A new Burgess Shale-type locality in the “thin” Stephen Formation, Kootenay National Park, British Columbia: stratigraphic and paleoenvironmental setting

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ABSTRACT

A new Burgess Shale-type locality in the Middle Cambrian Stephen Formation was excavated in August 2008 by a team organized by the Royal Ontario Museum. This locality lies below Stanley Glacier in Kootenay National Park, approximately 40 km SE of Walcott’s Quarry in the Stephen Formation on Fossil Ridge, near Field, British Columbia. Regionally, the Stephen Formation has two different expressions, which historically have been termed the “thick” and “thin” Stephen, the former now called the Burgess Shale Formation by some workers. Respectively, these units have been interpreted to represent deposition on a drowned carbonate platform and in an adjacent basin, which was separated from the platform by a submarine escarpment, known regionally as the Cathedral Escarpment. Whereas the Walcott Quarry and other fossil-bearing localities in the area of Field occur in the “thick” Stephen Formation, directly adjacent to the escarpment, the new Burgess Shale-type locality occurs in the “thin” Stephen Formation, deposited either above an escarpment which has no local expression, or on a ramp where no escarpment was present. The sediments which contain the exceptional biota at the Stanley Glacier locality are similar to those of the Burgess Shale in cm to µm scale attributes; however, the stratigraphic and paleoenvironmental setting of the two localities is different. The “thick” Stephen Formation is approximately 300 m in thickness and is shale dominated in the Field area, whereas the Stephen Formation at Stanley Glacier is 32.5 m thick, and is composed of six shale–wackestone parasequences, which range from 1.5 to 15 m in thickness. At Stanley Glacier, the Stephen Formation is similar in thickness and lithology to other “thin” Stephen sections described from the region but differs in that no evidence of grading, scour, hummocky cross-stratification or cross-bedding is present, indicating that the entire Stephen Formation at Stanley Glacier was deposited below storm wave base. The Stanley Glacier fossil assemblage occurs in the upper of two members of the Stephen Formation and thus is younger in age than those of the classic Burgess Shale lo-

RÉSUMÉ

Une nouvelle localité du type du Schiste de Burgess dans la Formation Stephen du Cambrien Moyen a été excavé en août 2008 par une équipe organisée par le Musée royal de l’Ontario. Cette localité se trouve au-dessous du Glacier Stanley dans le Parc National Kootenay, à environ 40 kilomètres sud-est de la Carrrière de Walcott dans la Formation Stephen sur Fossil Ridge, près de Field, en Colombie Brittanique. Dans la région, la Formation Stephen a deux expressions différentes, qu’on a appelées historiquement la Stephen “épaisse” et la Stephen “mince”, celle-là appelée maintenant la Formation du Schiste de Burgess par quelques travailleurs. Respectivement on a interpreté ces unités comme des représentants de dépôt sur une plate-forme carbonatée inondée, et dans un bassin contigu, qui a été séparé de la plateforme par un escarpement sous-marin qu’on appelle dans la région l’Escarpement Cathédrale. Tandis que la Carrière de Walcott et d’autres localités contenant des fossiles dans la région de Field se trouve dans la Formation Stephen “épaisse”, directement contigue à l’escarpement, la nouvelle localité du type du Schiste de Burgess se trouve dans la Formation Stephen “mince”, ayant été déposée ou au-dessus d’un escarpement qui n’a aucune expression locale ou sur une rampe où aucun escarpement n’etait présent. Les sédiments qui contiennent le biote exceptionnel à la localité du Glacier Stanley ressemblent à ceux du Schiste de Burgess dans des attributs de centimètres à microcentimètres. Cependant, la disposition stratigraphique et paléoenvironnementale des deux localités est différente. La Formation Stephen “épaisse” a une épaisseur d’environ 300 mètres et est dominée par de l’ardoise dans la région de Field, tandis que la Formation Stephen au Glacier Stanley est épaisse de 32.5 mètres et comprend six paraséquences d’ardoise–wackestone, qui ont une épaisseur de 1.5 jusqu’à 15 mètres. Au Glacier Stanley, la Formation Stephen est de pareilles épaisseur et lithologie à d’autres “minces” sections Stephen qu’on a décrites dans la région, mais elle est différente parce qu’il n’y a aucune évidence d’aggradation, de déblayage, de stratification

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calities. The Stanley Glacier locality occupies a stratigraphic and paleoenvironmental setting that is more similar to other Burgess Shale-type deposits found worldwide than to that of Walcott's original locality on Fossil Ridge. This finding highlights the role of the Cathedral Escarpment in promoting the preservation of the unparalleled abundance of soft-bodied fossils found just below it on Fossil Ridge and Mount Stephen, and also suggests that Burgess Shale-type fossils may be widespread regionally in similar lithofacies of the "thin" Stephen Formation.

croisée mamelonnée ni de litage encroisé, ce qui indique que toute la Formation Stephen au Glacier Stanley a été déposée au-dessous de la zone d'action de vagues de tempêtes. L'assemblage fossilifère du Glacier Stanley se trouve dans le plus haut de deux membres de la Formation Stephen, et est donc plus jeune que ceux des localités classiques du Schiste de Burgess. La localité du Glacier Stanley se trouve dans une disposition stratigraphique et paléoenvironnemental qui ressemble plus aux dépôts du type du Schiste de Burgess, qu'on trouve partout au monde, qu'à celui de la localité originale de Walcott sur Fossil Ridge. Cette découverte illumine le rôle de l'escarpement Cathédrale dans l'encouragement de la conservation de l'abondance sans pareil de fossiles à corps mou trouvés juste au-dessous sur Fossil Ridge et sur Mont Stephen. De plus, cette découverte suggère que des fossiles du type du Schiste de Burgess peuvent aussi être trouvés généralement dans la région dans des lithofaciès semblables à la Formation Stephen "mince".

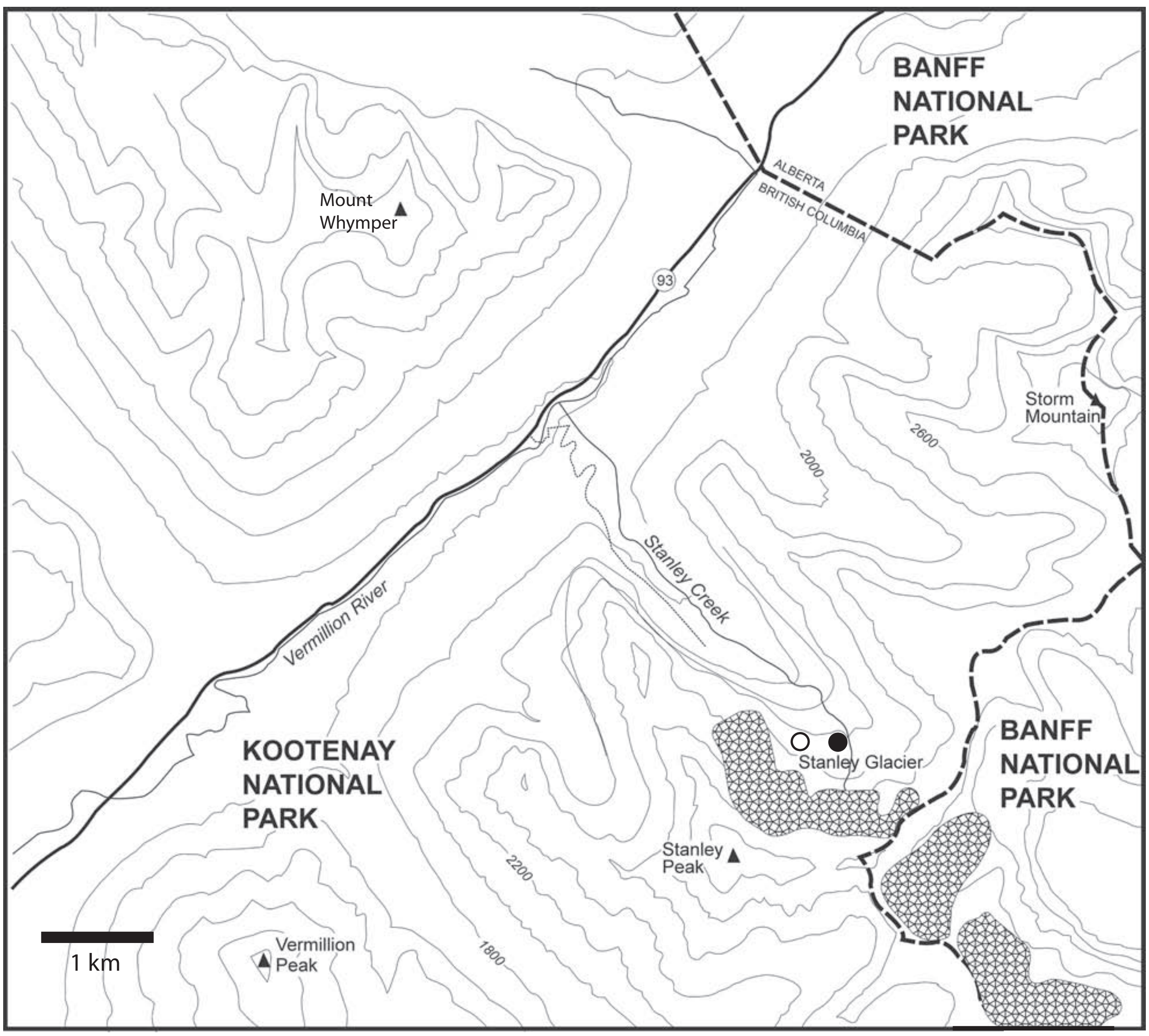
INTRODUCTION

The Middle Cambrian Burgess Shale at Fossil Ridge near Field, British Columbia, is arguably the most important fossil deposit in the world. Walcott's original quarry within the Stephen Formation (the Burgess Shale Formation of Fletcher and Collins, 1998) lies directly adjacent to the Cathedral Escarpment, a submarine cliff that was a prominent regional paleotopographic feature (Aitken, 1971; Aitken and McIlreath, 1981, 1984). Transgression during Stephen time resulted in burial of the escarpment in fine-grained siliciclastics, producing two different regional expressions of the Stephen Formation: the "thick" or "basinal" Stephen Formation accumulated offshore of the escarpment, whereas the "thin" or "platformal" Stephen Formation was deposited inboard of the escarpment (Aitken and McIlreath, 1984; Conway Morris, 1986; Stewart, 1991; Aitken, 1997; Fletcher and Collins, 1998). In the 100 years following Walcott's initial discovery on Fossil Ridge, numerous new localities in the Stephen Formation yielding soft-bodied fossils have been identified, all occurring within the "thick" or "basinal" Stephen Formation along the front of the Cathedral Escarpment (Collins et al., 1983). The Cathedral Escarpment has been considered important to the ecology of the Burgess Shale biota, which has been interpreted as a fore-reef faunal complex (Collins et al., 1983), and also to the preservation of the Burgess Shale biota, by promoting rapid downslope transportation of organisms and sediment from a living environment on the slope of the escarpment to a preservational trap below (e.g., Aitken and McIlreath, 1984; Conway Morris, 1986). Perhaps because of the importance ascribed to the escarpment, the "thin" Stephen Formation has received relatively little attention from paleontologists.

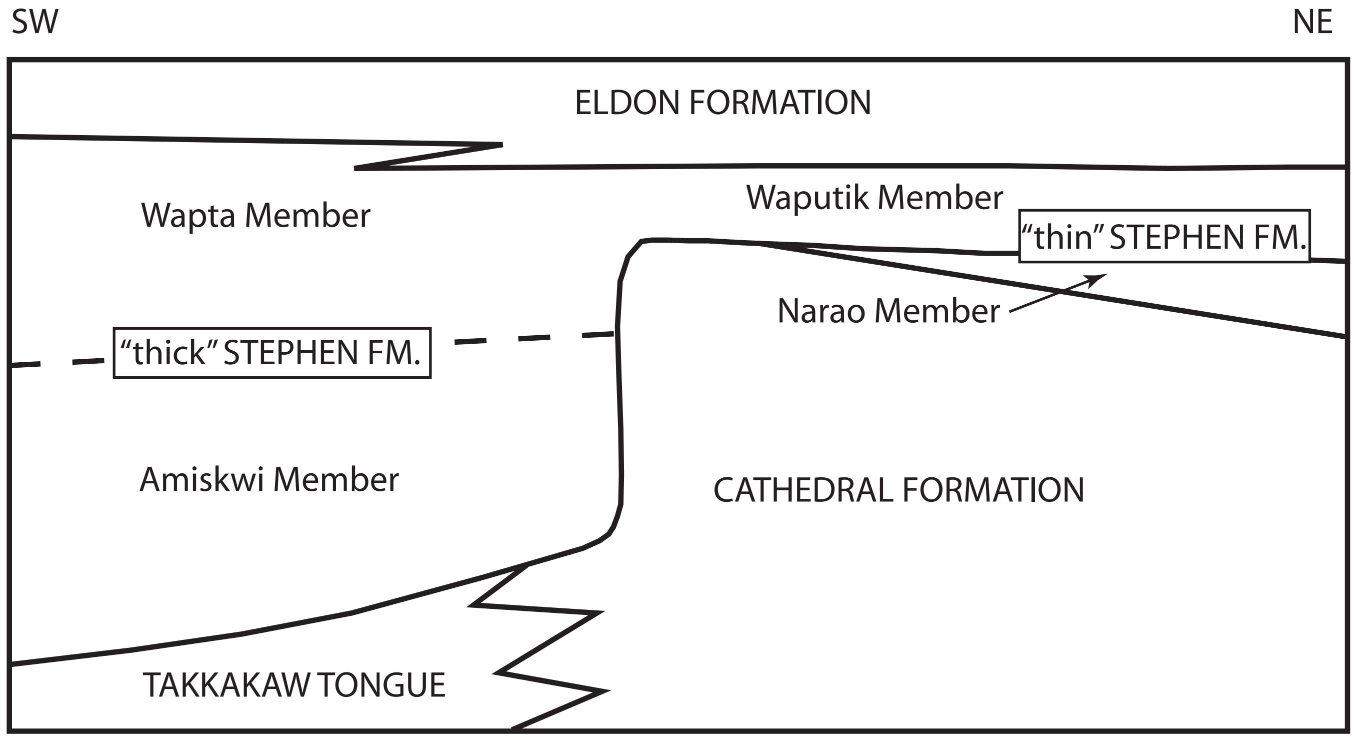
In 1989, an exploration party from the Royal Ontario Museum (ROM) recovered Burgess Shale-type (BST) fossils from talus thought to be derived from the "thin" Stephen Formation near Stanley Glacier in Kootenay National Park, approximately 40 km SE of Field (Rigby and Collins, 2004; Text-fig. 1). In 2008, the ROM organized a field party for the exploration and excavation of this locality. The 2008 expedition recovered hundreds of BST fossils from the "thin" Stephen Formation at the Stanley Glacier locality (Caron et al., 2010). The BST biota, described by Caron et al. (2010), includes eight new soft-bodied animals and is dominated by pelagic soft-bodied arthropods. The dinocarids *Hurdia victoria* and *Stanleycaris hirpex* (Caron et al., 2010) are the most abundant soft-bodied animals, followed by *Sidneyia inexpectans* and *Tuzoia retifera*. Sponges, worms, other arthropods and algae are also present. Soft-bodied fossils occur with a low-diversity shelly benthic assemblage dominated by the hyolithid *Haphlophrentis* and diminutive "ptychopariid" trilobites. Here, I describe the stratigraphic and paleoenvironmental setting of the Stanley Glacier BST biota and compare the depositional environment to that of the classic Burgess Shale localities near Field as well as to BST deposits of the western United States.

DEPOSITIONAL SETTING AND STRATIGRAPHY OF THE STEPHEN FORMATION

The Middle Cambrian stratigraphy of the southern Canadian Rockies is spectacularly exposed and has been documented extensively, beginning with Walcott's initial visits to the area (Walcott, 1908a,b, 1917; Deiss, 1939, 1940; Rasetti, 1951, 1956). Detailed, comprehensive syntheses were provided by Aitken (e.g., 1966, 1971, 1978, 1997; Aitken and McIlreath, 1984) and Stewart (1991). Aitken (1978) first recognized that the Middle Cambrian stratigraphy of the region may be divided into a series of transgressive-regressive packages that he termed "Grand Cycles". These shallowing-upwards sequences represent the lateral migration of three prominent facies belts which were widespread on the margins of Laurentia during the Cambrian: an inner detrital belt composed of clastics, a carbonate belt comprising largely platform facies, and an outer detrital belt characterized by fine grained siliciclastics (Robison, 1960; Aitken, 1978). The "Grand Cycles" of the southern Canadian Rockies record repeated episodes of transgression and basin filling that are expressed as thick successions (100s of meters) of outer detrital belt mudstones which grade upwards into thin-bedded carbonates representing ramp facies and then into massive carbonates representing local re-establishment of the carbonate platform. Massive carbonate units are abruptly overlain by outer detrital



Text-fig. 1. Location map of the study area, showing Highway 93 and the British Columbia–Alberta border. Closed circle represents the location of the SG1 locality; open circle represents the location of the WF1 locality. Hatched areas in the lower right indicate the locations of glaciers.



Text-fig. 2: Interpreted regional stratigraphic relationships within the Stephen and Cathedral Formations after Aitken (1997), along a SW–NE transect across the Cathedral Escarpment (center). The "thick" Stephen Formation is comprised of the Amiskwi and Wapta members and overlies thin bedded, deep-water carbonates of the Takkakaw Tongue. The "thin" Stephen overlies massive carbonates of the Cathedral Formation. Near the rim of the escarpment, the Narao Member (lower) may be absent with the Stephen Formation comprised of the Waputik Member only. The Stephen and Eldon formations together constitute the Stephen-Eldon Grand Cycle.

belt mudstones, marking transgression at the beginning of the next cycle (Aitken, 1978, 1997). The Stephen Formation comprises the lower portion of the Stephen-Eldon Grand Cycle (Text-fig. 2), the second of four Grand Cycles present in the Middle Cambrian of the southern Canadian Rockies, and represents deposition in the outer detrital belt (Aitken, 1997). Due to the presence of the Cathedral Escarpment, the stratigraphy of the Stephen Formation is unusually complex and laterally variable across the study area (Text-fig. 2). The Cathedral Escarpment developed during deposition of the Cathedral Formation in the latter part of the underlying Mount Whyte-Cathedral Grand Cycle (McIlreath, 1977; Aitken and McIlreath, 1984; Stewart, 1991; Aitken, 1997), resulting in deposition of a massive carbonate platform facies along the escarpment and inboard of it, and deposition of an apron of fine grained, thin-bedded carbonate offshore of the escarpment, with carbonate megabreccia and isolated large talus blocks derived from the vertical escarpment present locally (Stewart, 1991; Aitken, 1997, but see Johnston et al., 2009; Collom et al., 2009). The offshore expression of the Cathedral Formation, termed the Takkakaw Tongue (Stewart, 1991; Aitken, 1997), thins rapidly towards the west (basinwards). The escarpment itself has been explained as a result of primary growth of a near vertical shelf-margin reef, constructed by calcareous algae (McIlreath, 1977; Aitken and McIlreath, 1984), or, alternately as the result of large-scale platform margin collapse (Stewart, 1991; Stewart et al., 1993). The onset of Stephen deposition is marked by an influx of siliciclastic mud accompanying transgression (Aitken, 1997). The Stephen Formation has different expressions regionally, as controlled by the Cathedral Escarpment. The "thin" or "platformal" Stephen was deposited inboard of the escarpment and overlies the cliff-forming carbonates of the Cathedral Formation, whereas the "thick" or "basinal" Stephen Formation (the Burgess Shale Formation of Fletcher and Collins, 1998) was deposited offshore of the escarpment and overlies the thin bedded carbonates of the Takkakaw Tongue (Stewart, 1991; Aitken, 1997). As implied, the most conspicuous stratigraphic difference between these expressions of the Stephen Formation is in thickness. The "thick" Stephen commonly exceeds 300 m, as at Fossil Ridge, whereas the "thin" Stephen is commonly less than 60 m, in places less than 20 m (Aitken, 1997). Two members were defined in both the "thick" and "thin" Stephen by Aitken (1997), who considered the lower and upper members of each to be roughly correlative. The "thin" Stephen Formation is divided into the lower, carbonate dominated Narao Member and the upper, shale-dominated Waputik Member. The "thick" Stephen

Formation is composed of the shale-dominated Amiskwi Member which is overlain by shales and limestones of the Wapta Member (Aitken, 1997). The Burgess Shale biota occurs primarily in the Amiskwi Member.

ACKNOWLEDGEMENTS

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METHODS

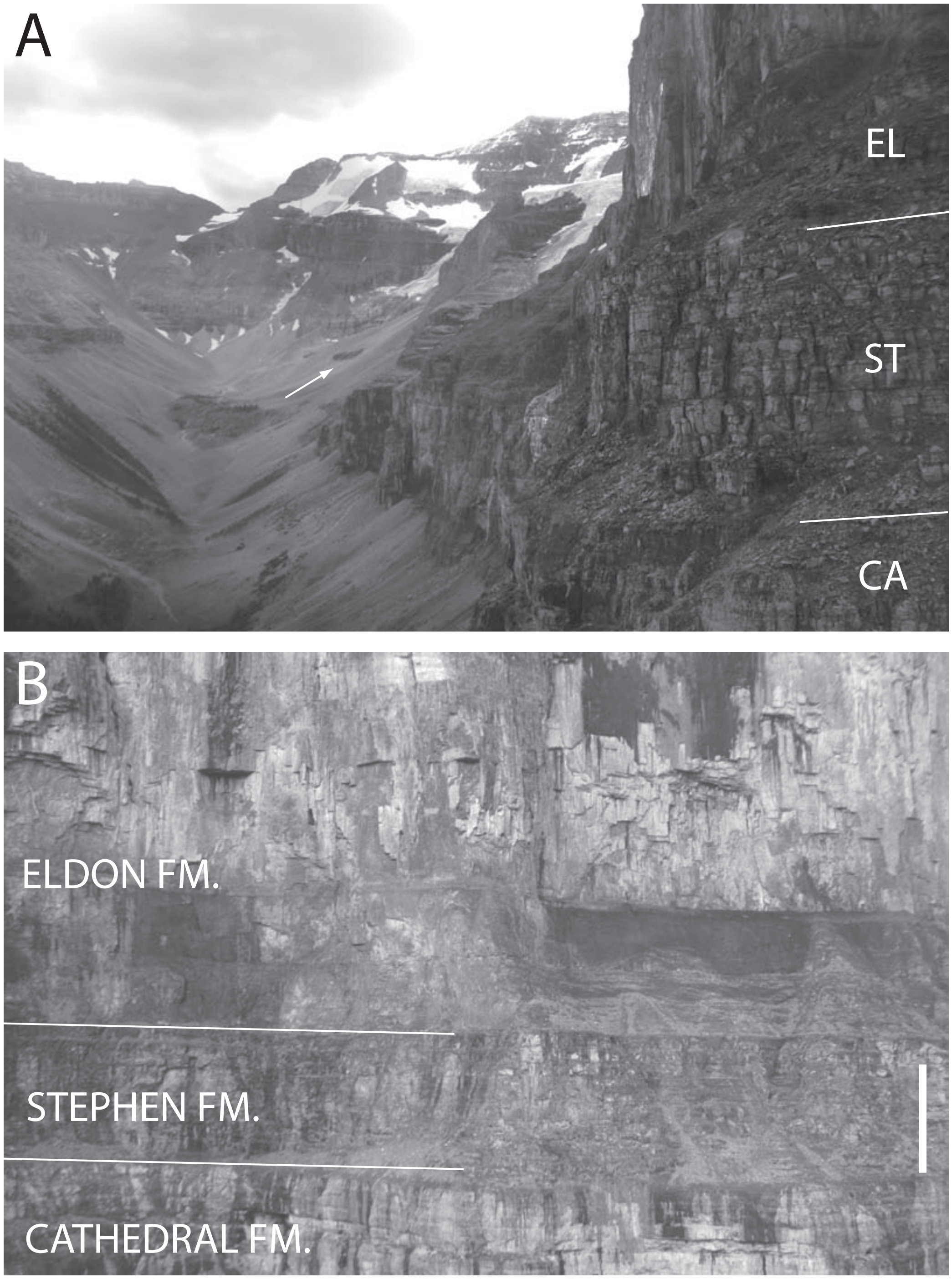
The study area is located in the Ball Range, in northwest portion of Kootenay National Park near Stanley Peak. In 2008, field work was conducted along the southwest side of a prominent northwest trending valley extending from the east side of Stanley Peak, and descending to Highway 93 (Text-fig. 1). Exploratory work recovered soft-bodied Burgess Shale-type fossils from the Stephen Formation over the entire 3 km length of exposure on the southwest side of the valley. A readily accessible section underneath the southeastern tongue of the Stanley Glacier was chosen for excavation. A composite section of the Stephen Formation was measured at this locality (SG1) and at a second exposure approximately 1 km northwest (WF1). The upper 20 m of the underlying Cathedral Formation was measured at WF1 and the lower 54.7 m of the Eldon Formation were measured at SG1. Sections were logged at the cm-scale. A 3.01 m interval in the upper Stephen Formation was excavated by the ROM party. A continuous section through this interval was collected during quarrying. After being logged into the ROM collections (ROM 59951) the samples comprising this section were returned to Pomona College where they were slabbed perpendicular to bedding, polished, X-radiographed, and scanned using a flatbed scanner. Using polished slabs and X-radiographs, the interval was logged at the mm-scale for primary depositional features, authigenic mineral precipitates, and ichnofabric. Mineralogy of whole rock powders and clay separates, prepared using the method outlined by Moore and Reynolds (1997), were analyzed using a Rigaku Ultima IV X-Ray Diffractometer. Percent carbonate was determined by carbon coulometry. Samples were also analyzed for microfabric using a Zeiss LEO-982 Field Emission Scanning Electron Microscope (SEM).

RESULTS

STRATIGRAPHIC SETTING OF THE STANLEY GLACIER BIOTA

The Stephen Formation in the Stanley Glacier area forms a recessive ledge between two cliff-forming carbonates, the underlying Cathedral Formation and the overlying Eldon Formation (Text-fig. 3). The recessive interval also includes 54.7 m of thin bedded nodular wackestones belonging to the lower Eldon Formation. The base of the Stephen Formation is recognized as the base of a 2.7 m thick package of calcareous claystones that directly overlie algally-laminated dolostone ("cryptalgal laminate") belonging to the Cathedral Formation. The contact is planar, with no evidence of exposure or erosion present. The top of the Stephen Formation, defined as the top of the uppermost shale (Aitken, 1997), lies 32.30 m above the base of the Stephen Formation. The transition into the overlying Eldon Formation is gradational, as observed elsewhere by Aitken (1997), who interpreted the contact as regionally conformable. The thickness of the Stephen Formation at this locality lies within the range of other "thin" Stephen exposures reported regionally (16 m to 164 m; Aitken, 1997), and well below the range of thicknesses reported for the "thick" Stephen (276 m to 370 m). At Stanley Glacier, the Stephen Formation rests directly on massive carbonates of the Cathedral Formation rather than on the thin-bedded carbonates of the Takkakaw Tongue. Based upon these two criteria, the Stephen Formation at Stanley Glacier may be readily assigned to the "thin" Stephen Formation as defined by Aitken (1997).

At Stanley Glacier, the Stephen Formation is a mixed siliciclastic-carbonate succession that is dominated by calcareous claystones and includes nodular lime mudstones and wackestones, as well as oncoid and/or intraclastic packstones (Text-fig. 4). This succession is consistent with Aitken's definition of the Waputik Member. The basal shales of the Waputik Member abruptly overlie <20 meters of dolomitic cryptalgal laminite. Typically, the Narao Member is composed of shale and thin-bedded lime mudstone, but near the transition zone between the "thick" and "thin" Stephen Formation at the Kicking Horse Rim, the Narao Member is composed



Text-fig. 3: The "thin" Stephen Formation in outcrop. **A**. Helicopter view along strike of the Stephen Formation (ST), between the cryptalgal dolostones of the Cathedral Formation (CA), and the thin bedded wackestones of the Eldon Formation (EL). The Stephen Formation as marked is 32.8 m in thickness. Arrow indicates the SG1 outcrop, 3 km to the SE along strike. **B.** Helicopter view of near-vertical exposure of the Stephen Formation on the SW side of the valley along Stanley Creek (Text-fig. 1). Scale bar equals 25 m.

of cryptalgal laminite (Aitken, 1997). Where composed of cryptalgal laminite, Aitken assigned the Narao Member to the Cathedral Formation, with the Stephen Formation at these localities comprising the Waputik Member only. Following Aitken's (1997) classification, the Stephen Formation at Stanley Glacier comprises the Waputik Member only. The Stanley Glacier biota excavated by the ROM (Caron et al., 2010) occurs in an interval of calcareous claystone near the top of the formation at 27 to 30 m above the base. A systematic survey did not recover soft-bodied fossils from lower claystone horizons. While the presence of soft-bodied fossils lower in the formation cannot be excluded, it is clear that soft-bodied fossils are most conspicuously abundant in the 27 to 30 m interval. The Waputik Member is roughly correlative to the Wapta Member of the "thick" Stephen Formation (Stewart, 1991; Aitken, 1997). Therefore, the Stanley Glacier biota is younger than the Burgess Shale biota, which occurs in the Amiskwi Member. The presence of the zone trilobite *Ehmaniella burgessensis* in the Stanley Glacier assemblage confirms a younger age.

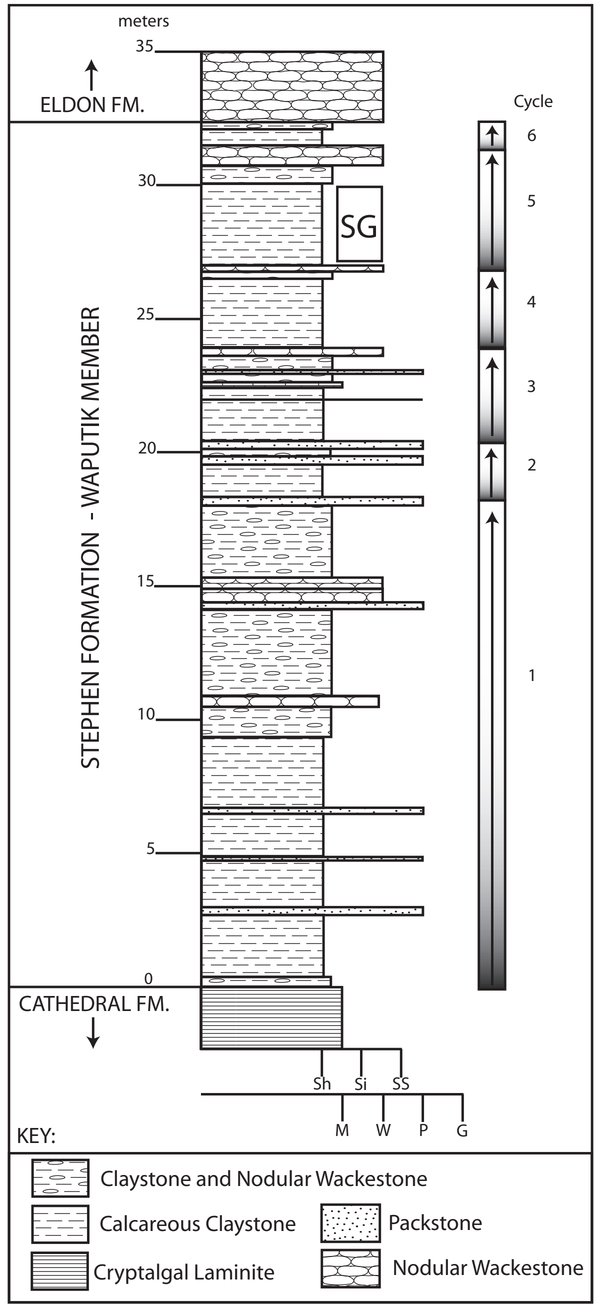
DEPOSITIONAL ENVIRONMENTS OF THE STEPHEN FORMATION AT STANLEY GLACIER

LITHOFACIES

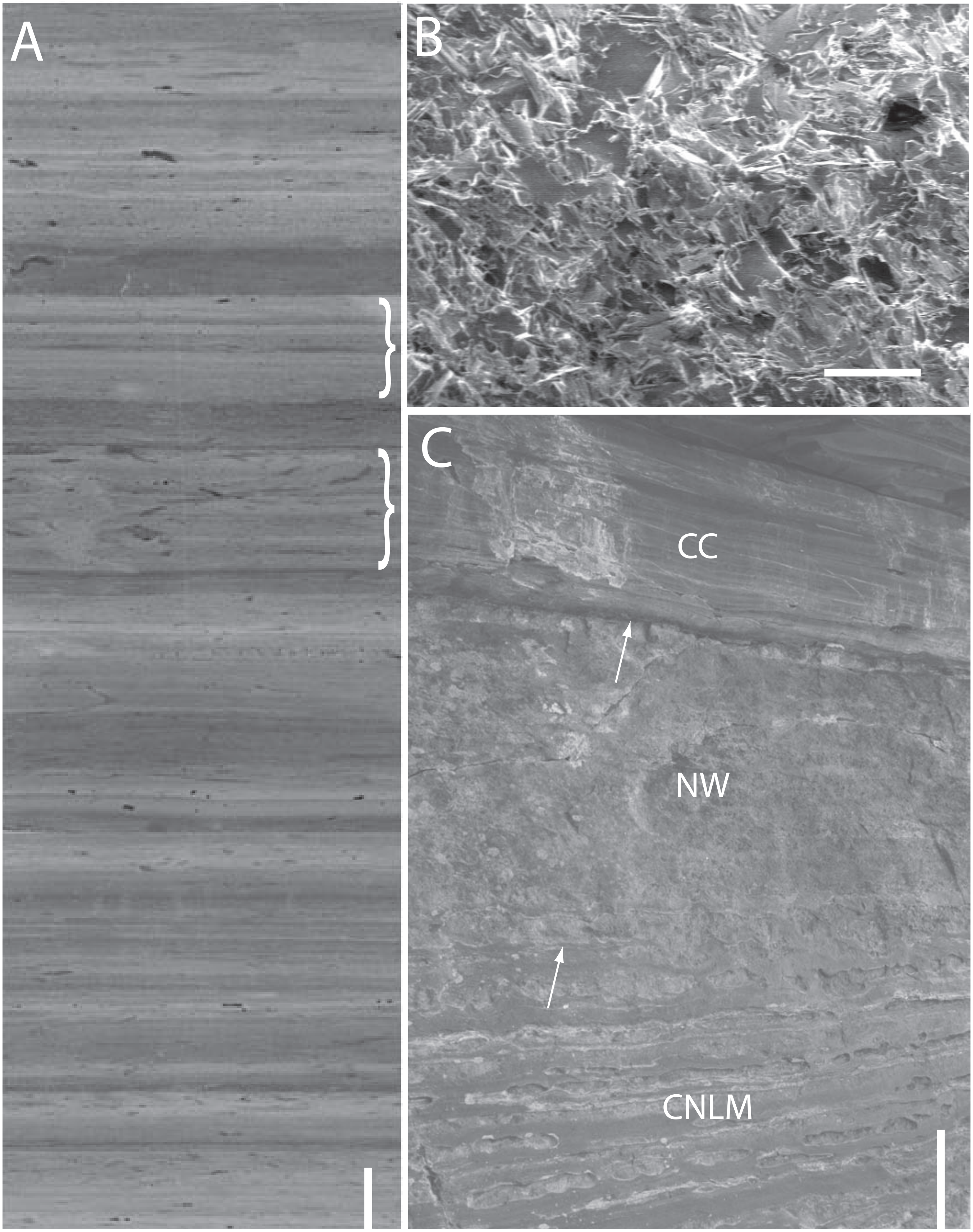
The Stephen Formation at Stanley Glacier is composed of four principal lithofacies: calcareous claystone, claystone and nodular lime mudstone, nodular wackestone, and packstone (Text-fig. 4).

Calcareous claystone lithofacies
The calcareous claystone lithofacies, which contains all occurrences of Burgess Shale-type preservation, forms resistant faces in outcrop and is finely laminated. This lithofacies is ultra fine-grained and contains only two components: detrital clays (<20 µm) and authigenic carbonate cement. Laminae range in thickness from 1–13 mm (avg. 4 mm; Text-fig. 5) and are defined by clay rich-bases with carbonate-rich tops, as revealed by X-radiography and wt% $CaCO_3$, determined by coulometric analysis. Skeletal accumulations or "pavements" commonly occur at bed junctions (as figured in Caron et al., 2010); however, no evidence of winnowing or scour is present, and no cross-lamination occurs within this facies. SEM analysis reveals that clay microfabric is randomly oriented (Text-fig. 5), and that no silt-sized or coarser grains are present. Soft sediment deformation slump folds 5–35 cm in thickness occur within this lithofacies at nine discrete horizons in the section (Text-fig. 6). XRD analysis of clay separates indicates that illite is the dominant clay mineral phase, with chlorite present in smaller amounts. XRD analysis of whole-rock powders indicates that carbonate cements are composed of calcite. Analysis of whole rock powders by coulometry indicates that the calcareous claystone lithofacies contains 2–37 wt% calcite (n=8). Microstratigraphic analysis of 3.02 m of continuous section indicates that it is dominantly weakly bioturbated (ichnofabric index 2), although brief (1–4 cm) intervals of laminated (i.i.1) and moderately bioturbated (i.i.3) sediments are present.

Interpretation of calcareous claystone lithofacies. The calcareous claystone lithofacies was deposited in discrete events from density-driven currents, as indicated by randomly oriented clay microfabric (Text-fig. 5; O'Brien et al., 1980). Event deposition of only clay-size particles has been described experimentally (Schieber et al., 2007) and is characteristic of BST deposits (Gaines and Droser, 2005), including the Greater Phyllopod Bed of the Burgess Shale (Gabbott et



Text-fig. 4. Composite measured section of the Stephen Formation at Stanley Glacier, showing depositional cycles 1-6, which are interpreted as parasequences. "SG" marks the occurrence of the Stanley Glacier Burgess Shale-type biota in the calcareous claystones of cycle 5, 27 to 30 meters above the base of the Stephen Formation.


A
B
C
CC
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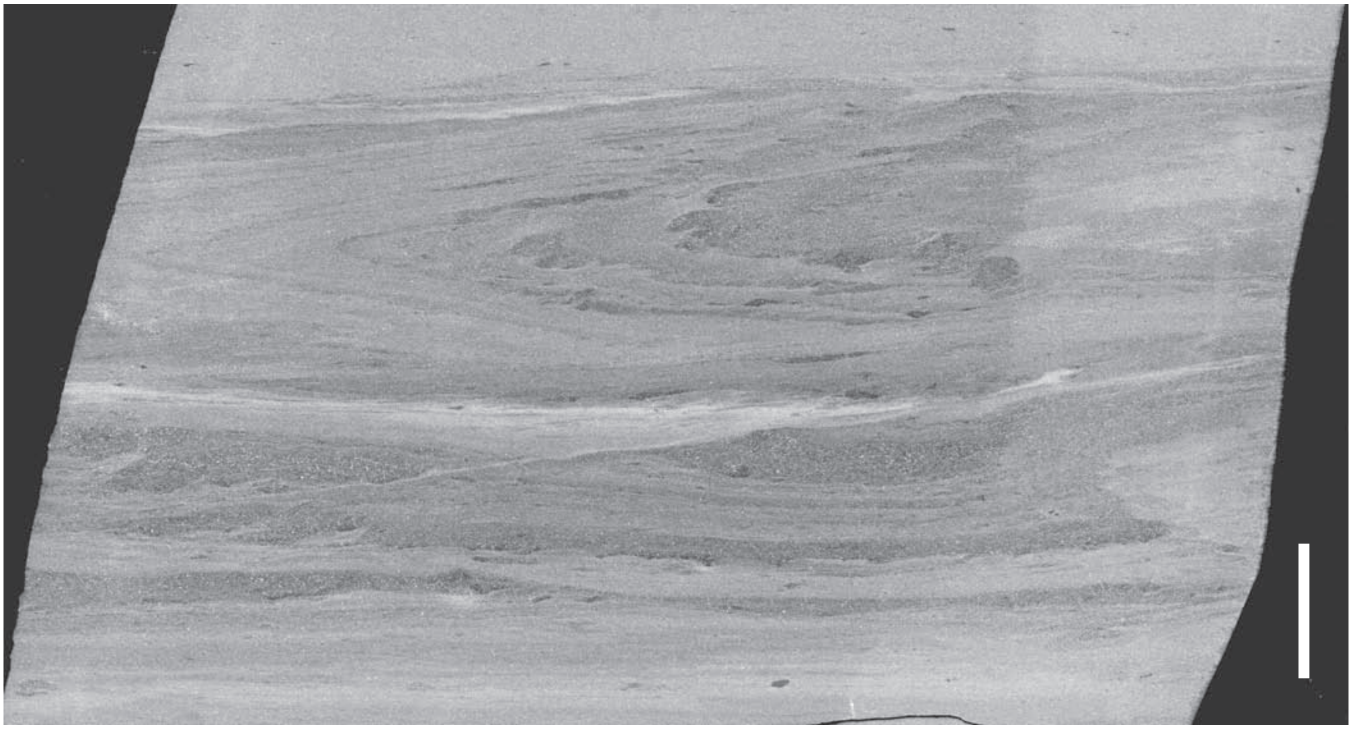


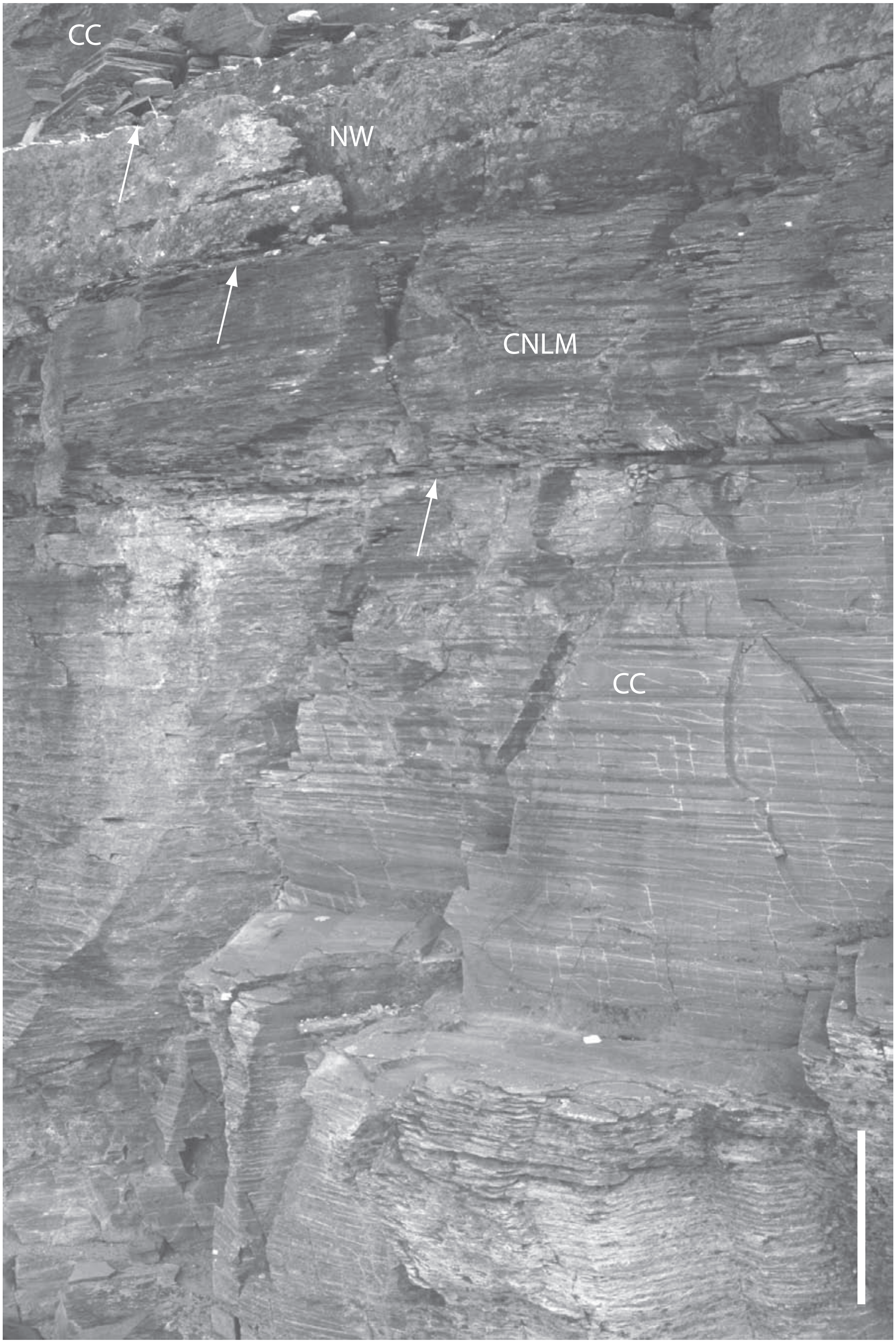
Text-fig. 6. Polished slab showing soft sediment slump feature in the calcareous claystone lithofacies, from 29.50 m above base of the Stephen Formation at SG1. Calcite-cemented bed tops appear dark; claystone bed bases are lighter in color (ROM 59951). Scale bar equals 1 cm.

al., 2008), and the Chengjiang (Zhu et al., 2001). Clays were likely deposited from distal gravity flows, presumably set up by storm wave disturbance of muddy substrates upslope of the locality. Individual laminae 1–13 mm in thickness occur as amalgamated claystone event beds, with tops extensively cemented by authigenic calcite (Text-fig. 5). Pervasive authigenic calcite cements, which have been proposed to be important in Burgess Shale-type preservation (Gaines et al., 2005; Gaines, 2008), were emplaced during early diagenesis, as evidenced by displacive microfabrics observed under SEM, and by the occurrence of calcite cements at the tops of folded beds within syn-sedimentary slump features (Text-fig. 6), indicating emplacement of cements prior to slump-induced folding. Common slump deposits also indicate deposition on a sloping surface. The low extent of bioturbation and the presence of nonbioturbated intervals suggests a dysaerobic environment prone to oxygen fluctuation (e.g., Gaines and Droser, 2005). As evidence of winnowing is absent, shelly pavements, dominated by *Haphlophrentis* and trilobite sclerites, are interpreted to represent *in situ* accumulation between claystone deposition events, during intervals when benthic conditions were permissive.

Claystone and nodular lime mudstone lithofacies

The claystone and nodular lime mudstone facies is identical to the calcareous claystone facies with the addition of 30–60% lime mudstone. Lime mudstone occurs both in 0.5–2.5 cm thick wavy beds and as isolated nodules 0.5–8 cm in diameter and 0.5–2.5 cm thick that occur in discrete layers (Text-fig. 7). Lime mudstone beds and nodular layers are regularly interbedded within the claystone at 1–3 cm intervals. This lithofacies overlies the calcareous claystone

Text-fig. 5. The calcareous claystone lithofacies and its relationship to other lithofacies of the Stephen Formation. **A**. Composite of continuously collected polished slabs of the calcareous claystone lithofacies representing the interval 27.01–27.20 m above the base of the Stephen Formation at SG1. Millimeter-scale laminae are visible. Brackets mark examples of weakly-moderately bioturbated intervals (lower) and nonbioturbated intervals (upper). Scale bar equals 1 cm. **B**. SEM micrograph of shale microfabric in the calcareous claystone lithofacies, showing randomly oriented clay microfabric. Sample taken from 27.78 m above the base of the Stephen Formation. Scale bar equals 20 µm. **C.** Outcrop of the contact between cycle 3 and cycle 4, showing the calcareous claystone lithofacies (CC) in the basal part of cycle 4, abruptly overlying the calcareous claystone and nodular lime mudstone lithofacies (CNLM) and the nodular wackestone facies (NW) at the top of cycle 4. Arrows mark lithologic contacts. Scale bar equals 10 cm. All specimens belong to ROM 59951.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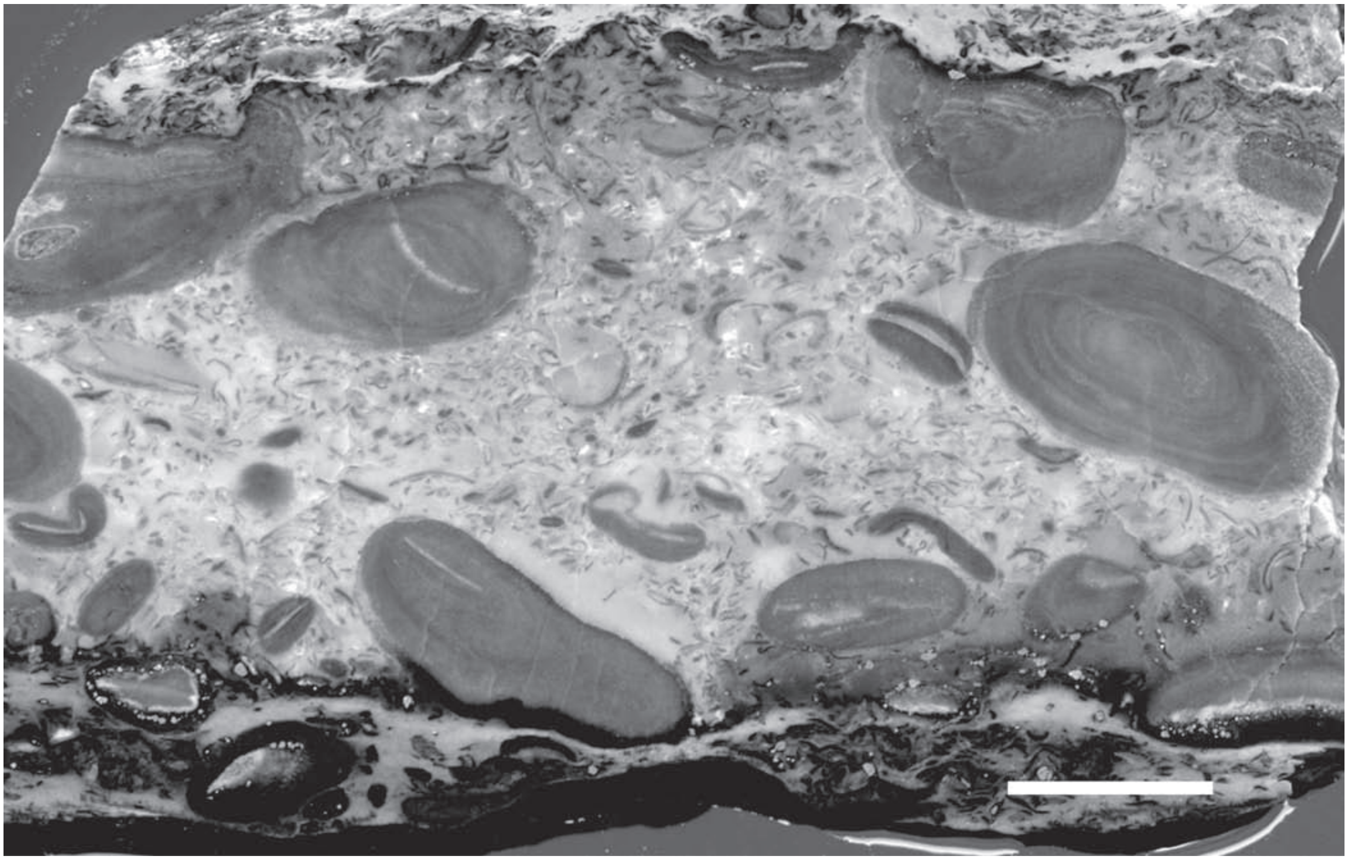

Text-figure 8: Polished slab of oncoid-trilobite packstone from 6.7 m above the base of the Stephen Formation, showing random fabric and presence of significant micrite matrix (ROM 60726). Scale bar equals 1 cm.

facies and the contact between the two lithologies is sharp and planar. Lime mudstone bed thickness and the relative proportion of lime mudstone to claystone typically increase upwards towards contacts with overlying coarser carbonates. Floating fossil grains occur rarely within lime mudstones, but no grading or cross-bedding is present.

Interpretation of claystone and nodular lime mudstone lithofacies. The same depositional processes active in the calcareous claystone facies continued to operate in the claystone and nodular lime mudstone lithofacies, with the addition of the deposition of lime mud, probably sourced from carbonate producing environments upslope. The wavy and nodular textures of the lime mudstones indicates that they have been at least partially redistributed following deposition through physical (compaction) or chemical (e.g., "rhythmic unmixing"; Hallam, 1964) processes. Therefore, it is unclear whether lime mudstones were deposited by the same depositional events as the claystones, or whether lime muds were deposited by discrete events of greater magnitude, as analysis of stratigraphic cycles suggests (see below).

Text-fig. 7:. Outcrop of Stephen Formation at SG1 showing cycle 5 and the base of cycle 6. Calcareous claystone (CC) is overlain by claystone and nodular lime mudstone (CNLM) and then by nodular wackestone (NW). Contacts, indicated by arrows, are sharp, including the contact between the nodular wackestones at the top of cycle 5 and the calcareous claystones at the base of cycle 6. The BST biota occurs throughout the calcareous claystone (CC) interval figured. Scale bar equals 50 cm.

Thin bedded wackestone lithofacies

Thin-bedded nodular wackestones, 2–5 cm in thickness, with thin clay laminae (1–2 mm) occur as amalgamated packages (20–30 cm) overlying the claystone and nodular lime mudstone facies (Text-fig. 7). These contain sparse bioclasts, typically only trilobite sclerites, which often occur at high angles to bedding. No evidence of grading, cross-bedding, or scour is present.

Interpretation of thin bedded wackestone lithofacies. Thin-bedded nodular wackestones were deposited from poorly organized gravity-driven flows, as indicated by chaotic orientation of bioclasts. Micrite was probably sourced from carbonate producing environments upslope, but bioclasts indicative of shallow water, such as oncolites and oöilites, do not occur in this lithofacies.

Packstone lithofacies
Ten discrete packstone beds, 3–30 cm in thickness, occur within the section and may be traced for at least 1 km laterally. These contain oncolites, oöilites, and trilobites; several also contain intraclasts of lime mudstone. No grading or cross bedding is present, and the rock fabric is chaotic, with bioclasts commonly occurring at high angles to bedding. Significant micrite matrix is present within the grain-supported framework (Text-fig. 8).

Interpretation of packstone lithofacies. Packstones are interpreted to represent tempestites deposited from storm generated back-currents that delivered bioclasts from shallow water environments (oncolites, oöilites) downslope into a deep water environment where no evidence of storm wave disturbance is present. The chaotic fabric of packstones indicates rapid deposition from single events. Unlike other lithofacies which occur in regular order (see below), packstones occur as interbeds within intervals dominated by each of the other three lithofacies, although they occur in the tops of cycles 1–3. Deposition of packstone tempestites in the Stephen Formation is interpreted to have resulted from disturbance only by the largest storms that affected the region.

CYCLICITY

Parasequences, representing depositional cycles within individual formations, are characteristic of the Middle Cambrian succession of the study area and have been extensively documented (Aitken, 1997). These cycles are expressed as "clearing upwards" (Aitken, 1997), or diminishing supply of terrigenous mud relative to carbonate. Aitken (1997) provided regional-scale evidence that these cycles represent true shallowing-upwards.

The Stephen Formation at Stanley Glacier is characterized by cyclic stacking of lithofacies: calcareous claystones pass upwards into the claystone and lime mudstone lithofacies, which is overlain by nodular wackestones and/or packstones, which are abruptly overlain by calcareous claystones at the base of the next cycle (Text-fig. 7). Six depositional cycles are recognized in the section, ranging from 0.7 to 18.3 m in thickness. These are interpreted as parasequences that reflect upwards shallowing followed by abrupt transgression.

The calcareous claystone lithofacies represents the deepest part of each of the six cycles, with deposition occurring from distal, dilute density flows. Moving upsection, carbonate mud appears, expressed at first as thin beds of lime mud and nodules. Carbonate becomes more prevalent upwards, reflecting increasing input from carbonate producing environments upslope. Increasing carbonate content within each cycle may also represent increasing proximity of the carbonate producing environments by progradation of the carbonate factory during each cycle. Cycles culminate in nodular wackestones or packstones that bear evidence of greater energy of deposition, although all lithofacies were deposited below storm wave base. At the top of the sixth cycle, the Stephen Formation grades conformably into the thin-bedded nodular wackestones of the lower Eldon Formation, which are interpreted to represent deposition on a carbonate ramp. The thin-bedded wackestones of the lower Eldon Formation thicken upwards into massive shallow-water carbonates that form prominent cliffs (Aitken, 1997).

PALEOENVIRONMENTAL SETTING OF THE STANLEY GLACIER BIOTA

The Stanley Glacier biota occurs in the calcareous claystone interval of cycle 5, in mm-laminated clay sediments (<20 µm) (Text-figs. 4, 5B). The laminae represent deposition from dilute gravity-driven currents that likely resulted from storm wave disturbance of muddy sediments upslope. This depositional process and the upward passage of this lithofacies into carbonates suggest a depositional setting on a distal ramp, below storm wave base. Ichnofabric evidence indicates that oxygen-limited conditions were prevalent.

RELATIONSHIP TO CATHEDRAL ESCARPMENT

No evidence of an escarpment has been reported in the Stanley Glacier area (Stewart, 1991; Aitken, 1997), nor was any identified in 2008 reconnaissance study. As described above, the Stanley Glacier area exposures clearly belong to the "thin" Stephen Formation and were either deposited in a ramp setting above an escarpment, which has no local expression, or on a ramp that formed the platform-basin transition where no escarpment was present. The absence of the Narao Member of the Stephen Formation (or its inclusion in the Cathedral Formation; Aitken, 1997) is characteristic of sections located near the platformal margin of the Kicking Horse rim near Field and may suggest a depositional setting closely adjacent to an escarpment, which is not presently exposed in the study area. However, unlike sections of the "thin" Stephen Formation reported near the Kicking Horse Rim, the Stanley Glacier section contains no evidence of grading, cross-bedding, or scour. It is possible that the Stephen Formation in the Stanley Glacier area represents a more distal depositional environment than other "thin" Stephen Formation sections described regionally (Aitken, 1997). If so, the Stanley Glacier section may have been deposited on a distal ramp where no escarpment was present locally. However, it is also possible that depositional environments within the Waputik Member of the Stephen Formation were broadly comparable across the region. If this was the case, then Burgess Shale-type assemblages may be widespread in the "thin" Stephen Formation. This question awaits future study.

COMPARISON WITH THE GREATER PHYLLOPOD BED, FOSSIL RIDGE

The Burgess Shale localities of Fossil Ridge contain an abundance of soft-bodied fossils that is unparalleled elsewhere in the Cambrian. The sedimentology of the Greater Phyllopod Bed of Walcott's Quarry in the Burgess Shale has recently been studied in detail (Gostlin, 2005; Gabbott et al., 2008). Greater Phyllopod Bed sediments are similar to the calcareous claystone lithofacies of the Stanley Glacier locality in that they are composed of event-deposited laminae of clay sized particles only and are characterized by pervasive carbonate cements (Gostlin, 2005; Gabbott et al., 2008). The only significant difference is in bed thickness: claystone event beds up to 10 cm thick occur in the Greater Phyllopod Bed (Gostlin, 2005; Gabbott et al., 2008). The Cathedral Escarpment has long been considered important to the preservation of the Burgess Shale Biota, by facilitating downslope transport of organisms and mud from habitable environments on the face of the escarpment or above it to a preservational trap below (Conway Morris, 1986). The depositional setting of the Greater Phyllopod Bed and other Burgess Shale localities of Fossil Ridge at the toe of the Cathedral Escarpment is unique among Burgess Shale-type deposits known worldwide. Either repeated destabilization of mud on its upper slopes or preferential accumulation of sediment offshore of the break in slope promoted the deposition of thick claystone event beds. By comparison, the distal ramp setting of the Stanley Glacier area was subject to lower velocity density currents moving across a low angle slope, resulting in the deposition of thinner laminae (1–13 mm; Text-fig. 6). Many authors have suggested that the preservation of BST biotas requires transport of organisms to the locus of preservation (Conway Morris, 1986; Gaines and Droser, 2005; Zhang et al., 2006; Zhang and Hou, 2008), which occurs under anaerobic conditions (Allison, 1988; Allison and Brett, 1995; Butterfield, 1995; Gaines et al., 2005; notwithstanding Powell et al., 2003, Caron and Jackson, 2006, Johnston et al., 2009). The steep slope of the Cathedral Escarpment provided ideal conditions for downslope transport of organisms and their rapid entombment in clay sediments. Furthermore, the escarpment provided a ready means of transporting organisms across vertically stratified chemical gradients, from aerobic environments above to the anaerobic environment that persisted at the toe of the escarpment throughout the deposition of the Greater Phyllopod Bed, as evidenced by the absence of bioturbation (Gostlin, 2005; Gaines and Droser, 2010). In a low-angle ramp setting, significant horizontal transport would have been required to move organisms across chemical (redox) gradients, rendering the preservation of whole assemblages less likely. The prevalence of molts and disarticulated remains of BST fossils in the Stanley Glacier Biota (Caron et al., 2010) likely reflects this difference in physical depositional conditions. By comparison to the Stephen Formation at Stanley Glacier and to other Burgess Shale-type deposits of Laurentia (see below), the depositional setting of the Greater Phyllopod Bed provided optimal physical conditions for the preservation of BST fossils.

COMPARISON TO OTHER BST DEPOSITS

The depositional setting of the Stanley Glacier biota closely resembles that of the other BST deposits of western Laurentia. BST biotas of the Middle Cambrian Spence Shale and Wheeler and Marjum formations occur in distal ramp settings below the influence of storm waves, which are characterized by shale-carbonate parasequences of similar architecture and thickness to those of the Stephen Formation at Stanley Glacier (Rees, 1986; Liddell et al., 1997; Elrick and Snider, 2002; Langenburg, 2003; Brett et al., 2009; Halgedahl et al., 2009). In each, BST biotas occur in mm-laminated calcareous claystones, which, like those of the Stanley Glacier locality, are characterized by randomly oriented clay microfabric, pervasive early carbonate cements, and fluctuating bottom water redox conditions (Gaines et al., 2005; Gaines, 2008; Webster et al., 2008; Garson, et al., 2008). As at Stanley Glacier, intervals of calcareous claystones in these deposits occur at the bases of parasequences and pass upwards into lime mudstones and wackestones or packstones (Liddell et al., 1997; Elrick and Snider, 2002). This mixed siliciclastic-carbonate, dysoxic, distal ramp setting below storm wave base was a geographically widespread and recurrent facies in the Cambrian, which promoted the preservation of BST biotas. However, due to the problem of transport, the abundance of BST biotas and their potential for paleoecological study at the community level is limited. The paleoenvironmental setting of the Burgess Shale localities of the Field area immediately adjacent to the Cathedral Escarpment is unique among Burgess Shale-type deposits and provided optimal conditions for BST preservation with limited transport (e.g., Caron and Jackson, 2006). For this reason, the Burgess Shale localities of Fossil Ridge are perhaps the only localities where detailed paleocommunity analysis of BST assemblages is meaningful (Caron and Jackson, 2008).

CONCLUSIONS

A new Burgess Shale-type biota near the Stanley Glacier in Kootenay National Park (~40 km south of Walcott's Quarry) was excavated by a team from the Royal Ontario Museum in August, 2008. The Stanley Glacier BST Biota occurs within the "thin" Stephen Formation., which was deposited below storm wave base in a dysoxic, mixed siliciclastic-carbonate distal ramp setting. In the Stanley Glacier area, the Stephen Formation is 32.8 m thick and rests directly on cryptalgal dolostones of the Cathedral Formation, rather than the thin-bedded carbonates of the Takkakaw Tongue, the deep-water equivalent of the Cathedral Formation (Aitken, 1997). The Stephen Formation is divided into six depositional cycles that reflect shallowing upwards. These shale to wackestone/packstone cycles are interpreted as parasequences. No evidence of grading, scour, cross-bedding or hummocky cross-stratification is present in any of the four lithofacies comprising the Stephen Formation. The Stanley Glacier biota occurs in a 3 m interval of mm-laminated calcareous claystones in the base of cycle 5, from 27–30 m above the base of the Stephen Formation. The BST biota occurs in the Waputik Member, which comprises the entire Stephen Formation at Stanley Glacier, and is younger than the Burgess Shale biota, which occurs in the Amiskwi Member of the "thick" Stephen Formation. The sediments that contain the BST fossils are identical to those that contain other BST fossil assemblages worldwide (Gaines, 2008; Gaines et al., 2009); they are composed of: 1) a terrigenous component containing only clay sized-particles (<20 µm), and 2) pervasive authigenic carbonate cements, which are concentrated at bed tops. The depositional environment is interpreted as dysaerobic, distal ramp setting below storm wave base where no escarpment was present regionally or above an escarpment that has no local expression. This paleoenvironmental setting is common to other BST deposits of western Laurentia. This finding highlights the unique depositional setting of the Burgess Shale localities on Fossil Ridge at the toe of the Cathedral Escarpment and the significance of the escarpment in optimizing conditions for the preservation of the Burgess Shale biota on Fossil Ridge. Although the precise mechanism by which Burgess Shale-type fossils were conserved is not agreed upon (Butterfield, 1995; Petrovich, 2001; Gaines et al., 2005, 2009), it is clear that primary conditions of the physical depositional environment exerted important controls, which determined the abundance and composition of soft-bodied fossil assemblages that were rapidly buried in fine grained muds, prior to the operation of whatever pathway subsequently promoted their exceptional preservation.

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