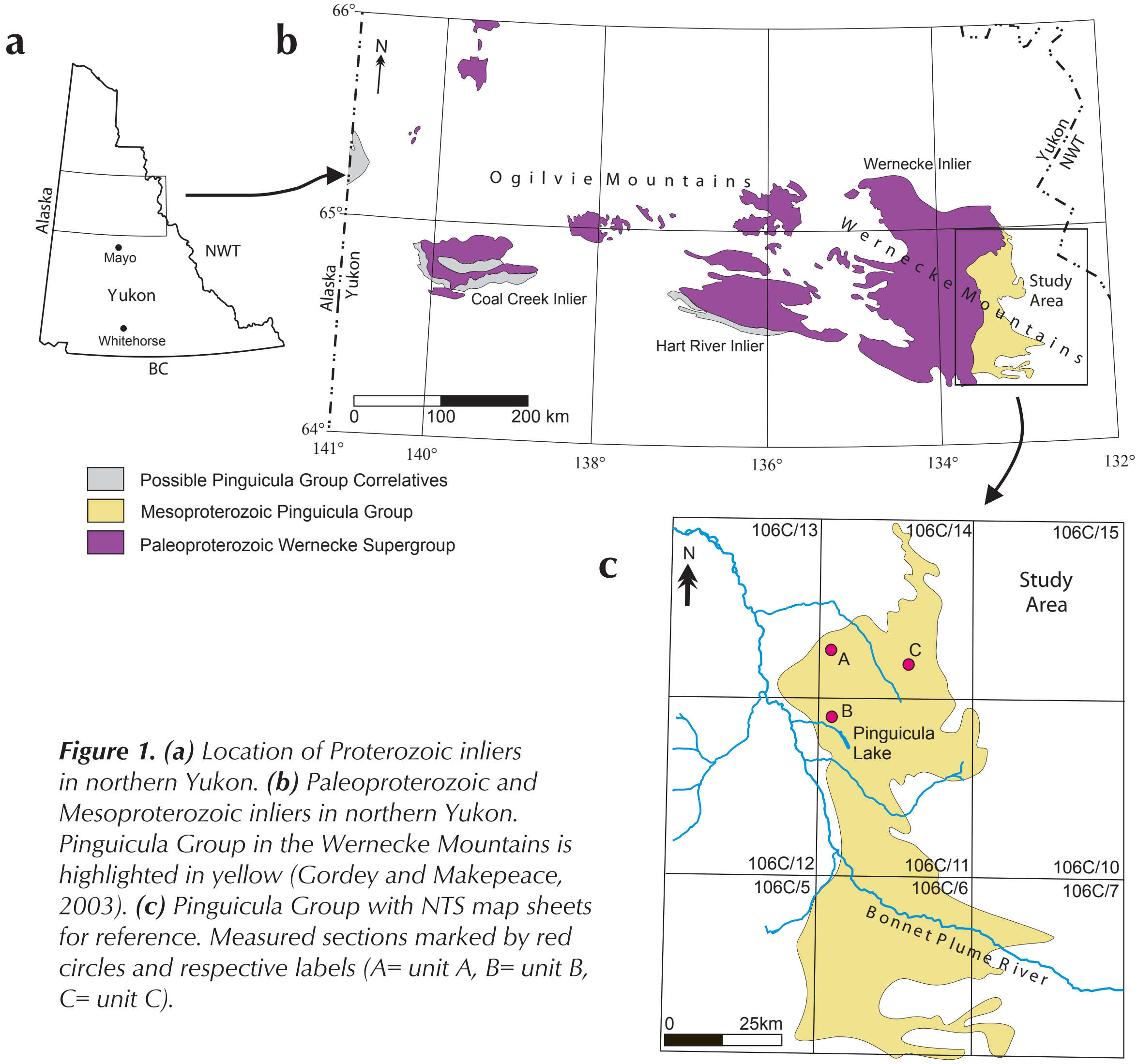

Figure 1. ***(a)*** *Location of Proterozoic inliers in northern Yukon.* ***(b)*** *Paleoproterozoic and Mesoproterozoic inliers in northern Yukon. Pinguicula Group in the Wernecke Mountains is highlighted in yellow (Gordey and Makepeace, 2003).* ***(c)*** *Pinguicula Group with NTS map sheets for reference. Measured sections marked by red circles and respective labels (A= unit A, B= unit B, C= unit C).*

REGIONAL GEOLOGY

The oldest exposed strata in the Wernecke and Ogilvie mountains are the Wernecke Supergroup. This includes (from oldest to youngest) the Fairchild Lake Group, the Quartet Group, and the Gillespie Lake Group (Thompson *et al.*, 1992; Abbott, 1997; Thorkelson, 2000). Detrital zircon ages from the Wernecke Supergroup indicate that the group is younger than 1610±30 Ma (Furlanetto *et al.*, 2009). The Wernecke Supergroup was affected by three generations of deformation, referred to collectively as the Racklan Orogeny, prior to intrusion of the Wernecke breccia at *ca.* 1595 Ma (Brideau *et al.*, 2002; Thorkelson *et al.*, 2005). The Wernecke Supergroup in both the eastern Ogilvie Mountains (Hart River inlier) and Wernecke Mountains (Wernecke inlier) is crosscut by the 1380 Ma Hart River sills (Abbott, 1997; Thorkelson *et al.*, 2005). In the *ca.* 200 Ma interval between the hydrothermal event forming the Wernecke breccia and the emplacement of the Hart River sills, there was either little activity in the area or the rock record has not been preserved. Deposition of the Pinguicula Group occurred well after emplacement of the Hart River sills. The erosional interval between emplacement of the Hart River sills and deposition of the Pinguicula Group may represent a significant time interval, as it is marked by a major gap in the rock record. Unconformably overlying the Pinguicula Group are strata of the Mackenzie Mountains supergroup strata (also known locally as the Hematite Creek Group) in the Wernecke inlier, unit D in the Hart River inlier, and lower Fifteenmile Group units PR3 to PR5 in the Coal Creek inlier (Medig *et al.*, 2010; MacDonald *et al.*, 2011; Turner, 2011).

PINGUICULA GROUP STRATIGRAPHY, WERNECKE MOUNTAINS

The Pinguicula Group was established in the Pinguicula Lake area by Eisbacher (1978), who described the group as unconformably overlying the Wernecke Supergroup and comprising six informal units (A through F; Eisbacher, 1978, 1981). Thorkelson (2000) and Thorkelson *et al.* (2003) identified a disconformity between units C and D and reassigned the upper three units to the Hematite Creek Group. Units D to F were correlated with the Tsezotene Formation and Katherine Group of the Mackenzie Mountains supergroup. Turner (2011) revised and subdivided the Hematite Creek Group into three formations: the Dolores Creek Formation, Black Canyon Creek Formation, and Tarn Lake Formation. Turner (2011) proposed correlation of the Black Canyon Creek formation of the Hematite Creek Group with the "H1 unit" of the Mackenzie Mountains supergroup. The Tarn Lake Formation was correlated with the Tsezotene Formation, also of the Mackenzie Mountains supergroup. The three new formations constitute the former unit 'D' of the Pinguicula Group. Former unit 'E' of the Pinguicula Group is now correlated with the Katherine Group, and former unit 'F' of the Pinguicula Group was identified as the lower part of the Little Dal Group. Units A through C, however, are internally conformable and remain part of the Pinguicula Group.

PINGUICULA GROUP

UNIT A

Description

Unit A is a siliciclastic succession that overlies the Gillespie Lake and Quartet groups of the Wernecke Supergroup, including zones of Wernecke breccia, with angular unconformity. Where Wernecke breccia underlies unit A, a pale, crumbly regolith is present at the erosional top of the breccia zones and extends downwards to as much as 12 metres in some areas (Thorkelson, 2000). In some locations, in both the Wernecke and Hart River inliers, the Pinguicula Group unconformably overlies the Hart River sills (Abbott, 1997; Medig *et al.*, 2010). This observation contrasts with a previous interpretation (Thorkelson, 2000; Thorkelson *et al.*, 2005) in which the Hart River sills in the Wernecke Mountains were thought to crosscut the Pinguicula Group. An unconformable rather than an intrusive contact relationship is supported by an apparent lack of metamorphism imposed by the Hart River sills on the Pinguicula Group. This relationship is in contrast to the Wernecke Supergroup and clasts within Wernecke breccia which are both affected by thermal metamorphism (Thorkelson, 2000). The upper contact between units A and B is gradational, and is marked by increased carbonate content in the siltstone immediately below the contact with unit B, as well as the appearance of bedding-parallel layers of carbonate nodules in the siltstone.

A detailed section through unit A was measured on an exposure in a creek bed at the PIKA mineral occurrence (Figs. 2 and 3; Yukon MINFILE, 106C 071; base at 573576E 7191036N NTS 106C/14[1]). This location was chosen because it is easily accessible (by helicopter and by foot) and exposes both a lower, unconformable

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[1] *UTM coordinates are zone 8W and NAD 27 unless otherwise noted.*

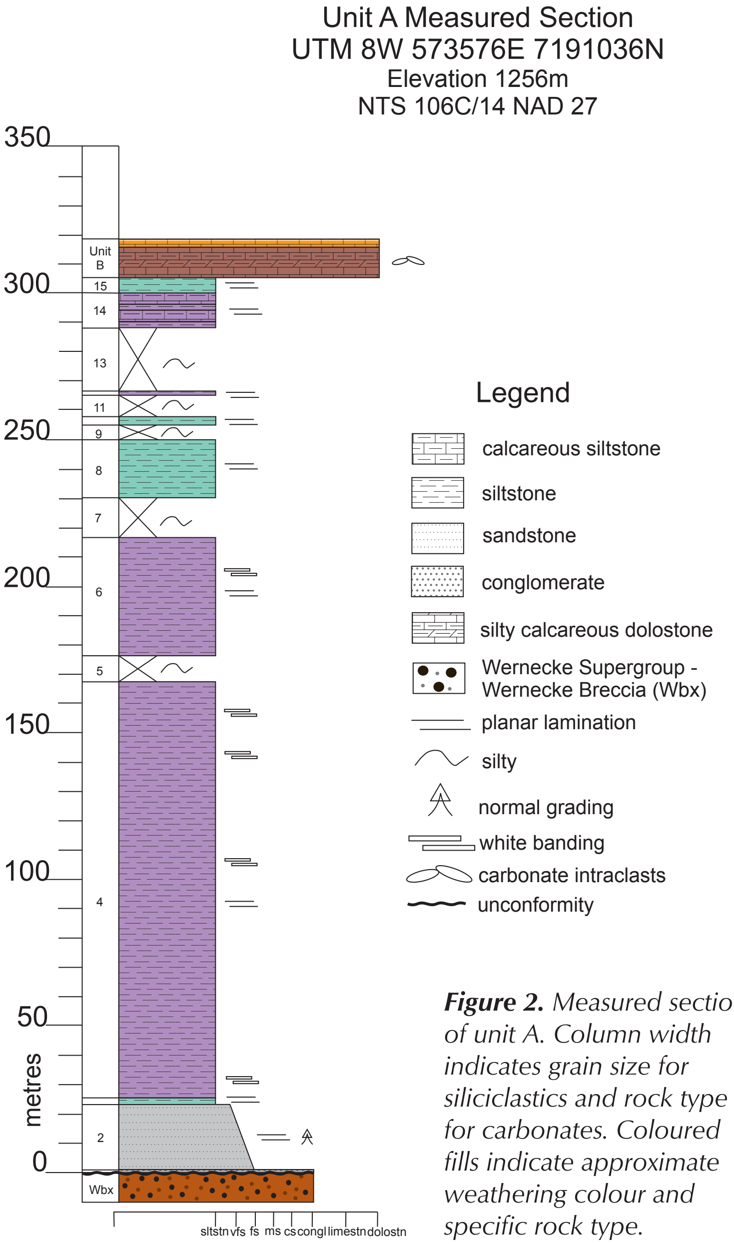

Figure 2. *Measured section of unit A. Column width indicates grain size for siliciclastics and rock type for carbonates. Coloured fills indicate approximate weathering colour and specific rock type.*

contact with the Wernecke breccia and an upper gradational contact with unit B. This location also has conglomerate and sandstone at the base of unit A: rock types that are commonly not exposed or not present in other locations in the study area.

At the measured section, unit A is 306 m thick. It consists predominantly of siltstone with minor conglomerate, and sandstone (Fig. 2). The base of unit A overlies a zone of Wernecke breccia. The lowest unit (unit 1) is an ~50 cm-thick layer of polymictic pebble conglomerate. The conglomerate is matrix-supported with a matrix of predominantly fine-sand grade quartz and carbonate grains. The clasts are predominantly of small to medium pebble grade. They are typically well-rounded and consist mainly of grey, hematitic red, and black siltstone, yellow-weathering, grey, and red carbonate, and rare clasts of Wernecke breccia. Within the conglomerate are 1-2 cm-thick beds of fine-sand grade quartz arenite (Fig. 4a). Overlying the conglomerate from 0.5 to 23 m is a succession of parallel-laminated to thin bedded rusty orange to grey-weathering sandstone layers (unit 2; Fig. 4b). The sandstone grades from a well-sorted fine-grained sandstone, texturally mature quartz arenite, with a minor lithic component and calcite cement, to a very fine-sand grade lithic wacke. Sandstone beds are typically from 3 to 10 cm-thick, but are locally up to 50 cm (Fig. 4c). Dark grey to black, planar-parallel laminae are present in the sandstone at a mm to cm-scale. The sandstone unit fines up-section and displays a transition in colour from grey to pale grey at the base to dark grey at the top. Pyrite is disseminated throughout the sandstone, resulting in a rusty orange-weathering surface.

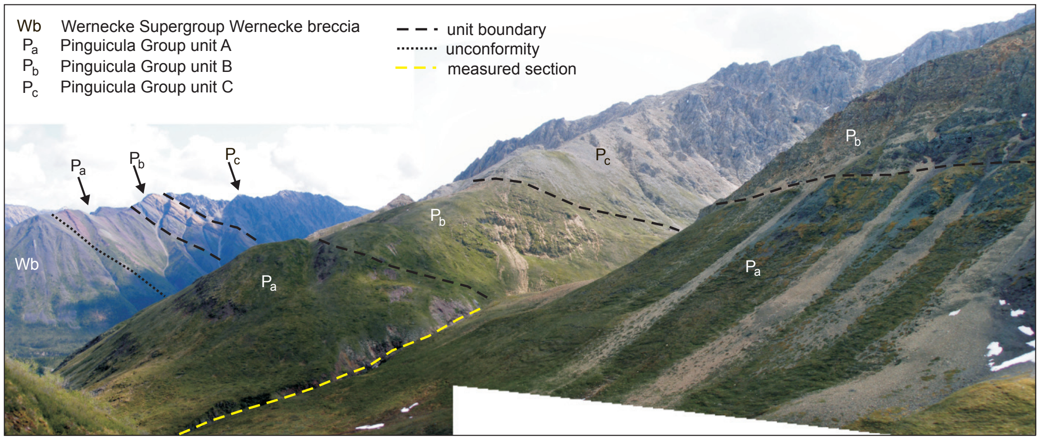

Figure 3. *Pinguicula units A, B, and C overlying the Wernecke breccia at the Pika occurrence. View to the northeast. Measured section of unit A was established along the creek. NTS map sheet 106C/14 UTM 8 W 573381E 7190576N NAD 27.*

The sandstone grades into a predominantly maroon and green-weathering (with some yellow to brown-weathering) siltstone that extends from 23 to 289 m (units 3-13 and 15), with intermittent covered intervals (Fig. 4d). The siltstone is planar, parallel-laminated and lacks other sedimentary structures and variation in grain size. The colour of much of the siltstone alternates between maroon and green, in units that are generally layer-parallel. In some locations, however, these colours form a cm to dm-scale mottled pattern, with patches of colour that cut across lamination. Distinct, continuous to discontinuous cm-thick white layers are present at several stratigraphic levels (Fig. 4e). The discontinuous to mottled appearance of the white, green and maroon layers suggests that the pattern of colours in unit A is diagenetic in origin, and is not strictly related to or derived from primary compositional differences among the siltstone layers. Just below the contact with unit B, the siltstone becomes increasingly calcareous (unit 14; Fig. 4f).

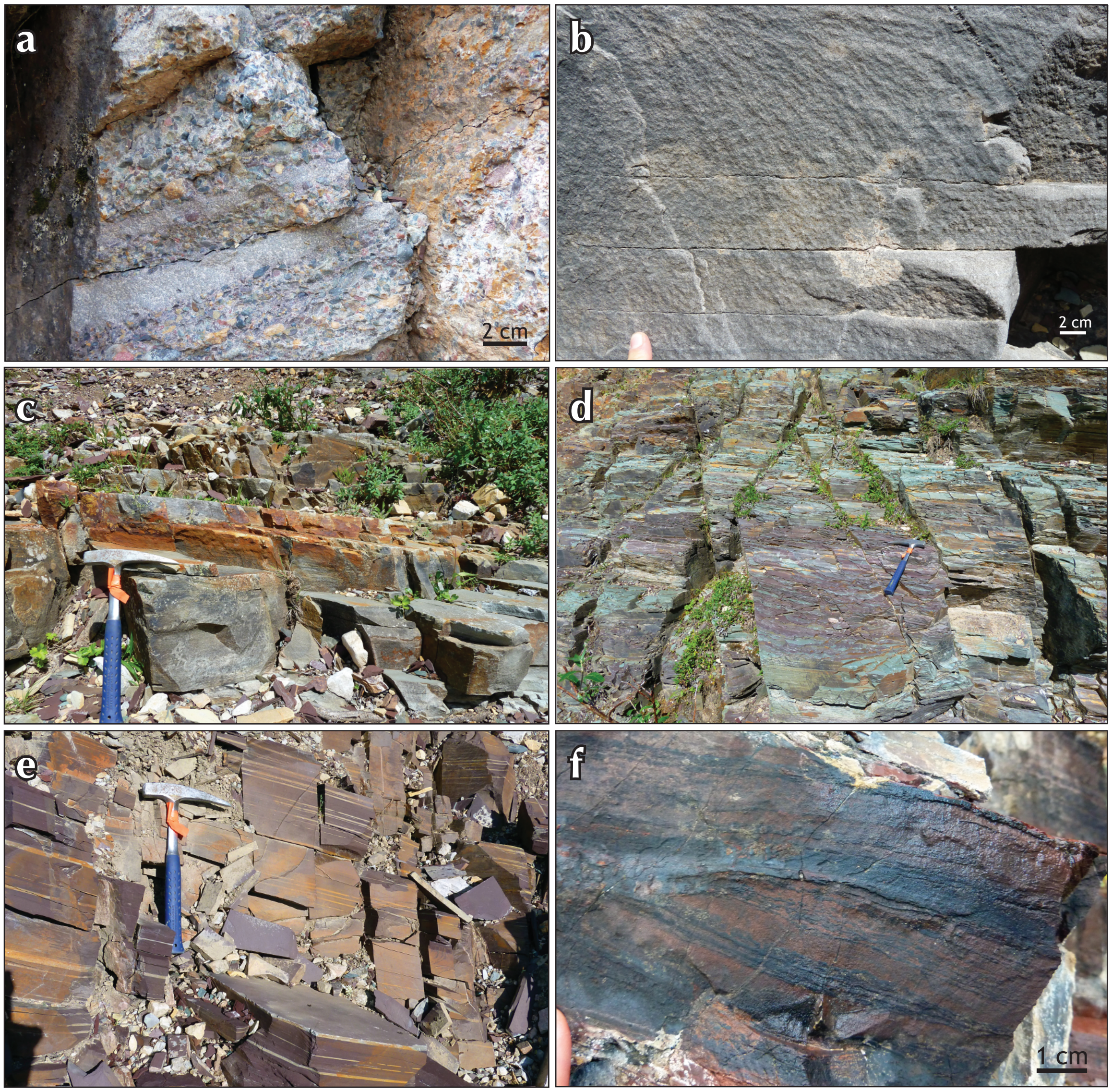

Figure 4. *Lithofacies of Pinguicula Group unit A in the Wernecke inlier.* ***(a)*** *Basal conglomerate with sandstone interbeds at the base of the measured section. Clasts are composed of limestone and siltstone.* ***(b)*** *Typical thinly bedded quartz arenite overlying the basal conglomerate.* ***(c)*** *Outcrop of orange-weathering, planar-laminated sandstone beds. Orange weathering colour is from pyrite disseminated in the sandstone weathering to limonite.* ***(d)*** *Outcrop of typical maroon and green siltstone.* ***(e)*** *Maroon, planar-laminated siltstone with distinctive discontinuous white banding.* ***(f)*** *Calcareous siltstone 6 m below the contact with unit B. Carbonate content in the siltstone increases before the transition to unit B.*

Regional Variation

Unit A extends from the northern part of NTS sheet 106C/14 southward to map sheet 106C/6, and farther south, beyond the extent of existing map coverage included in this study's mapping of 106C/6 (Fig. 1c). The thickness of unit A increases from north to south in the study area to approximately 1400 m, a phenomenon that has been attributed to a southward-deepening basin (Thorkelson, 2000). Weathering colours in the north are predominantly maroon and green (Fig. 5), and contrast with those in the south, which are dark grey, dark purple, and black. Weathering colour also varies stratigraphically. For example, at one location above the Gillespie Lake Group, unit A is orange-weathering at the base and dark grey-weathering up-section. The unit is recessive in the north and resistant in the south, where it forms steep cliffs and peaks. Unit A tends to be more ductile than overlying units B and C. Greater deformation is particularly apparent in the south, where tightly folded strata of unit A are overlain by unfolded, nearly horizontal beds of unit B. However, unit A grades stratigraphically upward into unit B, and the contrast in the amount of deformation cannot be interpreted as an angular unconformity. Instead, the difference in the degree of deformation is interpreted as an outcome of stress applied to rock units of different competence; unit A recorded more strain than the stronger, overlying carbonate units of units B and C.

Conglomerate, and conglomerate–sandstone assemblages are absent from the base of unit A in some locations in the study area. In these cases, either siltstone or sandstone directly overlies Wernecke Supergroup strata or Hart River sills. In other locations, conglomerate and sandstone are interbedded with siltstone lower in the unit.

Carbonate nodules in unit A are locally abundant within tens of metres of the contact with unit B at a number of locations (*e.g.*, northeast of the PIKA occurrence UTM 579053E 7193988N). Nodules are typically elongate with aspect ratios >20:1. Malachite stained pyrite nodules, having diameters of less than 1 to 3 cm, are also present south of the PIKA mineral occurrence along the Bonnet Plume River (UTM 563803E 7184575N).

UNIT B

Description

Unit B is a carbonate succession that is predominantly orange-weathering, with maroon weathering at the base and grey weathering toward the top. Unit B is exposed in cliffs that are crosscut by numerous gullies (Figs. 3, 5, and 7). Unit B gradationally overlies unit A and grades upward into unit C. Unit B thickens from approximately 150 m in the northern part of the study area (UTM 577907E 7193694N) to >450 m at the measured section described here and appears thicker beyond the southern limit of mapping in NTS 106C/6.

The detailed section for unit B was measured on an unnamed mountain west of Pinguicula Lake and south of Pinguicula Creek (Figs. 6 and 7; UTM 573055E 7175671N NTS 106C/11). Units A through C are easily accessible in a gully and along the ridgeline. The top and bottom of the unit are both exposed at this location.

In the measured section, the basal contact is placed at the transition from dominantly siliciclastic (calcareous siltstone) to dominantly calcareous beds (silty dolomudstone). Above the basal contact, siltstone-dominated lithologies are present, but the predominant rock type is dolomudstone.

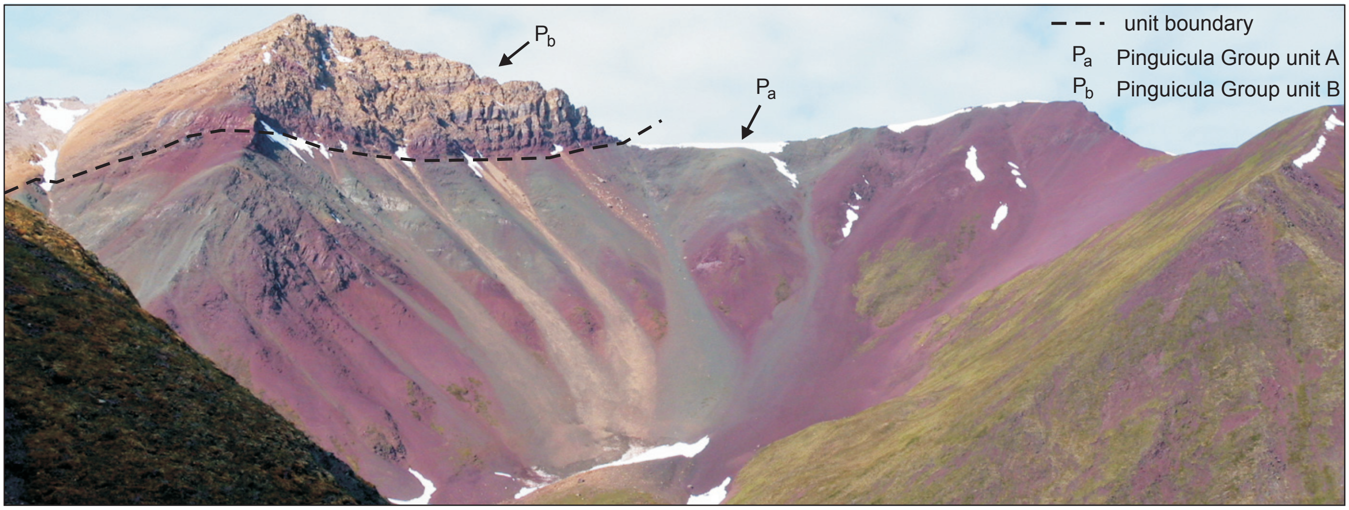

Figure 5. *Pinguicula units A and B in the northern part of the study area at the Pika occurrence. View to the southwest. NTS map sheet 106C/14 UTM 8W 573381E 7190576N NAD 27.*

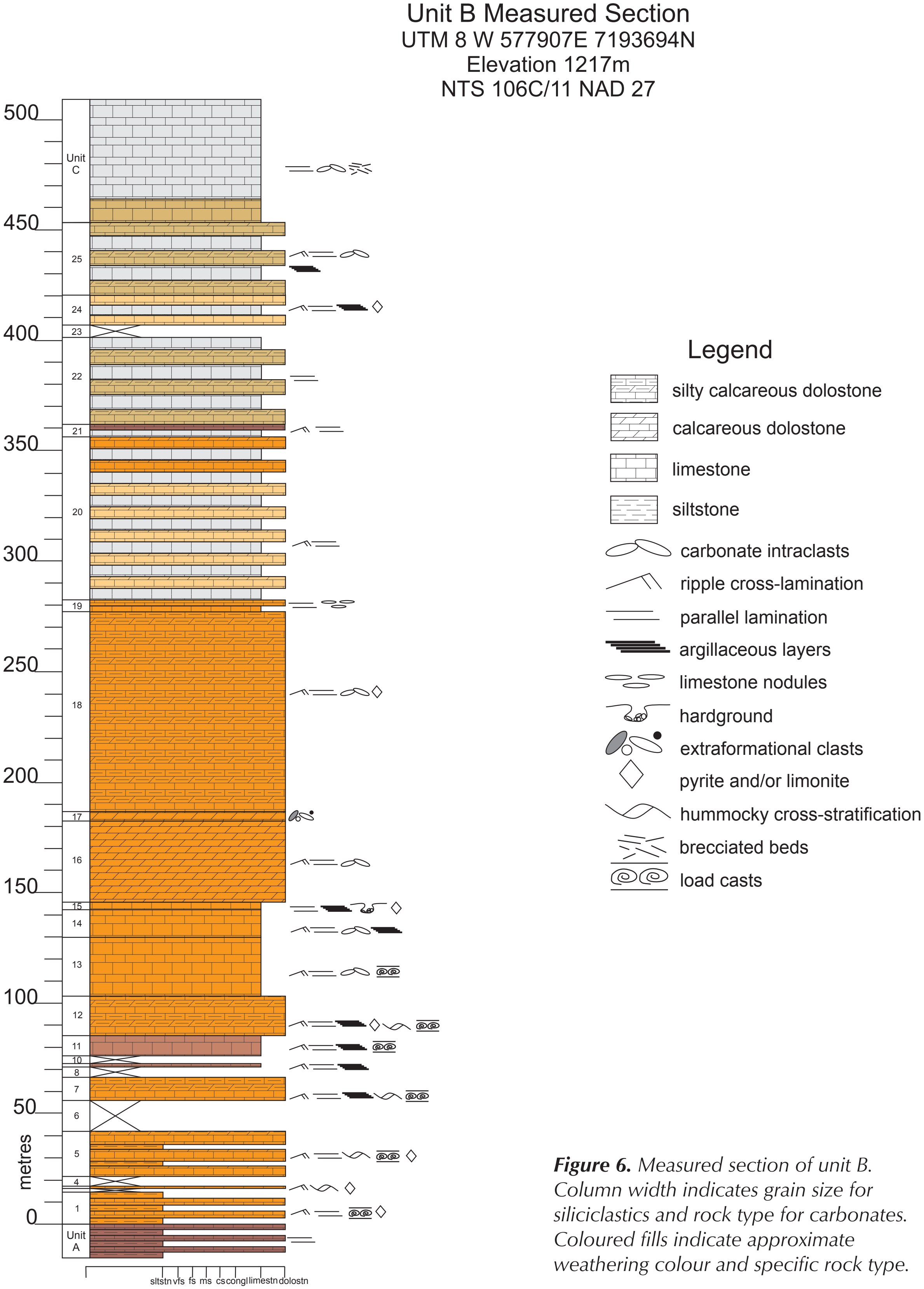

Figure 6. *Measured section of unit B. Column width indicates grain size for siliciclastics and rock type for carbonates. Coloured fills indicate approximate weathering colour and specific rock type.*

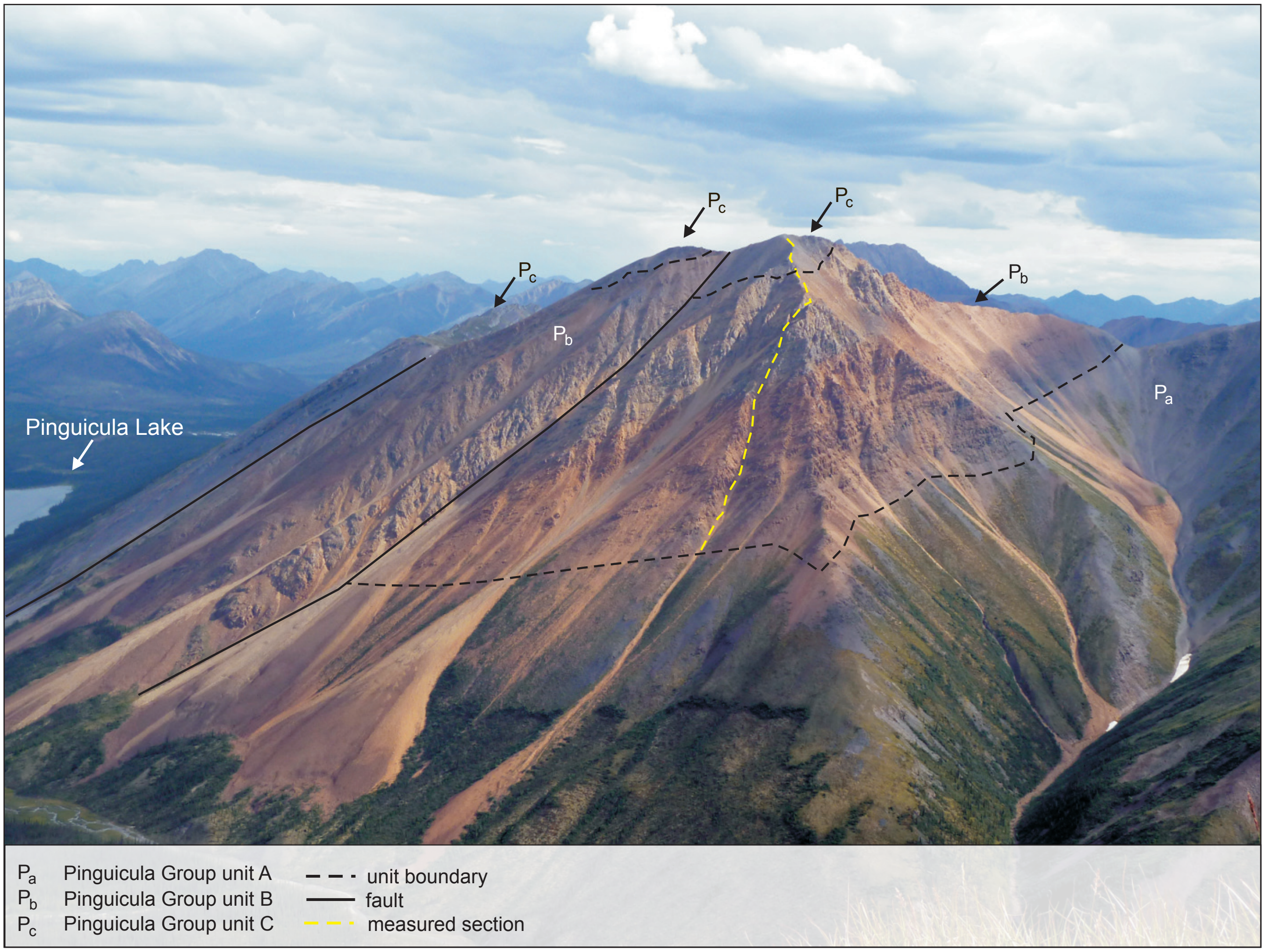

Figure 7. *Pinguicula units A, B, and C west of Pinguicula Lake and measured section. View to the southeast. NTS map sheet 106C/11 UTM 8W 573055E 7175671N NAD 27.*

The distinctive orange weathering colour cannot be used to define the boundary between units A and B because the lower part of unit B is maroon-weathering.

At base of the section, from 0 to 15 m (unit 1), is a rusty orange to maroon-weathering silty calcareous dolomudstone with interbeds of planar-laminated, maroon to grey siltstone. The silty calcareous dolostone contains abundant, disseminated, millimetric limonite-after-pyrite pseudomorphs. Discontinuous layers of carbonate mud, interlaminated with larger, sub-millimetric carbonate particles and organic matter form a wispy-laminated texture on the weathered surfaces. This wispy texture is present in most unit B dolostone and has been generated by differing degrees of pressure solution. Wispy-textured dolostone is interbedded with massive dolomudstone layers lacking any visible structures. In the overlying units 3 and 5, similar wispy lamination is present in the silty calcareous dolostone, but terrigenous silt and limonite pseudomorphs are also present. Unit 7 has similar characteristics, with the exception of disseminated limonite. Load casts, hummocky and swaley cross-stratification (HCS/SCS), ripple cross-lamination, and planar lamination are prominent in the lower 130 m of the section (Figs. 8a,b,c,d respectively). From 55 to 147 m (units 7-15), recessive, black, argillaceous, planar-laminated layers are interbedded with limestone and silty calcareous dolostone (Fig. 8e). Ripple cross-lamination and parallel lamination appear throughout the section. Units 9 and 11 (71 to 85 m) are composed of maroon-weathering, planar-laminated lime mudstone and wispy laminations are notably absent. Orange-weathering, silty calcareous dolomudstone in unit 12 (85 to 105 m) resembles the underlying dolomudstone units with black wispy laminations and millimetric limonite pseudomorphs. Units 13 through 15 (105 to 147 m) are composed of orange-weathering lime mudstone with intermittent intraclast rudstone layers and lenses that are approximately 20 cm thick (Fig. 8f). Up-section in unit 16, intraclast rudstone layers are up to 1.5 m thick and are interbedded with dolomudstone. These layers consist of matrix and clast-supported tabular limestone clasts <1 cm to 15 cm long in a dolostone matrix. Some clasts maintained their tabular form during deposition whereas others did not and are slightly folded. Clasts are ungraded and are locally imbricated. Intraclast rudstone layers are intermittent in the section from 100 to 450 m; in total six intraclast rudstones are present in the section. In unit 16, small-scale, granular intraclast rudstone and floatstone are also present. Clasts are rounded and in a dolomudstone matrix. These intraclast rudstones are typically 1 to 3 cm-thick, and are overlain by dolomudstone. Some layers of

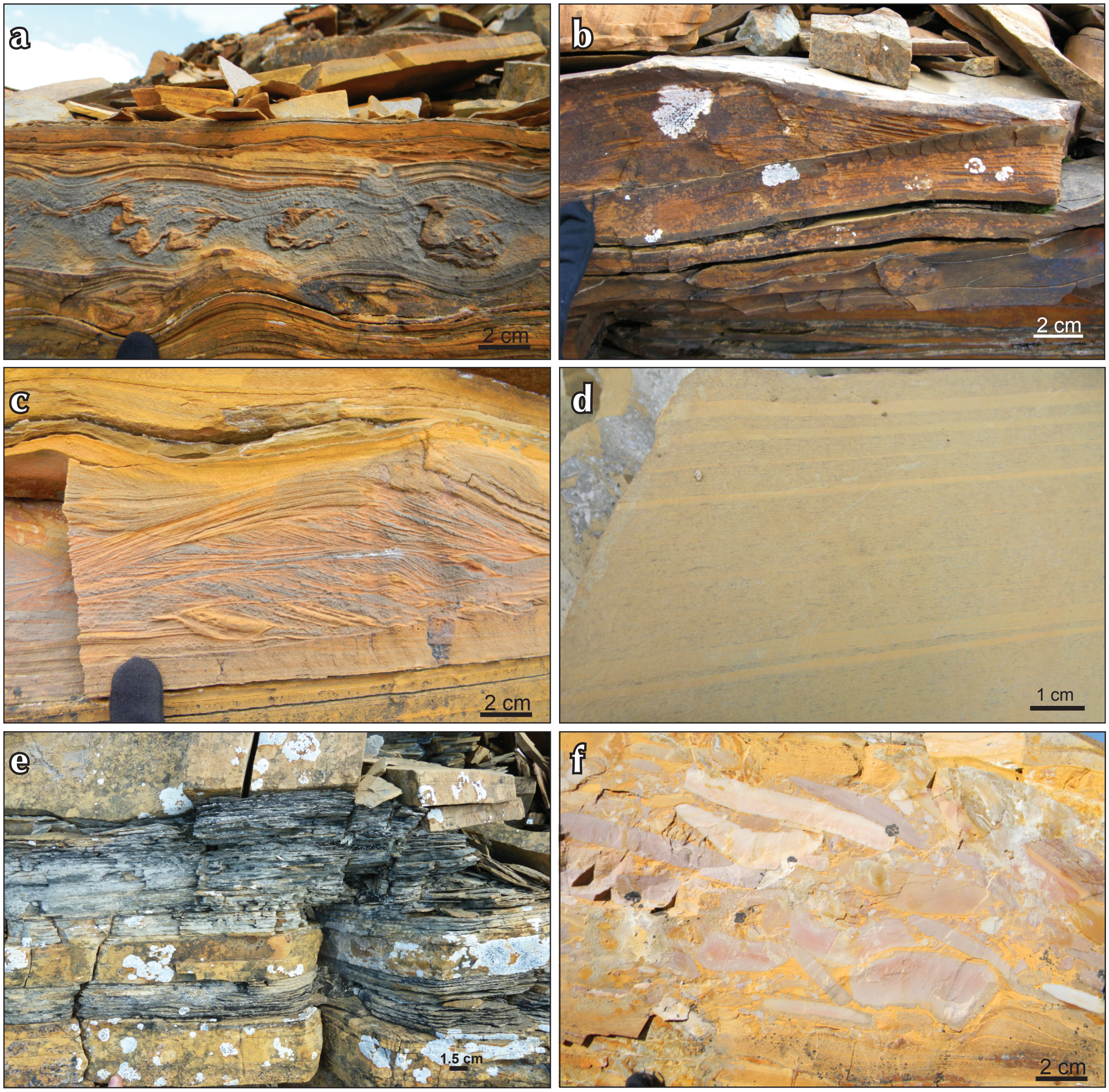

***Figure 8.** Lithofacies of Pinguicula Group unit B in the Wernecke inlier. **(a)** Load casts from the lower 130 m of the section represent rapid deposition of high density sediment on low density sediment forming pillows. **(b)** Hummocky/swaley cross-stratification deposited above storm wave base in the lower 100 m of the section. **(c)** Ripple cross-lamination in orange-weathering silty calcareous dolostone. This is possibly a tempestite sequence with combined flow currents. **(d)** Parallel lamination in orange-weathering dolostone. **(e)** Argillaceous interbeds in silty calcareous dolostone. **(f)** Intraclast rudstone of limestone clasts in a dolostone matrix.*

small-scale intraclast rudstones are laterally discontinuous and suggest deposition onto a dolomud substrate.

In addition to limonite, pyrite is disseminated throughout beds in units 12, 15, 18, and 24 in the measured section (Fig. 9a). An in-filled cavity at ~147 m in unit 15 exhibits iron staining, pyrite, and void-filling, laminated argillaceous sediment, and possibly represents a hardground (Fig. 9b). Hardgrounds are lithified surfaces that develop on the sea floor because of low sedimentation rates or episodes of non-deposition (Collinson and Thompson, 1982; Flügel, 2004; Dalrymple *et al.*, 2010).

At approximately 185 m (unit 17) sparse extraformational matrix-supported clasts (orange-weathering limestone, green siltstone, and pink sandstone), several cm to >1 m in diameter, are randomly distributed in the dolostone (Fig. 9c). Some of the clasts are well rounded (e.g., sandstone) whereas others are subangular (e.g., siltstone and limestone).

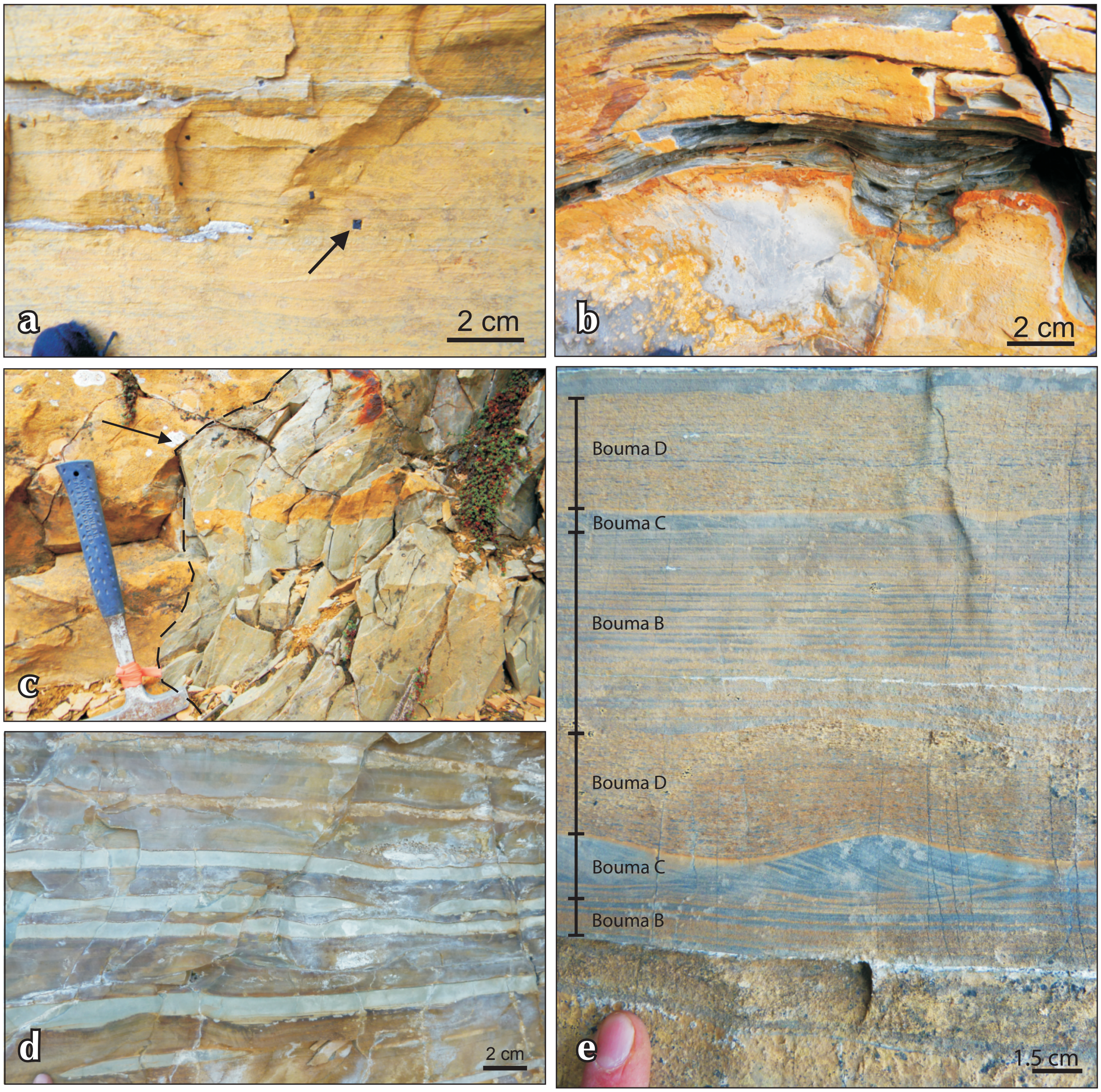

Figure 9. *Lithofacies of Pinguicula Group unit B in the Wernecke inlier.* ***(a)*** *Sparse sulphides in dolomudstone.* ***(b)*** *Hardground (lithified surface) that developed on the sea floor due to low sedimentation rates or episode of non-deposition.* ***(c)*** *Extraformational clast of green siltstone in orange-weathering dolomudstone possibly derived from the Wernecke Supergroup and transported into the basin.* ***(d)*** *Lime mudstone (grey) interbedded with dolomudstone (orange) is a common lithofacies in unit B.* ***(e)*** *Apparent partial Bouma sequences in unit 25 of measured section reflects transport and deposition of sediment on a carbonate slope or basin floor.*

Unit 18 (187 to 276 m) is silty calcareous dolostone with intraclast rudstone layers (30 cm thick) and pyrite crystals and limonite pseudomorphs. Massive microcrystalline dolostone laminae and beds are interbedded with wispy-laminated beds, as well as small-scale intraclast rudstone beds. At 257 m a graded bed with intraclasts at its base contains asymmetrical ripple foresets in which the grain size of foreset laminae alternates between silt and coarse sand grade.

Units 19 to 25 from 276 to 452 m (Fig. 9d) consist of distinctive interbedded grey-weathering limestone (cm-scale thickness) and orange-weathering dolostone (cm to dm-scale thicknesses). Both the lime mudstone and dolomudstone have more resistantly weathering wispy laminae with interlaminated particles and/or crystals of carbonate and quartz. The weathering colour grades from orange and yellow near the base of the formation to grey, with brown near the top of the section. In units 23-25, well-preserved ripples overlain by planar lamination (Fig. 9e) are present. Below the transition into unit C, three intraclast rudstone beds 20 cm - 1 m thick are present in unit 25. The transition from unit B to unit C is placed where planar-laminated, pervasively veined, predominantly grey-weathering dolomudstone first appears and yellow-weathering dolostone is less prevalent.

Regional Variation

Throughout the study area, unit B has a uniform assemblage of sedimentary structures, lithologies and stratigraphic patterns. Ripple cross-lamination, parallel lamination, hummocky and swaley cross-stratification, intraclast rudstone, and possible turbidites or tempestites are exposed in most outcrops of unit B. Differences in unit B stratigraphy throughout the study area are related to the scale of the structures and sedimentary components. For example, intraclast conglomerates are more abundant, thicker, and lower in the section at the PIKA mineral occurrence (UTM 573887E 7190732N) and other locations to its northeast. Pyrite is especially conspicuous at the measured section and locations to its south (UTM 580954E 7155399N).

UNIT C

Description

Unit C is a carbonate-dominated succession that is distinguished at the outcrop-scale from unit B by its blue-grey weathering colour. Unit C is also distinguished from unit B by its greater abundance of diagenetic features such as carbonate veins, zebra dolomite, masses of crosscutting coarse dolomite spar, locally abundant stylolites, and by a fetid odour when broken. Unit C conformably and gradationally overlies unit B, and is 590 m-thick in the measured section. It is thickest in the northern part of the study area (1800 m). Locally apparent thicknesses may be deceptive, especially where unit C has been thickened by structural repetition of strata by west-directed thrust faulting (Fig. 10; Thorkelson, 2000).

A detailed section was measured adjacent to the headwaters of 'Dolores Creek' (Figs. 11 and 12; 588305E 7190109N NTS 106C/14). The lower part of the section follows 'Dolores Creek' and a tributary of 'Dolores Creek' before tracing up a mountainside and ending at the top. Unit C is difficult to access in much of the study area due to its steep cliffs. Attempts were made to measure unit C strata in other locations, but were abandoned on account

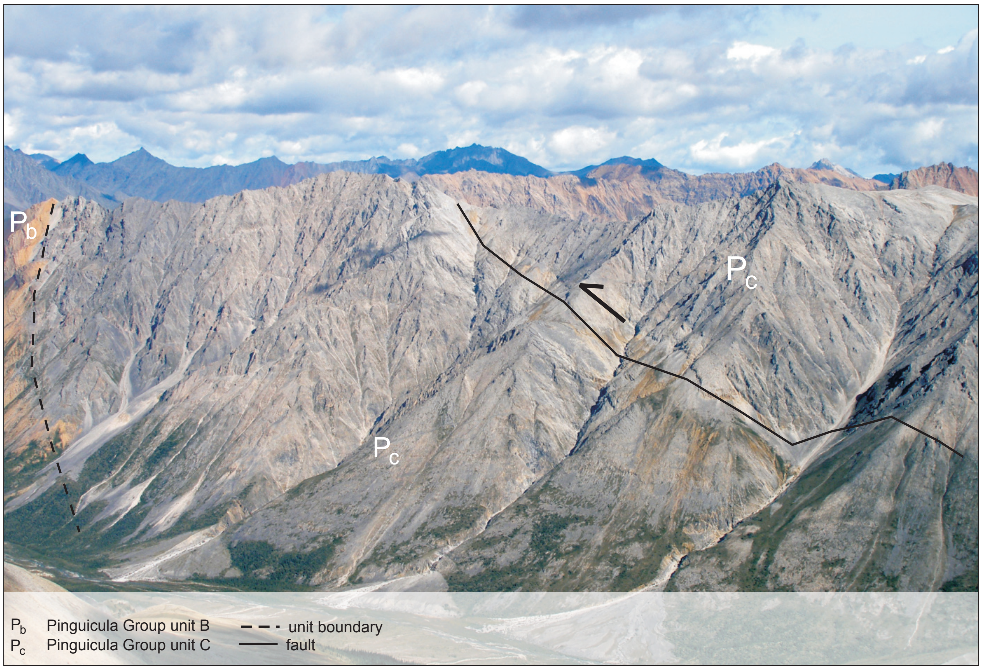

Figure 10. *Pinguicula units B and C with structural repetition of Unit C strata from west-directed thrust faulting. View to the northeast. NTS map area 106C/14 UTM 578147E 7193042N.*

of the impassible nature of the exposures. The measured section offers an accessible route to a gradational, although partly covered, lower contact with unit B. The upper contact with the overlying Dolores Creek Formation of the Hematite Creek Group (Turner, 2011) is possibly faulted. The contact throughout the study area varies from faulted to angular to concordant. An alternate location north of Pinguicula Creek provided an undisturbed section of unit C and the unit C-Dolores Creek Formation contact (575186E 7177355N NTS 106/C/14). At this location both the strike and dip of unit C and the Dolores Creek Formation differ by 30°, whereas east of the measured section the structural orientation of the two units do not differ; these observations suggest that unit C may have been locally tilted prior to deposition of the basal Mackenzie Mountains supergroup or that the units reacted differently during deformation.

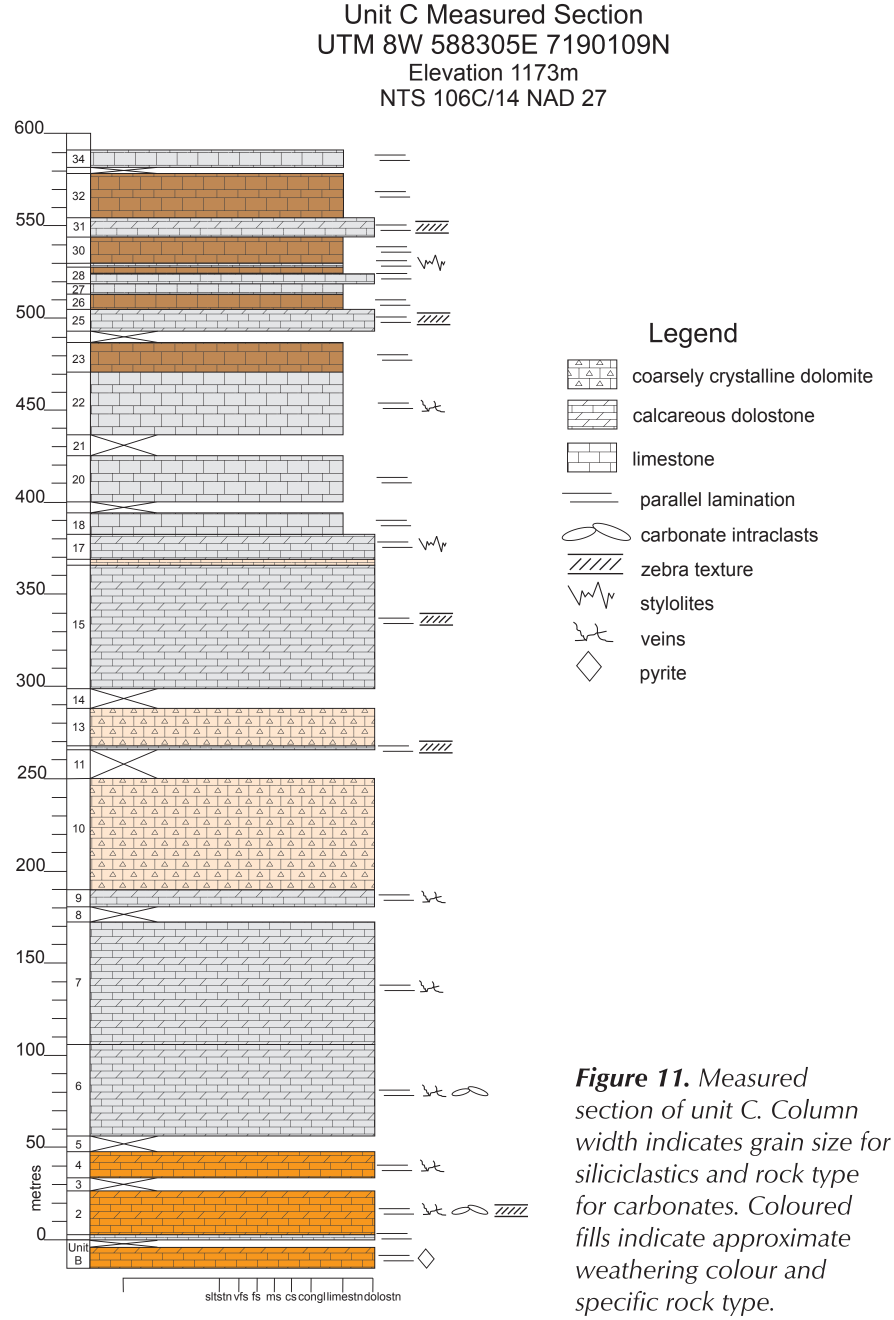

Figure 11. *Measured section of unit C. Column width indicates grain size for siliciclastics and rock type for carbonates. Coloured fills indicate approximate weathering colour and specific rock type.*

At the measured section (Fig. 11), the base of unit C overlies a thin (6 m) covered interval. The transition from unit B to unit C is marked by the disappearance of interbedded cm-scale limestone and cm to dm-scale dolostone, turbidites, and yellow to brown-weathering; instead, strata are characterized by grey weathering, planar lamination, abundant carbonate veins, and zebra texture. The contact is placed where planar-laminated, pervasively veined, predominantly grey-weathering dolomudstone first appears. The lower part of the section from 0 to 48 m (units 1, 2, and 4) are yellow-orange to grey-weathering, blue-grey and white calcareous dolostone with planar, parallel-laminated to cm and dm-scale bedding. Both massive, microcrystalline mm to cm-scale beds, wispy planar laminations with millimetre carbonate crystals, and black intraclasts are present in the rock. Zebra dolomite texture (Vandeginste *et al.*, 2005) and dolostone breccia masses associated with copious volumes of coarsely crystalline sparry dolomite are common (Fig. 13a,b). Submillimetre to centimetre black and white banding is common, and may have formed by the same processes as the zebra texture that is apparent higher up in the section. After a short covered interval (7 m), buff to pale grey-weathering, medium to dark grey, planar, parallel-laminated to bedded calcareous dolostone with pervasive veining is present (56 to 190 m). Massive, microcrystalline beds are dominant, but wispy-laminated intraclastic beds are also present. The grey calcareous dolostone has a wispy white texture in unit 7 (Fig. 13c). There are two dm-scale intraclast rudstone

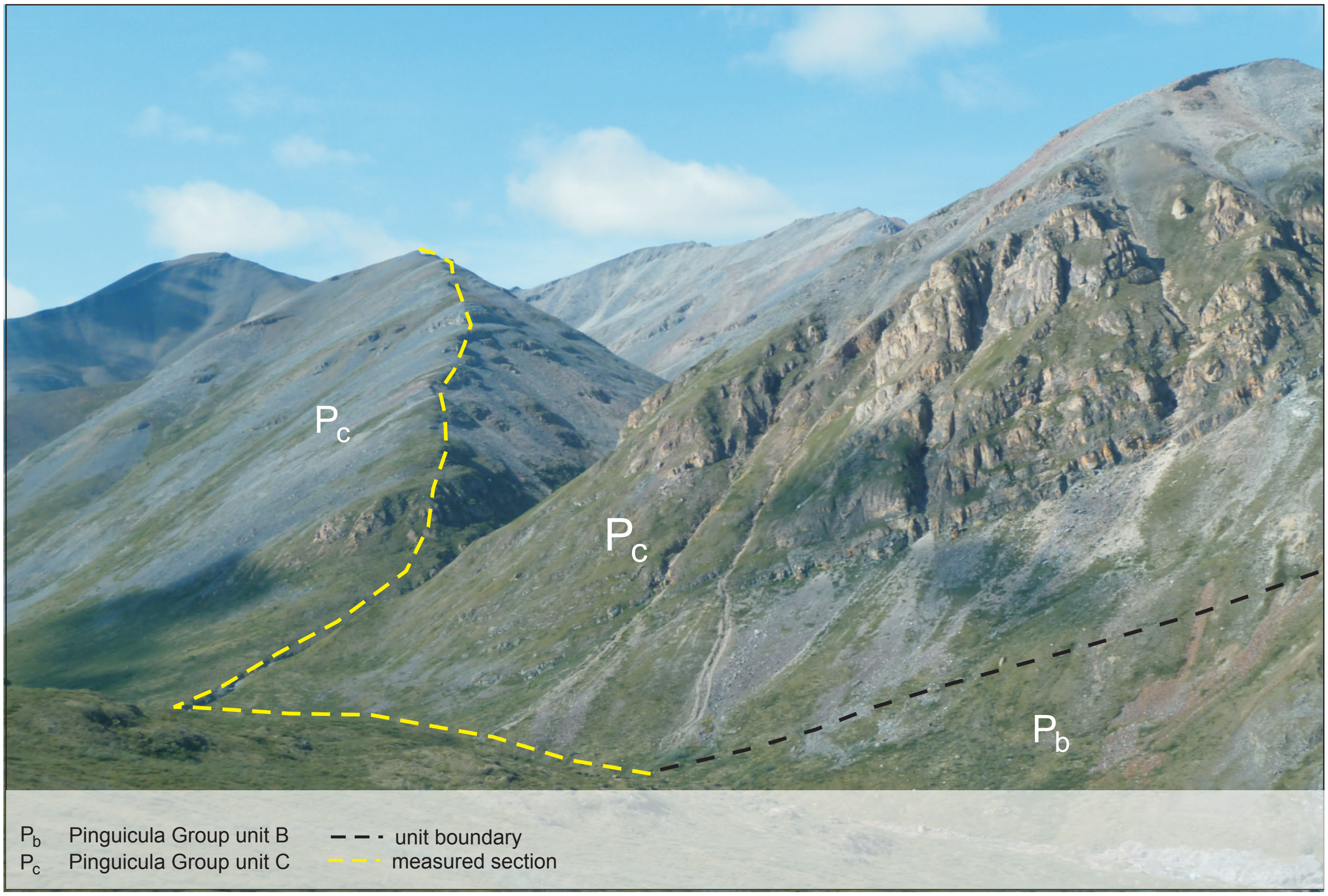

Figure 12. *Pinguicula units B and C. View to the southwest. Measured section runs along two creek beds before following the ridgeline up mountain. NTS map sheet 106C/14 UTM 8W 588305E 7190109N.*

layers in the lower 75 m of the section (units 2 and 6), with tabular clasts up to 7 cm long. The layers are similar to those described in unit B. A dense network of calcite veins cut across the lower 190 m of the section. Two distinctly pink-weathering units (units 10 and 13 from 190 to 287 m) of coarsely crystalline dolostone spar with cm-scale crystals occur midway through the section (Fig. 13d). In one location coarsely crystalline dolostone crosscuts the zebra dolostone, suggesting that units affected by zebra dolomitization were subsequently affected by a separate generation of coarsely crystalline dolomite veins and zones. The combined 80 m of exposed outcrop of coarsely crystalline dolostone (with a covered section and zebra dolomite bed in between) is overlain by ~80 m of yellow-grey-weathering, white and grey calcareous dolostone with planar, parallel-laminated cm to dm-scale beds containing zebra texture (units 15 and 17). These units are above and below a sparry dolostone layer (unit 16) approximately 3 m thick. In the overlying 100 m, units 18, 20, and 22, are yellow-grey-weathering, dark grey cm to dm-scale planar-bedded limestone with crosscutting veins (Fig. 13e). The uppermost 110 m of the section (units 23 to 34 with some covered intervals) consist of brown-weathering, thinly bedded limestone units interbedded with calcareous dolostone with zebra texture (Fig. 13f). The section ends at the top of the mountain in grey-weathering limestone. Where the upper contact is structurally undisturbed, it is an unconformity characterized by an angular to concordant boundary with the Dolores Creek Formation. Mineralization in unit C occurs as malachite and azurite staining, with rare galena and pyrite in crosscutting veins, zebra dolomite, and brecciated dolostone.

Regional Variation

Unit C thins toward the southern part of the study area, where it expresses the same features as in the north but in varying degrees. Zebra texture is less abundant in the south, but pervasively veined limestone beds are common. In some southern locations, unit C is interbedded with fissile black siltstone beds.

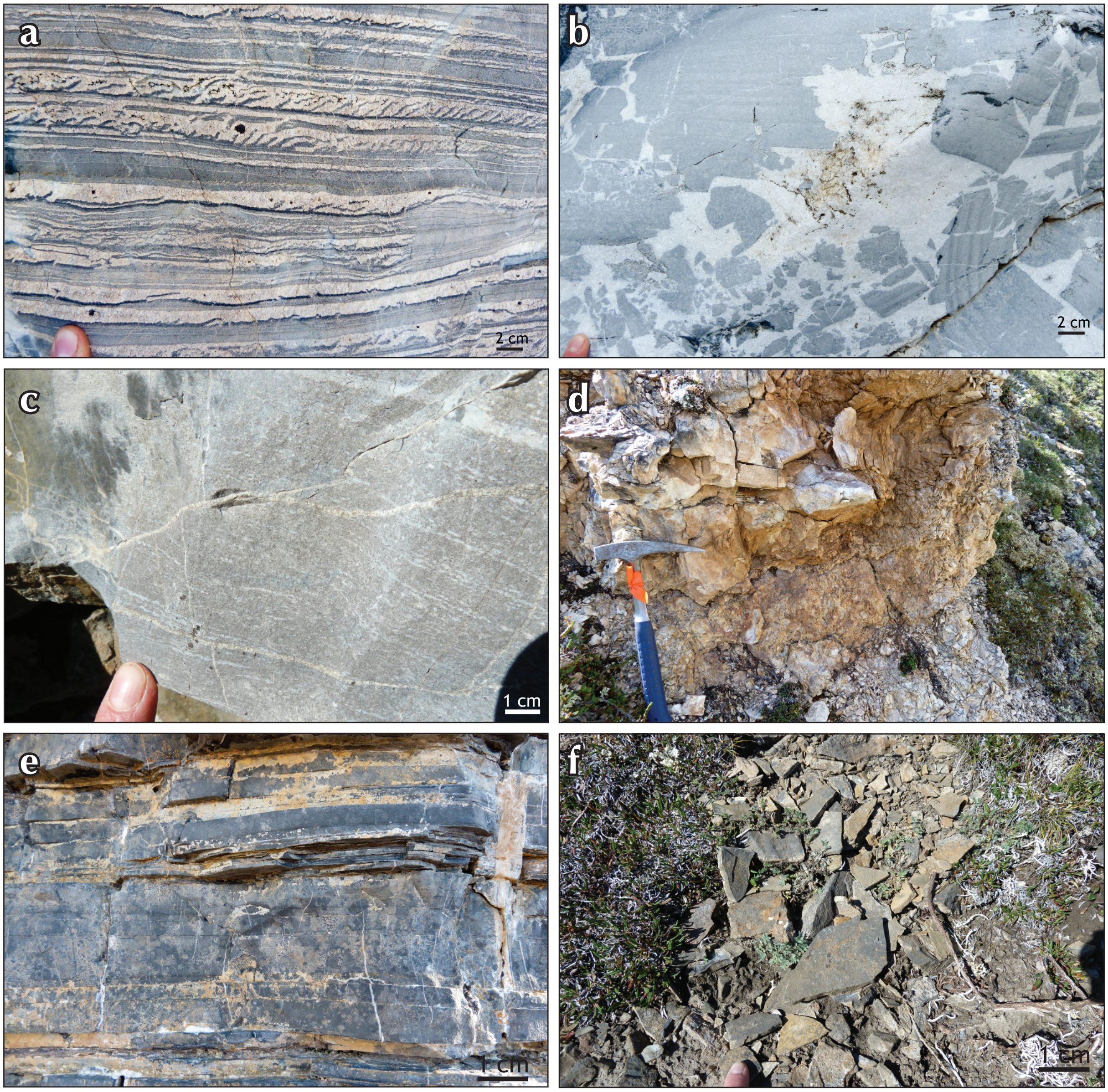

Figure 13. *Lithofacies of Pinguicula Group unit C in the Wernecke inlier.* ***(a)*** *Zebra texture in dolostone.* ***(b)*** *Brecciated and dolomitized limestone beds.* ***(c)*** *Wispy texture in dolostone in unit 7 of measured section.* ***(d)*** *Pink-weathering coarsely crystalline dolomite spar.* ***(e)*** *Dark grey limestone bedded limestone with pervasive veining.* ***(f)*** *Recessive brown-weathering, thinly bedded limestone that forms interbeds with thickly bedded grey-weathering, dark grey limestone near top of section.*

INTERPRETATION

Unit A is a fining-upward succession that appears to have been deposited in a subsiding basin. Based on thickness distribution, the deepest part of the basin was in the southern part of the study area. The basal pebble conglomerate and sandstone may represent beach deposits that accumulated during flooding of the underlying regolith of the Wernecke Supergroup. As the basin deepened, a monotonous succession of siltstone was deposited. The absence of sedimentary structures other than lamination, or significant grain size variation in the main siltstone-dominated part of the succession, suggests that this formation was deposited below storm wave-base and was largely unaffected by episodic flux in sediment supply.

Unit B was deposited mainly on a carbonate slope. As unit B grades from silty calcareous dolostone interbedded with siltstone at the base, the interpreted paleoenvironment becomes deeper, and the rocks are dominated by carbonate. Load casts truncated by overlying beds and the prominence of hummocky/swaley cross-stratification (HCS/SCS) reflect storm activity and deposition below fair-weather wave-base but above storm wave-base (Dalrymple *et al.*, 2010). For the water column to develop sufficient fetch to form structures such as HCS/SCS, the basin would probably need to be several hundred kilometres across. As HCS/SCS become less prominent up-section, intraclast rudstone layers and lenses become conspicuous, reflecting redeposition of thin beds of early-lithified slope lime mudstone down-slope by debris flows triggered by gravitational failure. Prominent, large extraformational clasts are interpreted to be derived from exposures of Wernecke Supergroup strata; given the slope-environment of deposition, the clasts were probably eroded rapidly from uplifted subaqueous fault blocks, and, if so, would indicate syndepositional tectonic activity. Sparse, black argillaceous interbeds represent a terrigenous sediment component that was either delivered episodically, or that accumulated during times when carbonate sediment production temporarily ceased. Moving up-section, turbidites are present. The graded bed with intraclasts at its base and asymmetrical ripple foresets suggests deposition of the bed as a tempestite rather than from a turbidity current because of the interlamination of foreset grain size; turbidites are generally characterized by gradual upward fining rather than fining by intergradation. Moving up-section, through the monotonous, interbedded limestone and dolostone beds, thin Bouma like sequences reflect deposition on a carbonate slope during continued basin deepening.

Unit C transitions from a carbonate slope facies at its base to a deeper-water facies. Intraclast rudstone at the base of unit C may suggest that the lower part of the formation was deposited on a carbonate slope (Dalrymple *et al.*, 2010). Unit C lacks sedimentary structures such as hummocky cross-stratification that would support deposition of the succession above storm wave-base and higher up on the slope. The planar-laminated carbonate rock that dominates unit C appears to have been deposited on a basin floor that lacked a significant slope as evidence of tectonic or gravitational instability is lacking, except at the base of the formation. The lime mudstone laminae in unit C probably formed as carbonate that was directly precipitated from solution in the water column (Grotzinger, 1989). Black siltstone beds reflect either intervals of increased fine terrigenous sediment supply or temporary cessation of carbonate deposition.

The development of zebra texture throughout much of unit C has led to the textural obliteration of some sedimentary structures. Consequently, identifying the depositional facies in the layers that have been affected by zebra texture is problematic. The timing of the hydrothermal activity that affected unit C is unknown; similar sparry dolomite is not common in unit B or in carbonate-dominated strata of the overlying Hematite Creek Group. Future work should include examination of basal siltstone of the Dolores Creek Formation in search of coarse lags that may contain clasts of unit C, to determine whether the hydrothermal event predated deposition of the Mackenzie Mountains supergroup.

The amount of time represented by the unconformity at the top of the Pinguicula Group is unknown owing to the as-yet uncertain depositional ages of both the Pinguicula Group and the basal Mackenzie Mountains supergroup. Previous interpretations of the unconformity as a karst surface infilled with coarsely crystalline spar attributed to emergent conditions (Thorkelson, 2000) are suspect as the pockets of coarse spar are herein interpreted to have been developed at depth as a result of hydrothermal activity.

DETRITAL ZIRCON GEOCHRONOLOGY

Detrital zircon geochronology on Pinguicula Group unit A sandstone (Wernecke and Hart River inliers) and lower Fifteenmile Group siltstone (Coal Creek inlier) can be used to determine sediment provenance and to provide maximum depositional age constraints. The maximum depositional age of the Pinguicula Group age has hitherto been constrained by its unconformable relationship with underlying Hart River sills (1380 Ma) and the minimum age of detrital muscovite in the overlying Hematite Creek Group (<1033 Ma; Thorkelson, 2000; Medig *et al.*, 2010).

METHODS

Three samples from Pinguicula Group unit A sandstone in the Wernecke inlier, one sample from unit A sandstone in the Hart River inlier, and one sample from the lower Fifteenmile unit PR5 in the Coal Creek inlier were collected for detrital zircon U-Pb geochronology. Sample details are summarized in Table 1.

Samples were processed at Simon Fraser University using standard crushing and milling techniques, with mineral separation using a Wilfley table and heavy liquids. All samples, with the exception of KM09-10-3-1C, were

Table 1. *Detrital zircon samples and locations.*

Sample	Rock Type	UTM Coordinate NAD 27	Field Relation	Inlier
KM09-1-4-1C	sandstone	8W 572876E 7191172N	Pinguicula Unit A above bleached Wernecke Supergroup regolith	Wernecke
KM09-10-3-1C	sandstone	8W 573352E 7167986N	Pinguicula Unit A – base not exposed	Wernecke
KM09-12-2-2C	sandstone	8W 574603E 7159828N	Pinguicula Unit A – base not exposed	Wernecke
KM10-8-1-1C	sandstone	8W 418221E 7165910N	Pinguicula Unit A above Hart River sills	Hart River
KM09-18-1-1C	siltstone	7W 552687E 7186821N	Lower Fifteenmile PR5 above calcrete regolith of Wernecke Supergroup	Coal Creek

run through an LB-1 Frantz magnetic separator at a low current (0.25 A; 15° front slope, 10° side slope) to remove ferromagnetic and highly paramagnetic minerals. A low current was used to avoid biasing the sample by preferentially separating out the more paramagnetic zircon grains, which are typically removed at much higher currents (1.2–1.8 A). Grains were then randomly chosen from the processed sample to avoid biasing.

The grains were mounted on an epoxy puck, polished, and coated with a thin gold coating at the J.C. Roddick Ion Microprobe Laboratory at the Geological Survey of Canada in Ottawa. The mounted grains were then imaged on the scanning electron microscope (SEM) at the GSC using both backscatter (BSE) and cathodoluminesence (CL) imaging techniques.

The zircon grains were analysed on the Sensitive High Resolution Microprobe (SHRIMP II) at the Geological Survey of Canada in Ottawa following analytical procedures summarized by Stern (1997). Zircon standards appropriate for the expected Proterozoic age range of the unknowns were interspersed on the epoxy puck with sample grains. Both a primary and secondary zircon standard was used; z6266 Sri Lankan zircon dated at 559 Ma and z1242 dated at 2679 Ma, respectively. Errors associated with standards and calibration methods followed Stern and Amelin (2003).

A small proportion of the grains exhibit relatively high common Pb content, and/or high measured UO/U ratios. These features are commonly an indicator of altered or imperfect (cracked or with inclusions) zircon grains, and so the data were screened for low common Pb counts and UO/U ratios within the range of the calibration standard. SEM images of each grain were examined after analyses to determine if the ion beam spot intersected inclusions, cracks, mixing of compositional zones, or metamict zones within the grain that may account for high common lead and high UO/U ratios. Some of the ion beam spots did intersect such features, but most grains did not appear to have any characteristics that might compromise the results. Intersection with grain anomalies may be attributed to stage drift during automated acquisition. In total, 23 analyses were excluded from further data interpretation based on high common Pb contents and/or measured UO/U ratios.

PRELIMINARY RESULTS

A total of 342 grains were analysed from the five samples. The three samples of the Pinguicula Group from the Wernecke inlier show similar patterns, with most ages between *ca.* 1430 and 3300 Ma, with significant peaks between 1600 and 1950 Ma and 2300 to 2800 Ma (Fig. 14). Based on stratigraphic consideration, the Pinguicula Group was deposited at some time between 1380 and 1033 Ma (Medig *et al.*, 2010): this is supported by the age of the youngest zircons in the samples. Results for sample KM09-10-3-1C from the Wernecke inlier included a single zircon grain with a ^{207}Pb/^{206}Pb age of 1144 ± 25 Ma[2]. This age was replicated with a second, although more discordant analyses on the same grain at 1131 ± 27 Ma. Although the occurrence of this grain suggests that the depositional age of the Pinguicula Group could be younger than 1144 ± 25 Ma, such an interpretation should not be made on the basis of a single, non-repeated result because it is not statistically viable. This result should be replicated with data from additional samples before accepting this as a maximum age. Until further work substantiates this result, the maximum age for the Pinguicula Group should be considered to be 1380 Ma based on the unconformable relationship with the Hart River sills (Medig *et al.*, 2010).

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[2] *1σ errors reported on ages.*

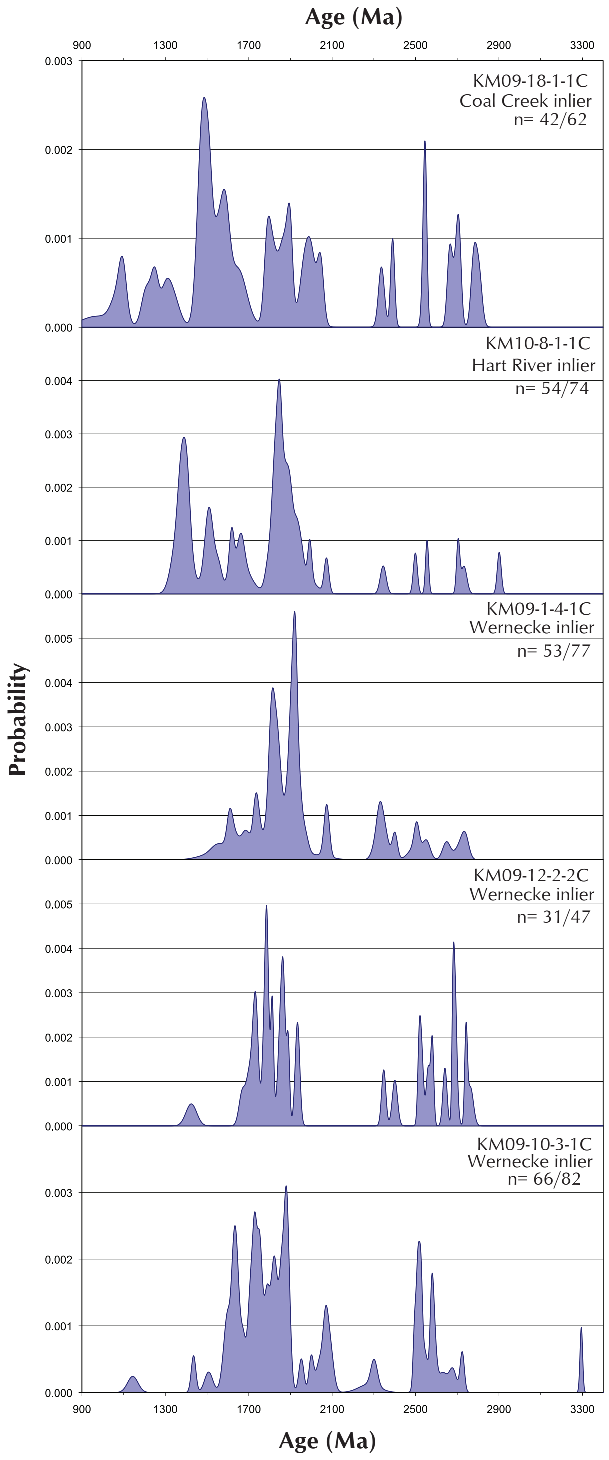

Figure 14. *Detrital zircon sample probability density distribution diagrams of* $^{207}Pb/^{206}Pb$ *ages. Grains with high common lead, high UO/U ratios, and/or analyses over 5% discordance were not included in the results. The quotient "n" indicates the number of 95-105% concordant grains over the total number of grains analysed. The graphs were produced using AgeDisplay (Sircombe, 2004).*

The sample from the Hart River displays significant 1750-2000 Ma and 1350-1450 Ma detrital zircon populations. There is also a series of minor peaks from the Neoarchean. The youngest zircon grains from the sample in the Hart River inlier (KM10-8-1-1C) have $^{207}Pb/^{206}Pb$ ages of 1342 ± 27 Ma and 1232 ± 172 Ma.

In the sample from the Coal Creek inlier, there is one prominent peak between 1450 and 1500 Ma. There are a series of smaller peaks between 1050 and 1350 Ma, 1500 and 2050 Ma, and 2300 and 2850 Ma. The youngest grain in the Coal Creek inlier sample, KM09-18-1-1C, has a $^{207}Pb/^{206}Pb$ age of 972 ± 78 Ma. Two other grains have $^{207}Pb/^{206}Pb$ ages of *ca.* 1100 Ma.

PROVENANCE

The samples analysed contain significant populations of Neoarchean and Paleoproterozoic detrital zircon grains. These grains may have been derived from the Laurentian craton or recycled from the underlying Wernecke Supergroup (Furlanetto, 2009). All samples have detrital zircon ages that overlap in time with the North American Magmatic Gap (NAMG; 1610-1490 Ma; Ross and Villeneuve, 2003). The underlying Wernecke Supergroup lacks grains from this time interval and is consequently not a plausible source. Ages in this range from North America have been recorded from the Western Channel diabase (*ca.* 1590 Ma), but the ages were derived from baddeleyite, which suggests that these mafic rocks would not be a plausible source for detrital zircon in the Pinguicula and lower Fifteenmile group samples (Ernst and Bleeker, 2010; Hamilton and Buchan, 2010). In addition, the age range from the Western Channel diabase does not encompass the full range of ages in the NAMG in Pinguicula and lower Fifteenmile group samples. Based on these two points, alternative sources for 1610-1490 Ma ages are needed to account for these grains. Other sources that have been proposed rely on paleocontinental reconstructions that suggest that Australia was adjacent to northwestern Laurentia in the Proterozoic and could be a source of 1610-1490 Ma zircon (Bell and Jefferson, 1987; Dalziel, 1991; Hoffman, 1991; Moores, 1991). Specific sources on the Australian continent include the Williams and Naraku batholiths in the Mt. Isa inlier (1520 to 1490 Ma), Hiltaba Granite Suite on the Grawler craton (1600 to 1560 Ma), and the Musgravian gneiss protoliths in the Musgrave Province (1600 to 1540 Ma; Betts and Giles, 2006; Wade *et al.*, 2008).

Another population of grains with ages between 1360 and 1400 Ma from the Hart River inlier sample are probably derived from the underlying Hart River sills. Three zircon samples were collected from the Hart River sills in the southern Ogilvie Mountains and all yielded zircon. Ages from these samples are 1380 + 4.0/-3.8 Ma, 1385.8 ± 1.9 Ma, and 1383.0 + 5.9/-5/2 Ma[3] (Abbott, 1997). A sample collected from the Hart River sills in the Wernecke Mountains yielded an age of 1382 Ma (Thorkelson, 2000).

The youngest grain in the samples analysed, with an age of *ca.* 1150 Ma, may have been sourced from the Grenville orogen as has been proposed for younger Neoproterozoic successions that have significant detrital zircon populations from this time interval (Rainbird *et al.*, 1997). Metamorphic and igneous rocks with Grenville-like ages are present in the subsurface of Yukon and nearby Northwest Territories (Milidragovic *et al.*, 2011) and may have contributed zircon to the sample populations; however, this option would require local exhumation of the middle crust, and appropriate sources have not yet been identified.

In summary, the detrital zircon analytical results show that Neoarchean and Paleoproterozoic populations were possibly derived locally from the underlying Wernecke Supergroup, Wernecke breccia, and Hart River sills or from adjacent Laurentia. Mesoproterozoic populations may also have been derived from the Laurentia or from far away as the Grenville orogen. Other populations have no obvious sources in North America and as such could have been derived from an exotic continent such as Australia.

CORRELATION

Pinguicula Group unit A in the Wernecke inlier is correlated with unit A in the Hart River inlier (Abbott, 1997). This correlation is not disputed because both overlie the Hart River sills and both contain analogous stratigraphy[4] (Abbott, 1997; Medig *et al.*, 2010). The previous correlation between unit A and unit PR1 in the Coal Creek inlier may not be correct, because recent work in the area indicates that units PR1 and PR5 are laterally equivalent (Medig *et al.*, 2010; Macdonald *et al.*, 2011). Macdonald *et al.* (2011) suggested that much of this stratigraphy was incorrectly mapped and is in fact part of the Mackenzie Mountains supergroup. If so, then these units are probably younger than the Pinguicula Group. Further work is needed to resolve these correlation problems.

The Pinguicula Group has been correlated with the Dismal Lakes Group in the Coppermine Homocline (Cook and MacLean, 1995). The depositional age of the Dismal Lakes Group is constrained by the overlying Coppermine River basalts and is therefore older than 1270 Ma (LeCheminant and Heaman, 1989; Cook and MacLean, 1995; Frank *et al.*, 2003). Based on the dataset this correlation is possible, but analysis of a single 1144 Ma zircon from Pinguicula Group unit A in the Wernecke inlier raises uncertainties. Further work to recover additional grains of this age is required in order to test the correlation between the Dismal Lakes Group and Pinguicula Group.

CONCLUSIONS AND FUTURE WORK

The Pinguicula Group (composite thickness ~1350 m) was deposited in comparatively deep water in a subsiding basin. Initial deposits of unit A were deposited during flooding of the post-Wernecke Supergroup unconformity and were followed rapidly by deposition of a monotonous succession of fine terrigenous clastic rocks; textural evidence for shallow-water conditions is everywhere absent. Deposition of the carbonate-dominated unit B began as an ephemeral shallowing event, which brought the sea floor within range of storm waves. Regional conditions changed to limit the supply of terrigenous material and promote the precipitation of carbonate mud. Gradual deepening ensued and was accompanied by development of widespread slope environments characterized by gravitational instability and resedimentation of carbonate material downslope as early-lithified tabular clasts and turbidites; it is unclear whether one regional slope is implicated or numerous, presumably fault-related slopes were present. Rare evidence for development of fault scarps from which large clasts of the Wernecke Supergroup were shed is, however, locally present. Unit C records generally quiescent conditions on a basin floor below storm wave-base and below the photic zone.

Zircon grains with Neoarchean to Paleoproterozoic ages may have been locally derived from the underlying Wernecke Supergroup and/or from Laurentia. A distinct population of zircon grains between 1610-1490 Ma (NAMG) does not have any known sources in Laurentia. They do, however, have several possible sources in

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[3] 2σ error reported on Hart River sill ages.

[4] Detailed stratigraphic sections measured in the Hart River inlier Pinguicula Group units A, B, and C and have analogous stratigraphy. This data will be published in a future paper.

Australia. Other younger Mesoproterozoic zircon grains with 1360-1400 ages were probably derived from the underlying Hart River sills. The youngest sample population, approximately 1100 Ma, may have been derived from the Grenville orogen.

Previous attempts to correlate the Pinguicula Group with other Proterozoic units such as the lower Fifteenmile Group to the west or the Dismal Lakes Group to the east have been based on similarities in lithology and the stratigraphic position of the succession between the <1610 Ma Wernecke Supergroup (Furlanetto *et al.*, 2009) and the overlying <1033 Ma Mackenzie Mountains supergroup (Thorkelson, 2000). The ~500 million year age gap between these two supergroups allowed for significant latitude in the positioning of the Pinguicula Group and a range of possible correlations. Field observations indicate it unconformably overlies, and is therefore younger than, the Hart River sills, which are dated at 1380 Ma. One detrital zircon age from Pinguicula unit A in the Wernecke inlier suggests that it may be younger than 1144 Ma; however, further work is required to replicate this result and make definitive statements. If additional detrital zircon grains of this age are found in unit A and a statistically viable population established, then correlations with the Dismal Lakes Group, which was deposited before 1270 Ma, would be dismissed. However, unless additional grains with ages <1270 Ma are found, the correlation with the Dismal Lakes Group will remain plausible.

Much remains unknown about the Pinguicula Group and future work is warranted in a number of areas. Investigation of the geochemistry of the basin may provide additional information on Mesoproterozoic ocean chemistry and may assist in regional correlations. A detailed petrographic and trace element study of unit A hematitic, maroon siltstone and dark grey siltstone would help to determine whether the formation was deposited under open-marine conditions or in a restricted basin, and the extent of shallow-water ferruginous conditions and deep-water anoxia. This information could contribute to the growing knowledge of Proterozoic geochemical evolution of Earth's surface.

A paleocurrent study from unit B current ripples and turbidites would provide provenance direction for the sediment and if the assumption was made that the direction had not changed drastically since the deposition of unit A, it could be used for provenance determinations in unit A in addition to the detrital zircon grain ages and an investigation into clasts from unit A conglomerate. Paleocurrents could also be used to determine the configuration of the tectonically active stage of basin development and locations of possible paleofaults.

Further investigation of the different phases of hydrothermal fluids in unit C may provide further information on age, mineralization, and temperature at the time of formation. Base metal potential and the possibility of hydrocarbon migration in the dolostone should be assessed through a paragenetic study of the hydrothermal dolomite and breccia bodies in unit C, using cathodoluminesence, trace elements, and fluid inclusions to determine fluid temperature and composition.

Finally, continuing study of the overlying Dolores Creek Formation would help to resolve some of the unknowns related to the Pinguicula Group. A detrital zircon study of this formation may help to constrain the age of the underlying Pinguicula Group as well as offer a comparison of sediment provenance.

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