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# **The Record of Neoproterozoic Glaciations in the Windermere Supergroup, southern Canadian Cordillera**

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## **Chapter Summary**

The Neoproterozoic Windermere Supergroup (WSG) is exposed over an area of 35,000 km<sup>2</sup> in the southern Canadian Cordillera, and consists primarily of deep-marine meta-sedimentary rocks interpreted to have been deposited during rifting and subsequent post-rift thermal relaxation. The main exposures of the WSG occur within thrust panels and structural culminations of the eastern Cordilleran orogen. Within the thick stratigraphic succession (~9 km) are three units of glacial affinity: Toby, Vreeland and Old Fort Point (OFP) formations. The Toby Formation is composed of up to 2500 m of diamictite, interbedded with conglomerate, sandstone, mudstone,

carbonate and mafic volcanic rocks. The Vreeland Formation ranges from 350 m to 2000 m thick and consists of diamictite, interbedded with mudstone, sandstone and conglomerate. The OFP ranges from 60 to 450 m in thickness and consists of a distinctive three-fold stratigraphic package of basal siltstone grading upward into limestone-siltstone rhythmite, organic-rich mudstone and an overlying heterolithic unit of diamictite, breccia, conglomerate, sandstone, siltstone to mudstone and limestone. A locally prominent unconformity marks the base of the OFP upper member. Both the Toby and Vreeland formations represent remobilized glacially-derived marine sediments deposited by sediment-gravity flows. Deposition of the Toby Formation was fault-controlled during an active tectonic phase (rifting) whereas the Vreeland Formation accumulated during the subsequent quiescent phase (post-rift) with limited structural control. The OFP is interpreted to be a regionally extensive deep-marine post-glacial marker temporally associated with the glacial Vreeland Formation. Although direct geochronological ages for WSG units in southwestern Canada are generally absent, high-precision radiometric ages of underlying and overlying igneous events constrain the relative maximum and minimum timing of deposition from ca. 740-728 Ma to ca. 569 Ma. At the base of the WSG succession, the Toby Formation may be as young as ca. 685 Ma based on ages obtained from potential stratigraphic correlatives in the United States. There is no direct age constraint for the deposition of the Vreeland Formation; its minimum timing is based on its stratigraphic relationship with the post-glacial OFP. The middle member of the OFP was precisely dated at  $607.8 \pm 4.7$  Ma using the Re-Os method placing it in the Ediacaran Period. Published geochemical and stable isotopic data are similarly limited for all three units with only some  $\delta^{34}\text{S}_{\text{py}}$  values available from

one section of the OFP. Recent work has focused on detailed sedimentologic and stratigraphic studies of the Toby and the OFP formations with future efforts being directed towards integrated geochemical and isotopic research. Additional geochronological constraints are needed to refine palaeogeographic models and strengthen regional correlations with other North American Cordilleran glacial units.

## **Introduction**

The record of Neoproterozoic glacial sedimentation in the southern Canadian Cordillera (Fig. 1) is preserved in three units within the Windermere Supergroup (WSG): a glacial interval at the base of the succession is inferred from the diamictite-bearing Toby Formation, with another event higher in the succession inferred from the diamictite-bearing Vreeland Formation (glacial) and Old Fort Point Formation (post-glacial) (Fig. 2) (Ross *et al.* 1989; Ross *et al.* 1995).

### *Toby Formation*

The Toby Formation (also known as the Toby Conglomerate) is best exposed in the Purcell Mountains of southeastern British Columbia. The variability of its lithofacies has precluded the identification of a type section; the formation was named by Walker (1926) after well exposed outcrops located along Toby Creek, west of Invermere, British Columbia (50° 30' N, 116° 02' W) (Fig. 1: A). This area has been extensively modified by Proterozoic, Devonian and Mesozoic deformation and the structural context of these rocks is often complicated (e.g. Root, 1987).

Previous studies of the Toby Formation are relatively few, with primary emphasis on regional mapping relative to Proterozoic- and Mesozoic-age structures (Walker 1926; Leech 1954; Aalto 1971; Reesor 1973; Root 1987; Pope 1990; Warren 1997). The glacial origin of the Toby Formation was first proposed based on a more detailed study of facies types and variability, petrography, as well as trends in clast characteristics in the Toby Formation itself (Aalto 1971). Additional mapping of specific regions have followed including mapping of the Toby Formation and related structures in the Paradise Mine (Atkinson 1975), Delphine Creek (Root 1987), Mount Forster (Bennett 1986), Creston/Salmo (Glover & Price 1976) and Crawford Bay/Columbia Point areas (Lis & Price 1976). Ongoing investigations are focusing on the relationship between Toby Formation facies variability and structural trends as well as isotopic analyses of associated strata.

#### *Vreeland Formation*

The Vreeland Formation has received little study (due largely to inaccessibility) despite its impressive exposures and thickness in the Pine and Monkman Pass regions, central British Columbia (from 54° 05' N to 57° 00' N) (Fig. 1). It was originally mapped by Slind & Perkins (1966) as an unnamed Precambrian conglomerate–schist. Later, it was briefly examined by Stelck *et al.* (1978) but was not really described until regional mapping conducted by McMechan (1987) and McMechan & Thompson (1985, 1995a, 1995b). It was initially referred to as a diamictite within the Misinchinka Group or the Mount Vreeland – Paksumo Pass diamictites (McMechan 1990), until Hein and McMechan (1994) referred to it as the Vreeland Formation. McMechan (2000) provided

the first detailed stratigraphic description and paleogeographic interpretation in the Monkman Pass area. No type section has been defined for the Vreeland Formation, although the Mount Vreeland sections (54° 35' N, 121° 32' W) in the Snake Indian thrust sheet (Fig. 1: B) and the Paksumo Pass section (54° 20' N, 120° 49' W) in the Wapiti Pass thrust sheet (Fig. 1: C) of the Monkman Pass area are thought to be representative exposures (McMechan 2000).

### *Old Fort Point Formation*

The Old Fort Point Formation (OFP) is the preferred name to describe the unique stratigraphic marker in the WSG that is exposed locally over the entire outcrop region of southwestern Canada (Fig. 1: D - K). Walcott (1910) was the first to describe the OFP from the Lake Louise area of Alberta using its distinctive purple and green colours and lithology (siltstone, limestone, breccia) to separate the Precambrian Corral Creek (lower conglomerate to sandstone) and Hector (upper slate) formations. The name and type section (52° 52' 16" N, 118° 03' 40" W) come from outcrops at a prominent landmark near Jasper, Alberta (Charlesworth *et al.* 1967). A more representative and better exposed section crops out ~15 km west of Jasper along the major highway (52° 52' 21" N, 118° 17' 35" W). The regionally extensive nature of the OFP has led to various names: 1) basal Hector Formation (Walcott 1910) or Mount Temple and Taylor Lake members (e.g. Gussow 1957) in the Lake Louise area, Alberta; 2) Old Fort Point Formation (e.g. Weiner 1966; Charlesworth *et al.* 1967) in the Jasper area, Alberta; 3) Middle Miette Marker (e.g. McDonough 1989) in the Mount Robson area, British Columbia; 4) Kaza Group marker (e.g. Ross & Murphy 1988) in the Cariboo Mountains,

British Columbia; 5) Baird Brook Division (e.g. Kubli 1990) in the Dogtooth Range of the Purcell Mountains, British Columbia; 6) Comedy Creek unit (Grasby & Brown 1993), Selkirk Mountains, British Columbia; and 7) upper and lower markers (e.g. Warren 1997) in the Purcell Mountains, British Columbia (Fig. 1). Although there were early attempts to correlate between certain locations (Charlesworth *et al.* 1967; Aitken 1969), it was Ross & Murphy (1988) who first recognized the basin-wide correlation of the OFP (and equivalents), its palaeogeographic significance and importance in Neoproterozoic event stratigraphy. Subsequent work by Ross *et al.* (1995) examined the sulfur isotopic evolution of the OFP and WSG strata in the Cariboo Mountains, British Columbia (Fig. 1). A regionally comprehensive study of the OFP integrating sedimentology, stratigraphy, geochemistry, and stable isotopes has recently been completed (Smith 2009).

### **Structural Framework and Basin Setting**

The WSG forms part of a long arcuate belt of semi-continuous outcrops in western North America that extends from the Yukon-Alaska border region to northwestern Mexico (e.g. Ross *et al.* 1989). In southwestern Canada, exposures crop out over an area of 35,000 km<sup>2</sup> in a series of thrust sheets in the Main Ranges of the western Fold-and-Thrust Belt and the Omineca Belt of the southern Canadian Cordillera (Fig. 1). Major structures affecting WSG strata in the region include the Southern Rocky Mountain Trench (Fig. 1) and a broad gently north-plunging structure in the Purcell Mountains (the Purcell Anticlinorium). Proterozoic-age structures that affected WSG deposition include regionally significant transfer faults (e.g. Mount Forster and

Moyie) and associated uplifted blocks (e.g. Windermere High and Montania; Reesor 1973; Lis & Price 1976; Root 1987; Warren 1997).

All WSG strata were subjected to Mesozoic orogenic deformation that resulted in a wide range of structural complexity and metamorphic grade between different structural panels. Extensive tracts of sub-greenschist to greenschist grade exist in the western Main Ranges of the Rocky Mountains (Lake Louise, Jasper, northern Cariboo Mountains and eastern Purcells Mountains); whereas higher grade metamorphic rocks (biotite to upper amphibolite) are found in the southern Cariboo and western Purcell Mountains, as well as the Shuswap Complex (e.g. Simony *et al.* 1980; Ross *et al.*, 1995). Areas of low metamorphic grade and relatively uncomplicated tectonic deformation show exceptional preservation of primary sedimentary textures and structures. This allowed the development of a consistent internal stratigraphy of the WSG and reconstruction of the Windermere basin in southwestern Canada (Ross and Murphy 1988; Ross *et al.* 1989, 1995; Ross 2000).

The WSG is thought to represent deposition in two tectonic phases (e.g. Stewart 1972; Ross 1991). The first phase was characterized by rifting during the break-up of the supercontinent Rodinia, whereas the second phase occurred during post-rift thermal relaxation. At the base of the WSG, the Toby Formation together with the Irene Formation volcanic rocks, are interpreted to have accumulated during the rifting phase (Aalto 1971; Glover & Price 1976; Root 1987). The variable thickness of the Toby Formation is attributed to syn-sedimentary fault-controlled deposition (Aalto 1971; Root 1987). Based on the nature of Proterozoic-age faults, Root (1987) suggested that the basin underwent two episodes of extension; one trending approximately E-W, resulting



in a series of NNE and NNW faults and another trending NW-SE, resulting in a series of NE-SW normal faults.

The Vreeland Formation and OFP both accumulated during the post-rift phase with possible local structural control (McMechan, 2000; Smith 2009). During this later phase, the basin is thought to be an elongate northwest-flowing turbidite system (Ross *et al.* 1989; Ross 1991; Ross *et al.* 1995), based on consistent palaeocurrent data and bimodal pattern (>2.6 Ga and 1.9 to 1.75 Ga) of U-Pb detrital zircon provenance (Ross & Bowring 1990; Ross & Parrish 1991). Basement clasts from the Vreeland Formation yielded ages between 1865 to 1842 Ma (Ross & Villeneuve 1997) suggesting derivation from a source area to the north and northeast (McMechan 2000).

While there is broad agreement about these two tectonic phases, the exact tectonic setting of the Windermere basin and its evolution remains controversial. Some argue that the upper part of the WSG in the southern Canadian Cordillera accumulated on a continental passive margin with a substantial Proto-Pacific Ocean (Ross 1991; Ross *et al.* 1995; Dalrymple & Narbonne 1996). Others prefer an intracontinental rift and restricted ocean basin setting for the southern WSG, and a late Neoproterozoic-early Cambrian inception for the Proto-Pacific Ocean (Colpron *et al.* 2002). The controversy and uncertainty is in part due to the presence of two intervals of rift-related igneous rocks within the southern Canadian Cordillera (Bond & Kominz 1984; Ross 1991; Colpron *et al.* 2002), diachronous dates for the timing of rifting along the whole of Laurentia's Pacific margin (see discussion in Lund *et al.* 2003), and tectonic deformation that currently precludes certain identification of a western Windermere basin margin.

## Stratigraphy

In the southern Canadian Cordillera, the WSG is a thick (~9 km), unconformity-bounded succession of predominantly coarse-grained deep-marine siliciclastic rocks with subordinate carbonate and mafic volcanic rocks (Fig. 2). Older units associated with the rift phase (e.g. Toby and Irene formations) are more limited in areal extent and tend to show greater lateral facies variations compared with units associated with the post-rift phase (e.g. Ross *et al.* 1989; Ross 1991; Ross *et al.* 1995; Warren 1997). At the base of the WSG, the Toby Formation unconformably overlies shallow-water deposits of the Mount Nelson Formation (Neoproterozoic/Mesoproterozoic?, Root 1987; Ross & Villeneuve 2003) or deep-marine sedimentary rocks of the Mesoproterozoic Purcell Supergroup (Aalto 1971; Root 1987). The Toby Formation is associated with localized rift-related mafic volcanic rocks of the Irene Formation and a laterally discontinuous carbonate horizon at its top (e.g. Root 1987; Warren, 1997). These basal units of the WSG are largely restricted to the Purcell Mountains region (Fig. 1). Potential high-grade metamorphic equivalents of the Toby (e.g. Simony *et al.* 1980; Murphy *et al.* 1991) and the Irene volcanic rocks (e.g. Simony *et al.* 1980; Sevigny 1988) may exist in the Shuswap Complex and northern Cariboo Mountains, although the stratigraphic control is poor (Fig. 1).

The nomenclature of WSG succession that overlies the Toby Formation in the southern Canadian Cordillera is rather complex: a direct result of correlation challenges across thrust-bound panels with varying levels of metamorphism, general absence of reliable stratigraphic markers and poor geochronological constraints. The Horsethief Creek Group (Purcell Mountains), Kaza and lower/middle Cariboo groups (Cariboo

Mountains), Miette Group (Rocky Mountains) and Misinchinka Group (Rocky Mountains) all refer to parts of the same ~5 km deep-marine turbidite system exposed over 35,000 km<sup>2</sup> (e.g. Ross *et al.* 1989) (Figs. 1, 2). Lithologically, the thick package is dominated by coarse-grained arkosic sandstone and granule conglomerate interbedded with mudstone-dominated intervals or minor carbonate.

The Vreeland Formation of the Misinchinka Group is a local exception, being composed of up to 2000 m of diamictite interbedded with mudstone, sandstone and conglomerate (McMechan 2000). Mapping of the Vreeland Formation has shown that the diamictite units undergo a lateral facies change into typical deep-marine coarse-grained turbidites of the WSG in both a westward (McMechan 1987) and southward direction (McMechan & Thompson 1995a).

Throughout much of the basin, the overall monotony of the thick-bedded, immature turbidites of the Horsethief Creek, Miette and Kaza groups is interrupted by the fine-grained, regionally widespread OFP (and correlative units) (Ross and Murphy 1988; Ross *et al.* 1995). Nowhere is the OFP observed to be contact with diamictite of the Vreeland Formation, rather the OFP overlies WSG turbiditic strata interpreted as deep-marine lateral equivalents. The OFP is overlain by coarse-grained basin-floor turbidite deposits that form a km-scale shoaling upwards trend to mudstone-dominated upper slope units and shelf platform carbonates (Ross *et al.* 1989). A significant regional unconformity marks the end of WSG deposition and the beginning of a latest Neoproterozoic to Cambrian rift-drift succession with the clastic and volcanic sediments of the upper Cariboo, Hamill and Gog groups.

## Glacigenic deposits and associated strata

### *Toby Formation*

The Toby Formation consists primarily of diamictite interbedded with conglomerate, sandstone, dolomitized or recrystallized limestone and mudstone (Fig. 3) (Aalto 1971). Its thickness is highly variable, ranging from 0 to 2500 m. Lithofacies, in general, and sedimentary characteristics of diamictite, in particular, (including clast concentration, clast size, matrix and clast lithology, lateral continuity and bed thickness) are highly variable over short distances; a fact that has been stressed by all workers in this region. The following descriptions rely heavily upon the regional study of Aalto (1971), with additional observations based on more recent field work by E. Arnaud and K. Root.

Diamictite is predominantly massive, matrix- or clast-supported with subangular to subrounded clasts up to 2 m floating in a muddy sandstone or sandy mudstone matrix. Clast lithology includes quartzite, volcanic greenstone, slate, dolomite and chert derived from the underlying Mount Nelson Formation as well as rare extrabasinal granite (Leech 1954; Reesor 1973; Loveridge *et al.* 1981). The diamictite matrix exhibits a similar lithological variability. Tectonic overprinting typically obscures clast fabric in many outcrops. Where relatively unaltered, clasts show no preferred orientation. Diamictite units vary in thickness from several m to 10s of metres. In outcrops with good lateral exposure, basal contacts are relatively planar, and conformable or erosional.

Conglomerate occurs in lenticular or planar units (cm to m scale) interbedded with diamictite and sandstone. It is distinguished from the diamictite by its coarse sandstone matrix, and consistently high clast concentration (65 to 80%). It is generally unorganized and massive with occasional subtle coarse-tail grading. Sandstone varies from coarse- to fine-grained, moderately to poorly sorted and occurs in planar beds or lenticular units (cm to m scale). It is most commonly massive or laminated, though some sandstone units exhibit ripple cross-lamination, climbing ripples or normal grading. Dolomitized or recrystallized limestone (cm to m scale thick) with varying amounts of quartz grains is also observed within and at the top of the Toby Formation at various sites within the region. These carbonate strata are planar-tabular and can be laterally persistent over 100s' of metres, though their overall distribution is patchy. Lastly, mudstone is relatively common throughout the Toby Formation. It is massive or laminated and occurs in relatively planar tabular units (cm to m scale thick). Outsized clasts are found within these mudstone units and some are seen to depress or puncture underlying laminations (Aalto 1971).

In terms of associated strata, the underlying Mount Nelson and Dutch Creek formations consist of thick packages of carbonate and siliciclastic strata (km scale; Walker 1926; Reesor 1973, Root 1987). Slate predominates in the Dutch Creek Formation, whereas thick packages of white quartzite and dolomite interbedded with intervals of argillite, siltstone and conglomerate characterize the Mount Nelson Formation. In the Purcell Mountains, the Toby Formation is overlain by the Horsethief Creek Group, which consists of a thick package (<100 to 2000+ m) of mudstone, sandstone, conglomerate, calcareous mudstone and dolostone (Walker 1926; Root

1987; Kubli 1990; Warren 1997). Further to the south, the Toby Formation is interbedded and overlain by volcanic greenstone of the Irene Formation, and coarse- to fine-grained clastic and carbonate lithofacies of the Monk Formation (Aalto 1971).

### *Vreeland Formation*

Description of the Vreeland Formation is based entirely on regional mapping studies in the Pine and Monkman Pass areas (McMechan 1987; McMechan & Thompson 1985, 1995a, 1995b) and geological descriptions from the Snake Indian and Wapiti Pass thrust sheets (Fig. 1) (McMechan 1990, 2000). The Vreeland Formation comprises a thick succession of diamictite interbedded with mudstone, sandstone and conglomerate (Fig. 4). Diamictite units are generally massive (~98%) with a sandstone or siltstone to mudstone matrix and form laterally extensive (up to 2 km) tabular sheets that range from a few metres to >40 m thick. The basal contact of massive diamictite units is sharp and locally erosive. Subtle normal grading is observed locally in diamictite in addition to rare stratified diamictite defined by clast layers, or sandstone/siltstone stringers and lenses. Clasts are lithologically diverse and consist of both intra-basinal (mudstone, sandstone, carbonate) and extra-basinal (felsic or mafic plutonic, volcanic, quartzite) varieties. Differing provenance trends are apparent in the two main areas based on clast lithology.

Interstratified mudstone units are up to 38 m thick with rare sandstone interbeds, and common limestones. Sandstone units are sharp-based and range from very fine- to very coarse-grained and very thin- to thick-bedded. Sedimentary structures include scours, cross-stratification, graded bedding and intraclast rip-ups. Conglomerate and

sandstone units commonly form lenticular channel-like deposits. Conglomerate is matrix- and clast-supported with a sandstone matrix, which contrasts with the typical siltstone to mudstone matrix of the diamictite. Clast lithologies are similarly diverse, rounded to angular and range up to boulder size.

In the Snake Indian thrust sheet, the top of the Vreeland Formation is marked by a pyrite-rich zone up to 30 cm thick and locally the diamictites are overlain by a thin (few metres), parallel laminated limestone. The conformably overlying Framstead Formation is mudstone-dominated, but locally is composed of sandstone to conglomerate or limestone. Locally, large (up to 650 m long) carbonate olistoliths occur on, or just above the basal contact with the Vreeland Formation, and also near its upper contact. These olistoliths occur as discrete, randomly-oriented blocks that lack internal deformation. Lithologies are predominantly tan-weathered shallow-water carbonates and include: laminated dolomite with rare layers of teepee structures and bladed calcite, stromatolitic dolomite, sandy- to pebbly dolomite, dolomite conglomerate, and quartzose fenestral and vuggy dolomite.

#### *Old Fort Point Formation*

The following sedimentological and stratigraphic description stems mostly from a recent detailed regional study (Smith 2009) but also incorporates work of earlier authors (Fig. 1: D to K) (Walcott 1910; Weiner 1966; Charlesworth *et al.* 1967; Aitken 1969; Murphy 1986; Pell and Simony 1987; Ross & Murphy 1988; McDonough 1989; Deschesne 1990; Kubli 1990; Grasby & Brown 1993; Ross *et al.* 1995; Warren 1997; Ross & Ferguson 2003a, 2003b). The OFP comprises three distinctive lithological

members, which despite variable metamorphic grade, form a consistent stratigraphic relationship throughout the southern Canadian Cordillera (Fig. 5).

The lower member is a purple, green, grey, or red-brown fine-grained unit that ranges from 50 to 125 m thick. The basal portion is composed of siltstone to mudstone that grades upward into rhythmic couplets of limestone-siltstone. Beds typically range from <1 cm to 10 cm in thickness and exhibit common tractional sedimentary structures including: planar lamination, lenticular bedding, ripple cross-lamination, normal grading and minor scours. Subordinate lithofacies include very fine- to fine-grained sandstone interstratified with uncommon limestone-clast breccia beds. Palaeocurrents measured from 3D current-ripples generally indicate flow toward the southwest to northwest.

The middle member ranges from 2 to 15 m thick and consists of a dark-grey organic-rich mudstone/pelite. The basal contact with the underlying lower member is usually gradational over a few metres. The unit is characterized by alternating siltstone and mudstone laminae with subtle normal grading. Isolated, thin-bedded dark-grey massive or planar-laminated limestone and very fine ripple-stratified sandstone occur locally. This member is regionally extensive. Its fissile nature typically results in poor or covered exposures, although notable exceptions occur (e.g. Ross *et al.* 1995; Kendall *et al.* 2004).

In contrast to the lower two members, the upper member is lithologically diverse and highly variable in thickness (<0.5 to 165 m). The basal contact with underlying strata is always sharp, and locally, it completely erodes the lower two members. Lithologies include diamictite, breccia, conglomerate, mudstone, siltstone, sandstone, quartz arenite, calcareous arenite, arenaceous limestone and limestone. Diamictite and



breccia to conglomerate are generally sharp, commonly erosively-based, massive beds with mudstone/siltstone or well-sorted, coarse quartz-rich sandstone matrix. Bed thickness (<0.5 to >10 m), clast-size (cm to m) and clast lithologies are variable. Clasts include fragments of the OFP members and shallow-marine carbonates, some with rare bladed calcite crystals. Mudstone and siltstone exhibit planar laminations, micro-scours, subtle normal grading, large single chlorite flakes and rare scours. This lithofacies is locally thick (~100 m) and monotonous with rare interbeds of diamictite, breccia, conglomerate or sandstone. Sandstone in the upper member consists of a range of textures: fine- to very coarse-grained, poor- to well-sorted and mineralogical maturity (immature to supermature). The well-sorted, mature quartz arenites are interbedded with dark, organic-rich limestone beds and these units can exhibit a range of compositions between the two end members (e.g. calcareous arenites or arenaceous limestones). Sedimentary structures include massive beds, planar lamination, and cross-stratification. Rare palaeocurrent measurements from the upper member are consistently towards the southwest to northwest. Soft-sediment deformation features such as load structures, convolute or contorted bedding and ductile folding are common in both fine- and coarse-grained facies of the upper member.

### **Boundary relations with overlying and underlying non-glacial units**

#### *Toby Formation*

The Toby Formation rests unconformably on various members of the Mount Nelson Formation or the underlying Dutch Creek Formation. In outcrop, the

unconformity is commonly subtle ( $<10^\circ$ ), though a distinctive angular unconformity with tilted underlying Mount Nelson strata is evident in some places. The upper contact of the Toby Formation with the Horsethief Creek Group is conformable and gradational throughout the Purcell Mountains and typically established based on the loss of diamictite. To the west and south of the Purcell Mountains, the Toby Formation is conformably overlain by pillow lavas of the Irene Formation as well as conglomerate and diamictite facies of the lower Monk Formation (Aalto 1971). Considering there are localized lenses of conglomerate and diamictite in the Irene Formation, and that the upper contact of the Toby Formation is defined in the Purcell Mountains with the loss of diamictite facies, the upper contact of the Toby Formation may actually occur several 10's of metres above the Irene volcanic rocks (Aalto 1971).

#### *Vreeland Formation*

In the western Snake Indian thrust sheet, the basal contact of the Vreeland Formation is not exposed (McMechan 2000). In the eastern Wapiti Pass thrust sheet, the basal diamictite appears to interfinger with the upper 150 m of the fine-grained facies of the underlying Paksumo Formation (McMechan & Thompson 1995b). The Vreeland Formation is conformably overlain by the Framstead Formation: in the western exposures by a carbonate olistolith bearing unit; whereas in the eastern exposures by a sandstone unit (McMechan 2000). The carbonate olistolith bearing unit correlates from west to east where it overlies the lowermost Framstead Formation sandstone. This suggests at the western Snake Indian thrust sheet locality that either local erosion of the

sandstone unit occurred or it is actually a lateral equivalent of diamictite of the Vreeland Formation (McMechan 1990).

### *Old Fort Point Formation*

The OFP conformably and gradationally overlies deep-marine turbiditic strata of the WSG interpreted to be lateral facies equivalent of the Vreeland Formation diamictite. The contact is commonly marked by a distinctive change in colour (e.g. grey to purple) and lithology (appearance of lower member siltstones). However, at some locations the lower and middle members have been eroded and the upper member forms a sharp unconformity over older WSG strata. The top of the OFP is conformably overlain by younger WSG strata. In many cases the contact is identified by a sharp change in grain-size and/or framework mineralogy (e.g. OFP quartz arenite to WSG arkosic sandstone). The challenge arises where OFP mudstone units are overlain directly by a younger mudstone unit of the WSG. The contact is taken to coincide with the termination of organic-rich limestone beds or the appearance of common sandstone interbeds. Field observations can sometimes be confirmed by a decrease in gamma-ray counts or correlative geochemical trends (e.g. decrease in TOC, Mo) (Smith 2009).

### **Chemostratigraphy**

The only published geochemical or isotopic data from the three units is the sulfur isotopic study of Ross *et al.* (1995) on pyrite in the post-rift strata of the WSG, Cariboo Mountains, British Columbia (Fig. 1: E). A total of 170 samples were analysed for  $\delta^{34}\text{S}_{\text{py}}$  and these showed a broad range of isotopic values (approximately 50‰) (Ross *et al.*

1995). As part of that study, a suite of 36 samples were collected from a measured section that includes the OFP. A strong correlation between lithology (and inferred sedimentation rate) and pyrite isotopic composition was reported (Ross *et al.* 1995). For example, the most negative  $\delta^{34}\text{S}_{\text{py}}$  values (-31.9‰ to -25.3‰) corresponded to siltstone and mudstone of the OFP whereas the interval in the underlying Kaza Group with the highest sandstone-mudstone ratio were the most positive (around +11.9‰ to +14.5‰) (Ross *et al.* 1995).

New isotopic data ( $\delta^{18}\text{O}_{\text{carb}}$ ,  $\delta^{13}\text{C}_{\text{carb}}$ ,  $\delta^{13}\text{C}_{\text{org}}$ ,  $\delta^{34}\text{S}_{\text{py}}$ ) from OFP sections and lithochemical (major-, trace- and rare-earth-element analyses) data from a regional study of WSG mudstones has recently been obtained (Smith 2009). Preliminary analysis shows lower member limestone units exhibiting negative  $\delta^{13}\text{C}_{\text{carb}}$  isotopic values and the middle member characterized by distinctive chemical (e.g. TOC, Mo, V/Cr) and isotopic (e.g.  $\delta^{13}\text{C}_{\text{org}}$ ) signatures.

### **Other characteristics**

Economic deposits associated with the glaciogenic strata are limited. Local copper mineralization has been observed below, or in the basal parts of the OFP (Ross 2000; Smith 2009).

The only description of possible Precambrian fossils from glaciogenic strata are some problematic discoid structures at the base of the OFP near Arnica Lake, west of Banff, Alberta (Fig. 1). The structures are ~3 mm in size, lentil-shaped with either hypo- or epirelief, have concentric wrinkles and a 5-point star-like figure inside the concentric pattern (Hofmann 1971; Gussow 1973; Smith 2009). The specimens are attributed to

*Chuarina circularis* (Hofmann 1971; Gussow 1973) but they lack any carbonaceous material that would strengthen a biogenic origin and certainly require further detailed work. Ediacaran fauna (including *Namacalathus* and *Cloudina* assemblages similar to those found in the Nama Group of Namibia) have otherwise been reported from the uppermost part of the WSG (Hofmann & Mountjoy 2001 and references therein).

### **Palaeolatitude and palaeogeography**

There are no published palaeolatitude data for the WSG in southwestern Canada. A near-equatorial palaeogeographic position is based on palaeomagnetic data obtained from broadly correlative WSG strata in the Mackenzie Mountains, northern Canadian Cordillera (Park 1997).

### **Geochronological constraints**

The predominantly siliciclastic nature of the WSG in the southern Canadian Cordillera has led to a paucity of high-precision geochronological constraints. Currently, the local maximum depositional age of the WSG in the region is constrained by a U-Pb zircon date of  $736 \pm 23/-17$  Ma (MSWD 2.36, 4-point TIMS regression) from orthogneiss basement rocks of the Malton Gneiss Complex (McDonough & Parrish, 1991). This age corresponds well with U-Pb zircon dates obtained from WSG basement rocks elsewhere in the Canadian Cordillera, such as  $740 \pm 36$  Ma (Parrish & Scammell 1988) and  $728 \pm 8/-7$  Ma (Evenchick *et al.* 1984; see Ross *et al.* 1995 for a full review). A U-Pb zircon age of  $569.6 \pm 5.3$  Ma (3-point  $^{207}\text{Pb}/^{206}\text{Pb}$  weighted average) from syn-rift

felsic volcanic rocks of the Hamill Group that unconformably overlie the WSG constrains the minimum timing of deposition (Colpron *et al.* 2002).

No direct ages have been obtained from the Toby Formation or Irene volcanic rocks in southern British Columbia. Mafic metavolcanic rocks of the Huckleberry Formation in northeastern Washington, interpreted to be Irene Formation correlatives were imprecisely dated with a preliminary age of  $762 \pm 44$  Ma (MSWD 0.06) from a three-point Sm-Nd isochron of one whole-rock and two pyroxene separates (Devlin *et al.* 1988). Other possible treatments of the Sm-Nd data produced even larger error estimates:  $795 \pm 115$  Ma (MSWD 6.71) from all the data excluding one pyroxene separate;  $674 \pm 212$  Ma (MSWD 1.0) from a seven point whole-rock isochron; and  $719 \pm 200$  Ma (MSWD 1.0) from two whole-rock and two pyroxene separates (Devlin *et al.* 1988). More recent work on possible correlative rift-related volcanic rock units in Idaho have obtained precise SHRIMP U-Pb zircon ages, of  $685 \pm 7$  Ma,  $684 \pm 4$  Ma (Lund *et al.* 2003), and  $709 \pm 5$  Ma (Fanning & Link 2004). A comparable U-Pb zircon age of  $688.9 \pm 9.5/-6.2$  Ma was obtained from syn-rift felsic volcanoclastics of the Gataga Volcanics, northern British Columbia (Ferri *et al.* 1999).

No absolute age constraints are available for the Vreeland Formation: its relative age is based on regional mapping and lithostratigraphic correlations within the WSG (McMechan 1987, 1990, 2000). Kendall *et al.* (2004) obtained two comparable 5-point Re-Os isochron ages from organic-rich black mudstone of the OFP middle member in the Jasper area, Alberta (Fig. 1): an imprecise  $634 \pm 57$  Ma (MSWD 65) using the conventional inverse aqua regia digestion method; and a more precise  $607.8 \pm 4.7$  Ma

(MSWD 1.2) using the  $\text{CrO}_3\text{-H}_2\text{SO}_4$  digestion technique that is thought to best reflect depositional age of the OFP.

## **Discussion**

### *Toby Formation*

The variable level of erosion below the sub-Toby unconformity suggests a period of significant erosion and uplift preceded WSG sedimentation. The depositional setting of the Toby Formation itself has been controversial, specifically in regards to the extent of glacial influence on deposition. Most lithologies record remobilization of sediment by sediment-gravity flows. Some authors have favoured a glacial setting for these reworked deposits based on the regional extent of the Toby Formation, the presence (albeit localized) of extrabasinal clasts, striated clasts, clast clusters within diamictites and outsized clasts interpreted as far-travelled and ice rafted glacial debris (Aalto 1971; Warren 1997). Others favoured the resedimentation of locally derived material formed along a fault-bounded margin undergoing extension with limited or no glacial influence (Walker 1926; Reesor 1973; Root 1987). The predominance of intrabasinal clasts, the mounting evidence for structural controls on facies type and variability (ongoing research), in addition to the localized and rare occurrence of glacial indicators suggest that tectonic activity imparted a primary control on deposition with localized glacial influence.

Carbonate strata within, and at the top of the Toby Formation have received limited attention to-date. Preliminary results from ongoing work suggest that primary

carbonate was accumulating on topographic highs while coarse-grained clastics accumulated in fault-bounded basins. Stable isotopic analyses of these carbonates have so far yielded limited information with current research focused on assessing the effects of metamorphism on isotopic signatures.

### *Vreeland Formation*

The Vreeland Formation is interpreted to have been deposited in a mid-slope, glacially-influenced marine setting (McMechan 2000). The diamictite units are interpreted to be resedimented sediment-gravity flow deposits (e.g. unconfined debris flows) of glacial debris or the result of “rain-out” processes from fine-grained suspended sediment plumes and ice-rafted debris (McMechan 2000). The argument for a glacial origin is based on large, sub-angular extrabasinal basement clasts in the diamictite and the occurrence of lonestones interpreted as dropstones in the mudstone units of the Snake Indian thrust sheet (McMechan 2000). The absence of dropstones in the Wapiti Pass thrust sheet Vreeland sediments suggests that there was little to no ice-rafted material at this palaeogeographic location (McMechan 2000). The considerable strike length (~400 km) of diamictite suggests glacial erosion over a large area, whereas its thickness (~2000 m) suggests active subsidence accompanied by local faulting (McMechan 2000).

In the Snake Indian thrust sheet, diamictite units are overlain locally by a discontinuous thin-laminated grey limestone (cap carbonate?) deposited during post-glacial sea-level rise and concomitant shutdown of coarse clastic sediment flux to the basin (McMechan 1990, 2000). The large shallow-marine carbonate olistoliths in the



Framstead Formation suggest continued uplift or faulting causing instability and downslope movement of parts of the carbonate shelf edge (McMechan 2000), although simple highstand shedding during post-glacial eustatic rise could also be a potential delivery mechanism.

### *Old Fort Point Formation*

The OFP was deposited along a deep-marine basin-slope to basin-floor transect and overlies coarse-grained turbidites of the WSG. The OFP is interpreted to be related to an Ediacaran-aged post-glacial eustatic rise and a shutdown of the supply of coarse, immature siliciclastic sediment into the basin (Ross & Murphy 1988). Fine-grained, mostly turbiditic strata of the lower and middle members are regionally uniform in thickness and lithofacies suggesting synchronous, basin-wide deep-marine deposition during transgression and highstand (Ross and Murphy 1988; Ross *et al.* 1995; Smith 2009).

Conversely, the variable lithology and thickness of the upper member appears to be controlled by a combination of more local factors including: palaeogeographic location, topography along the slope, erosional mass wasting, structural activity and/or relative sea-level changes (Smith 2009). Deposition of the upper member is interpreted to have coincided with a fall of a relative sea-level caused at least in part, by regional uplift (Smith 2009). In western North America, other Ediacaran-aged uplift or erosion features have been observed suggesting some type of renewed extensional activity during the post-rift phase (e.g. Warren 1997; Fedo & Cooper 2001; Clapham & Corsetti 2005). Where observable, the locally sharp, basal contact is interpreted as a sequence

boundary (possibly overprinting the basal surface of forced regression) within OFP (Smith 2009). Related erosional mass wasting, submarine canyon incision and/or syn-sedimentary growth faults controlled initial sediment transport fairways (lowstand) that were subsequently filled during a renewed relative sea-level rise (transgression and highstand) (Smith 2009). The quartz-rich lithologies of the upper member compared to the arkosic sandstone of other WSG turbidites reflect winnowing and maturation from residence on the shelf during the earlier transgression and highstand (Ross 2000; Smith 2009).

### *Regional Correlations*

The Toby, Vreeland and OFP formations have been correlated with other units along the North American Cordillera based on lithostratigraphic similarities (see Lund *et al.* 2003 or Colpron *et al.* 2002 for most recent reviews). The Toby Formation has been correlated with the Kingston Peak Formation (Death Valley), the Edwardsburg and Pocatello formations (Idaho), the Shedroof Conglomerate (NW Washington) and the Sayunei and Shezal formations (Mackenzie Mountains, NW Canada) (Gabrielse & Campbell 1991; Link *et al.* 1993; Ross *et al.* 1995). The Vreeland Formation has been correlated to the similar diamictite-bearing Toobally (Pigage & MacNaughton 2004) and Icebrook (Aitken 1991; James *et al.* 2001) formations in the northern Canadian Cordillera. The Mount Lloyd George diamictite in north-central British Columbia (Eisbacher 1981a, 1981b) is of uncertain age and may correlate with either the Toby or the Vreeland formations.

The OFP overlies turbidites of the WSG that are interpreted to be correlative with the Vreeland Formation (McMechan 1990, 2000; Ross *et al.* 1995). The OFP lower member rhythmic limestone-siltstone couplets are interpreted as a deep-marine equivalent of the thin limestone overlying the Vreeland Formation (McMechan 2000) and of the cap carbonate succession overlying the Ice Brook Formation (Aitken 1991; James *et al.* 2001). The organic-rich OFP middle member potentially correlates with the pyrite-rich horizon at the top of the Vreeland Formation (McMechan 2000) and represents maximum flooding conditions and anoxic (?) bottom-water conditions during earliest post-glacial highstand. The correlative link between the glacial Ice Brook/Vreeland formations and the post-glacial OFP is based primarily on stratigraphic relationships and on the consistent stratigraphic presence of associated carbonates and carbonate olistoliths possessing distinctive bladed calcite crystals (Ross *et al.* 1995).

The basal glacial event in the southern Canadian Cordillera is represented by deposition of the Toby Formation, which is thought to be younger than ~740 to 728 Ma (see Ross *et al.* 1995 for full review). Various data treatments of the Sm-Nd ages (~795 to 674 Ma) from correlative volcanic rocks (Devlin *et al.* 1988) are considered too imprecise to be useful. Current precise ages from potentially equivalent strata in Idaho provide better absolute timing constraints on the glacial episodes because they were obtained from volcanic rocks intercalated with diamictite units, as opposed to unconformably underlying basement rocks. However, further geochronological studies are needed to determine the synchronicity between glacial conditions in Idaho and the southern Canadian Cordillera. The disparity in radiometric age constraints for rift-related magmatic rocks along the Cordilleran margin suggests a diachronous,

protracted history of crustal extension and magmatism and thus underscores the need for caution when correlating Cordilleran glacial deposits without precise geochronological constraints (Lund *et al.* 2003; Fanning & Link 2004). The timing of the younger glacigenic event is constrained by the ~608 Ma OFP (Kendall *et al.* 2004) which provides a relative minimum age for Vreeland diamictite deposition based on current regional stratigraphic correlations.

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## Figures Captions:

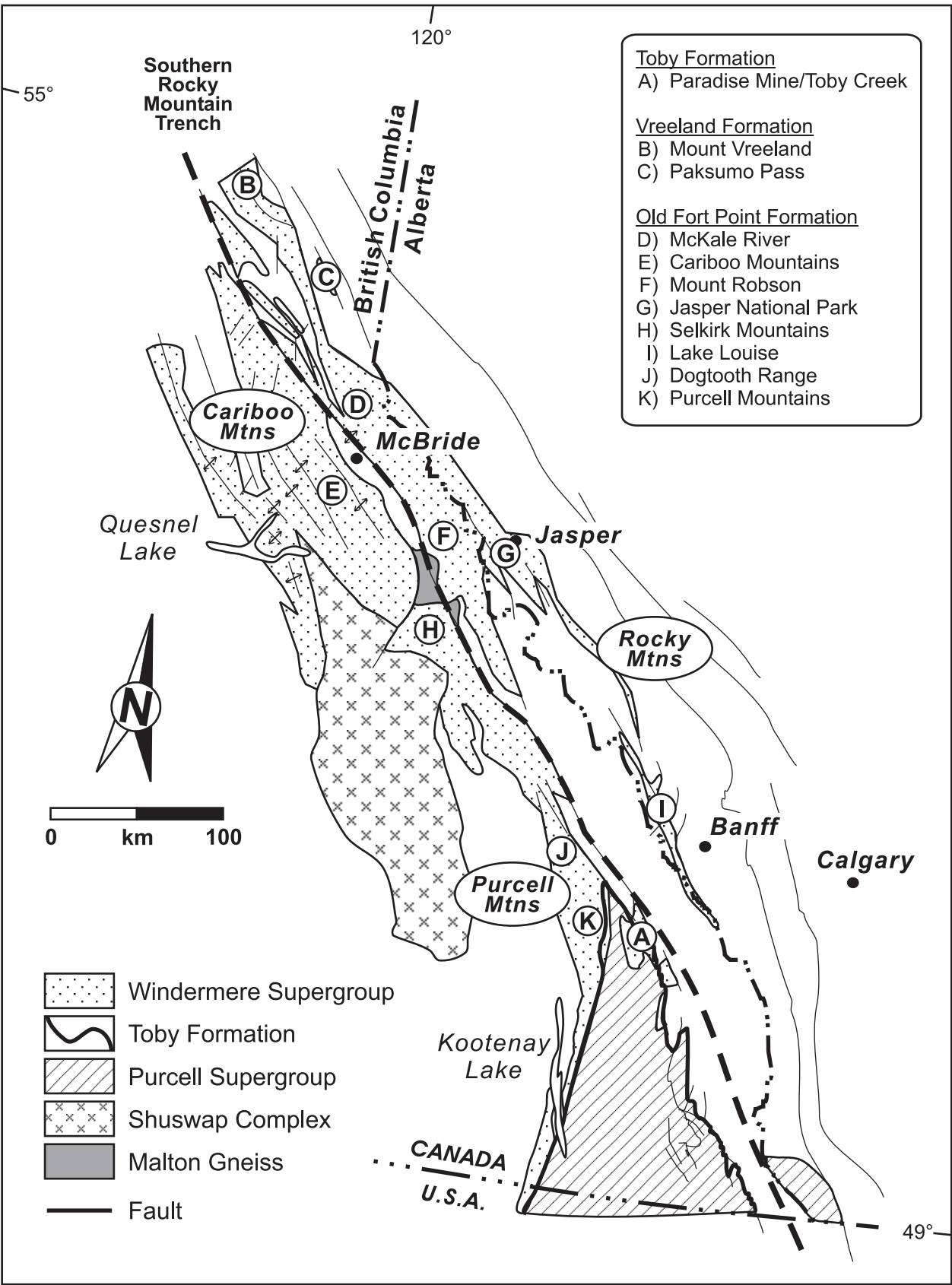
Fig. 1. Generalized geological map showing outcrop distribution of Windermere Supergroup in western Canada and specific outcrop localities (A – K) discussed in the text (modified from Ross *et al.* 1995). A comprehensive list of outcrop locations for the Toby Formation can be found in Aalto (1971) and Reesor (1973). Outcrop localities for the Vreeland Formation are from McMechan (2000) and for the OFP from Ross & Murphy (1988) and Smith (2009).

Fig. 2. Comparative stratigraphic columns for the Windermere Supergroup from the Monkman Pass area and the Cariboo-Purcell-Rocky Mountains (modified from Ross *et al.* 1995). Nomenclature of rift and post-rift strata (Kaza-Cariboo, Horsethief Creek and Miette groups refer to similar strata, depending on location within the region), relative stratigraphic position of the glacial Toby, Vreeland and Old Fort Point formations and proposed correlation between the basal Framstead and Old Fort Point formations are shown. Ages shown are discussed in the text and in stratigraphic order, are: Malton Gneiss (McDonough & Parrish 1991); rift-related volcanic rocks from Idaho (Lund *et al.* 2003; Fanning & Link 2004); Old Fort Point Formation (Kendall *et al.* 2004); and Hamill Group volcanic rocks (Colpron *et al.* 2002). Bracketed ages indicate that the ages are not from rocks of the southern Canadian Cordillera, but rather interpreted correlatives of the Irene Formation.

Fig. 3. Stratigraphic columns of the Toby Formation from the Mount Brewer (~ 50° 23' N, 116° 14' W) and Paradise Mine localities (~ 50° 28' N, 116° 18' W) with lithofacies representative of other outcrops; however, their lateral continuity, stratigraphic thickness and stratigraphic distribution vary widely across the Purcell Mountains. Note the different scales used in each log. Facies codes used: first letter corresponds to D-diamictite, G-Conglomerate, S-sandstone, F-fine-grained facies; second letter in diamictite and conglomerate refers to the following: m-matrix supported, c-clast-supported. Third letter in code refers to sedimentary structure as follows: m-massive, l-laminated, d-deformed, r-rippled, h-horizontally-bedded, s-stratified.

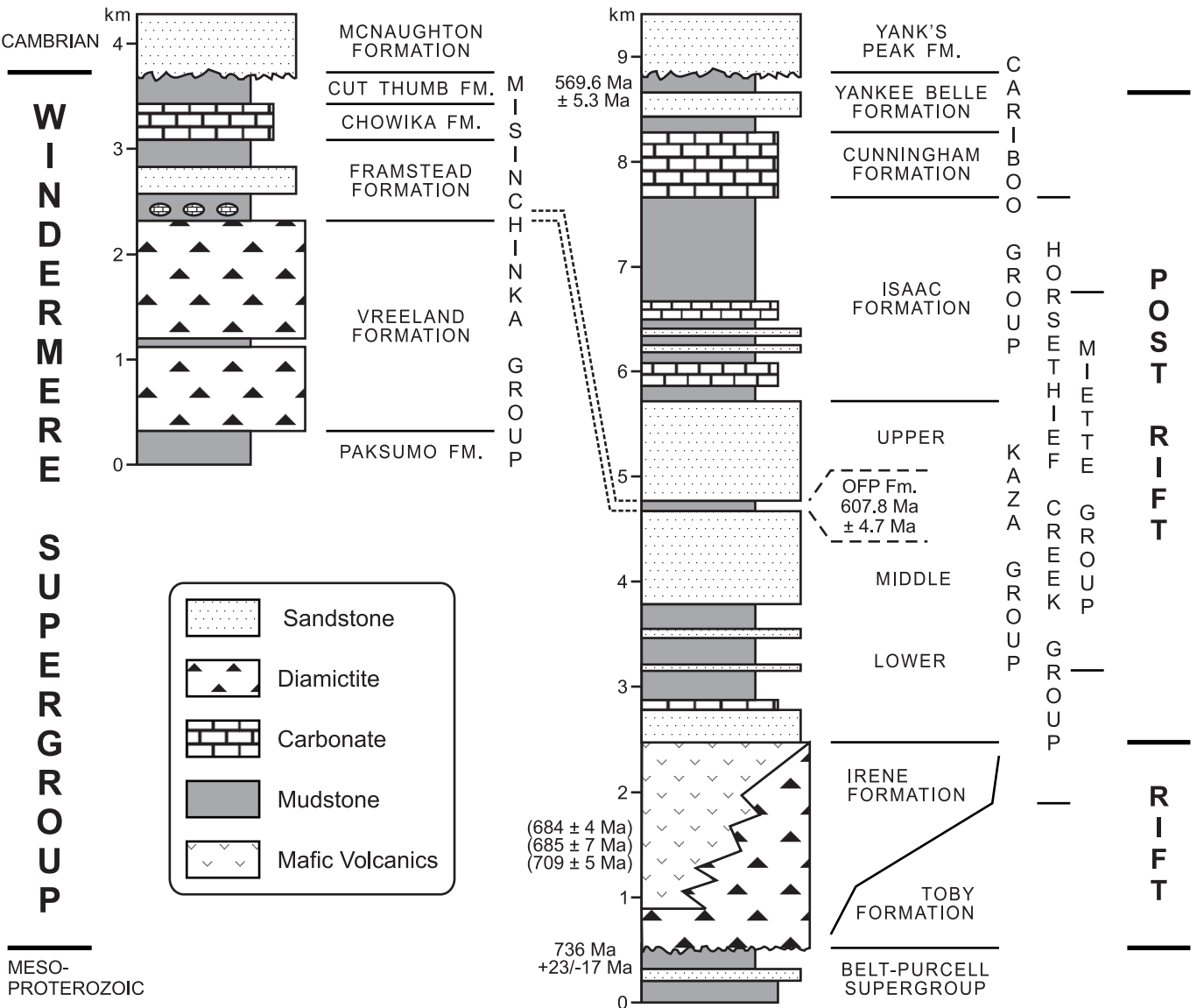
Fig. 4. Stratigraphic columns of the Vreeland Formation near Mount Vreeland in the Snake Indian thrust sheet, and Paksumo Pass in the Wapiti thrust sheet, modified from McMechan (2000). St-cross-trough bedded sandstone; Fld- laminated fine-grained facies with lonestones. See Fig. 3 for other facies codes.

Fig. 5. Stratigraphic columns of the Old Fort Point Formation, simplified from Smith (2009). At the Geikie Siding section in Jasper National Park, the regionally widespread lower two members are exposed and overlain sharply by a thinly developed upper member. The Re-Os isochron age was obtained from the middle member at this section (Kendall *et al.* 2004). At the Upper Boomerang section on the Lake Louise Ski Resort, only a thickly developed Upper Member is exposed with complete erosion of the lower two members. Str-stratified (ripple cross-laminated and cross-bedded). See Fig. 3 for other facies codes.



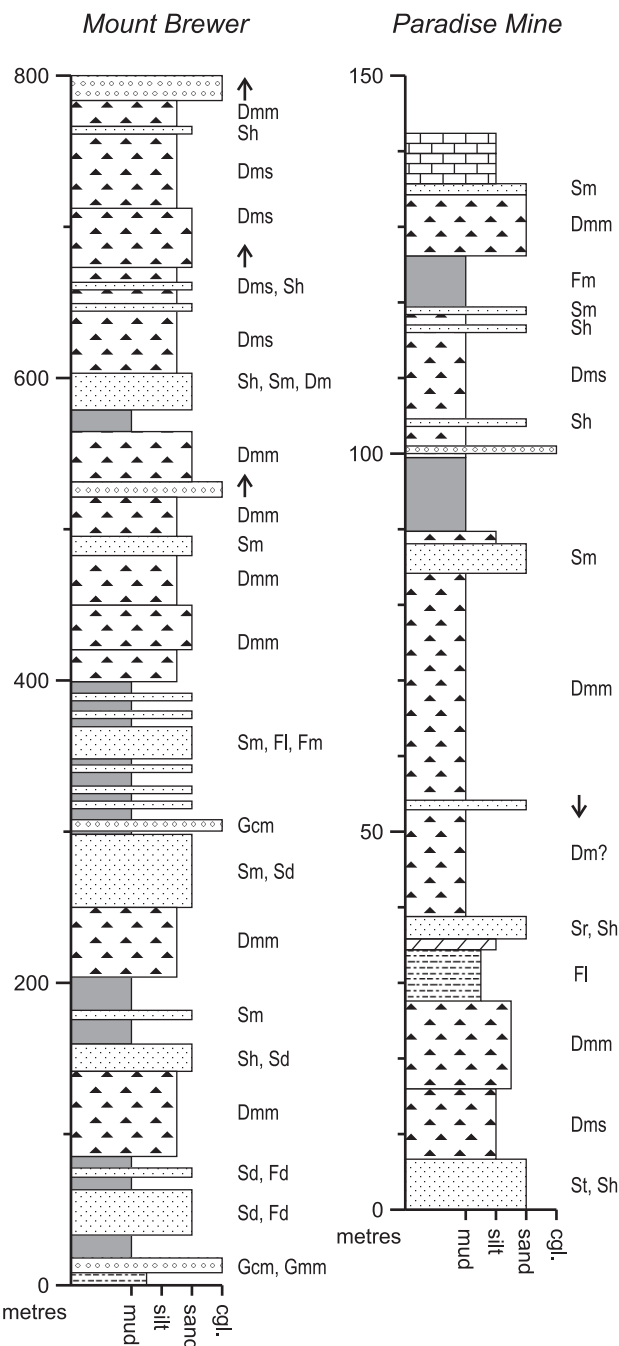
MONKMAN PASS AREA

CARIBOOS-PURCELLS-ROCKIES



Smith et al., Fig. 2

# Toby Formation



# Vreeland Formation

