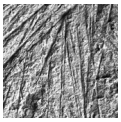
The extent of the Sirius Passet Lagerstätte (early Cambrian) of North Greenland

JOHN S. PEEL & JON R. INESON



Ancillary localities for the Sirius Passet biota (early Cambrian; Cambrian Series 2, Stage 3) are described from the immediate vicinity of the main locality on the southern side of Sirius Passet, north-western Peary Land, central North Greenland, where slope mudstones of the Transitional Buen Formation abut against the margin of the Portfjeld Formation carbonate platform. Whilst this geological relationship may extend over more than 500 km east–west across North Greenland, known exposures of the sediments yielding the lagerstätte are restricted to a 1 km long window at the south-western end of Sirius Passet. • Keywords: Early Cambrian, Greenland, lagerstätte.

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Almost all of the fossils described from the early Cambrian Sirius Passet Lagerstätte of northern Peary Land, North Greenland, were collected from a single, west-facing talus slope at the south-western end of Sirius Passet (latitude 82°47.6´ N, longitude 42°13.7´ ; Locality 1 in Figs 1, 2). The fossiliferous slabs are derived from the so-called Transitional Buen Formation (Ineson & Peel 2011) and have accumulated downslope of their point of origin in a small cliff composed of an 8.5 m thick succession of laminated mudstones (Ineson & Peel 2011); they display a degree of weathering that serves to enhance the visibility of most of the fossil remains. Extension of the known succession into stratigraphically older and younger sediments is hindered by a lack of continuous outcrops in the structurally complex, but often poorly exposed area, with southerly directed thrusting transporting siliciclastic slope sediments against the margin of a carbonate platform succession formed by dolostones of the Portfjeld Formation (Soper & Higgins 1990, Higgins *et al.* 1991, Ineson & Peel 2011; Fig. 1). Hence, the full stratigraphic range of the fossiliferous strata is not known. Fossiliferous strata, however, can be located at several other localities within 1 km of this main locality (Figs 1C, 2), although poorer exposure and the nature of weathering and lichen overgrowth make these less attractive for collecting. This paper briefly describes these localities and their faunas in reviewing the very limited distribution of the lagerstätte on the southern slopes of Sirius Passet. Similar fossiliferous localities have not been recorded elsewhere in North Greenland.

The first fragmentary fossils from the Sirius Passet Lagerstätte (GGU collection 313035) were collected by A.K. Higgins and N.J. Soper in 1984 on the hillside near Locality 2 (Figs 1C, 2; see discussion by Peel & Ineson 2011). In 1985 Higgins and N.C. Davis made the collections from talus at Locality 1 (GGU collection 319543) that formed the basis for the first description of the lagerstätte by Conway Morris *et al.* (1987). Expeditions to North Greenland in 1989, 1991, 1994 and 2006 collected more than 5000 slabs from the talus slope at Locality 1 and fossils from this material have been described in a series of papers by Babcock & Peel (2007), Blaker (1988), Blaker & Peel (1997), Budd (1993, 1995, 1997, 1998, 1999a, b, 2011), Budd & Peel (1998), Conway Morris & Peel (1990, 1995, 2008, 2010), Conway Morris *et al.* (1987), Daley & Peel (2010), Lagebro *et al.* (2009), Peel (2010a, b), Peel & Stein (2009), Rigby (1986), Stein (2010), Stein *et al.* (2010), Taylor (2002) and Williams *et al.* (1996). About 40 species have been identified in the lagerstätte and those described to date are listed in Fig. 3.

Specimen depositories. – Illustrated specimens are deposited in the type collection of the Geological Museum, a part of the Natural History Museum of Denmark, Copenhagen, Denmark (MGUH prefix). GGU indicates collections made under the auspices of Grønlands Geologiske Undersøgelse (Geological Survey of Greenland, now Geological Survey of Denmark and Greenland, Copenhagen, Denmark).

Sirius Passet fossil localities

Locality 1

Ineson & Peel (2011) gave a full description of the 8.5 m thick succession of mudstones exposed in small crags at this locality (Fig. 2B). Most fossils collected until 2006 were derived from talus downslope of the crags, but a team from the University of Copenhagen made systematic collections from the exposed section in late July and early August 2009 and from these a new vetulicolian was described by Vinther *et al.* (2011).

Simple geometric calculation suggests that 20 m or more of older sediments may be present beneath the exposed mudstone succession at this locality but the area is covered with talus yielding few fossils. A minimum of several metres of younger strata separate the exposed fossiliferous succession from sediments in the overlying thrust sheet at the hill top (Fig. 2B) but talus cover prevents precise location of the thrust plane and measurement of the thickness of the footwall succession in the hillside west of the fossiliferous exposures (left in Fig. 2B). Fossils occur sporadically on talus slabs in this area.

Locality 2

This locality is situated about 250 m north of Locality 1, on the northern side of the same hill. The fossiliferous strata were examined in a low mound and dip about 5 degrees to the west (Figs 1C, 2). Fossils were collected from talus and weathered outcrops immediately adjacent to the small exposures, but their recognition in the field is frequently obscured by lichen growth on exposed surfaces.

About 120 fossiliferous slabs (GGU collection 340112) were collected from this locality by J.S.P. and Simon Conway Morris in 1994. The assemblage contains essentially the same taxa known from Locality 1 (Figs 3, 4A–M), including *Halkieria evangelista* Conway Morris & Peel, 1995 (Fig. 4D) and frequent specimens of the bivalved arthropod *Isoxys volucris* Williams, Siveter & Peel, 1998 (Fig. 4J, K), but the trilobite *Buenellus higginsi* Blaker, 1988 (Fig. 4A) and isopygous arthropods (Budd 2011) are less conspicuous in the collection from Locality 2. *Kleptothule rasmusseni* Budd, 1995, common at Locality 1, and palaeoscolecidan and polychaete worms (Conway Morris & Peel 2008, 2010) have not been identified with certainty from Locality 2. This may reflect less perfect preservation due to increased weathering since these particular species are usually preserved with low relief even at Locality 1.

A poorly preserved head shield (Fig. 4G) from Locality 2 is tentatively assigned to *Aaveqaspis* Peel & Stein, 2009, described from Locality 1, but the form of the posterior margin is reminiscent of *Sinoburius* Hou, Ramsköld & Bergström, 1991 described from the Chengjiang Lagerstätte of China (Hou *et al.* 1999, 2004). An articulated hyolithid preserves the helens and the operculum (Fig. 4B), the latter not clearly differentiated in specimens described from Locality 1 by Peel (2010b). The crushed specimen shows the ventral surface of the conch and ligula, but the operculum is flipped backwards from the aperture to reveal its dorsal surface. The presence of rare, crushed, archaeocyathans (Fig. 4C, L), also present at Locality 1, reflects the proximity to the carbonate platform.

Locality 3

This locality is situated in a narrow swathe of black mudstone fragments located between the isolated pinnacles of the Portfjeld Formation and its main outcrop (Figs 1C, 2; GGU collection 340108). The patch of weathered mudstone has yielded *Isoxys volucris*, *Buenellus higginsi*, *Choia* sp. and disarticulated remains of a large undescribed arthropod common at Locality 1 but also present at Locality 2 (Fig. 4I).

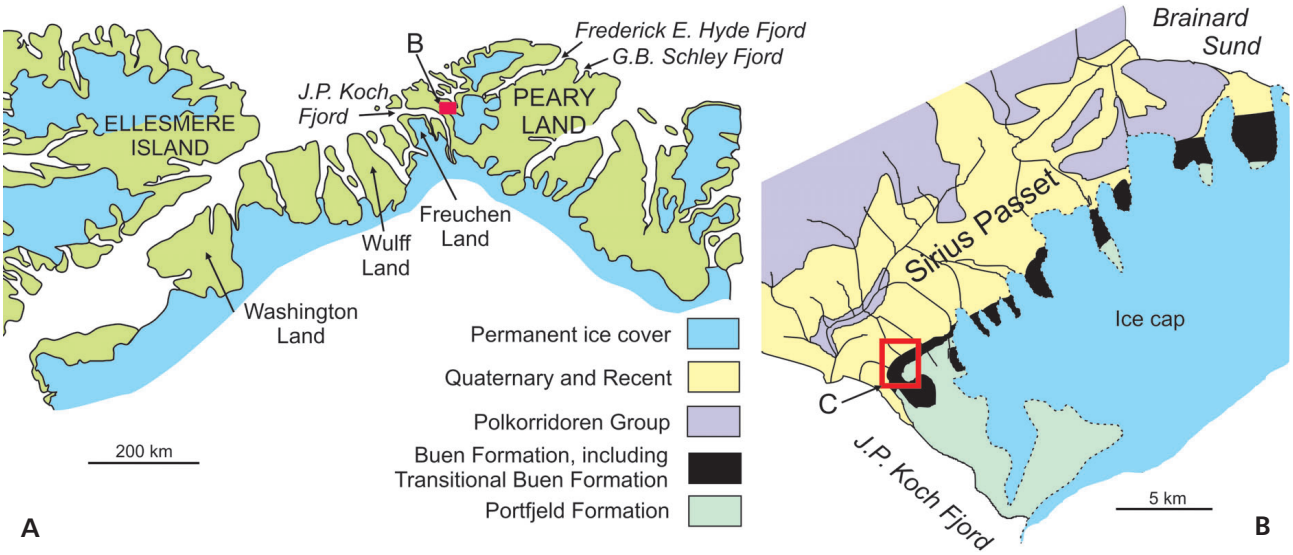
Locality 4

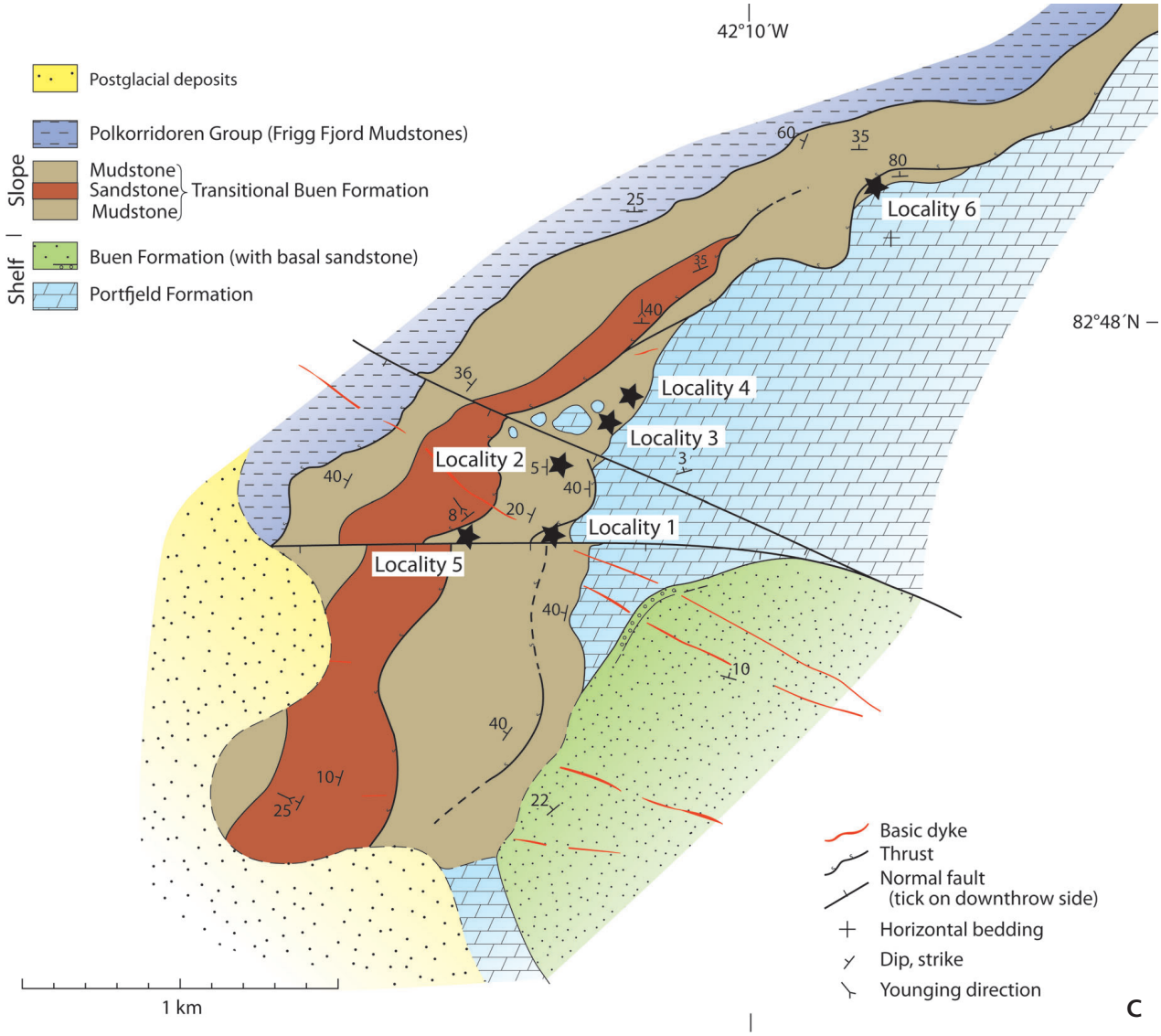
Located just across a small stream from Locality 3, this locality represents the easternmost of the small outcrops in the area between the Portfjeld Formation pinnacles and the main outcrop. *Isoxys volucris* and fragments of *Halkieria evangelista* were observed in the field from weathered mudstones at the front of a solifluction lobe.

Locality 5

Talus slabs below weathered outcrops at Locality 5 (Figs. 1C, 2; GGU collection 340105) have yielded rare specimens of *Isoxys volucris* and horizontal burrows which are mainly 2–3 mm in width but exceptionally up to 12 mm. One example, 1–2 mm in diameter, produces straight branches perpendicular to the main burrow at intervals of several centimetres. Smooth patches of sediment

Figure 1. A – map of North Greenland showing the location of the Sirius Passet region (B). • B – simplified geological map of Sirius Passet showing the location of detailed map (C). • C – geological map of the area around the Sirius Passet Lagerstätte in North Greenland showing fossiliferous localities indicated in Fig. 2 and discussed in the text (modified from Ineson & Peel 2011).


ELLESMERE ISLAND
PEARY LAND
B
Frederick E. Hyde Fjord
G.B. Schley Fjord
J.P. Koch Fjord
Freuchen Land
Wulff Land
Washington Land
200 km
Permanent ice cover
Quaternary and Recent
Polkorridoren Group
Buen Formation, including Transitional Buen Formation
Portfjeld Formation
A
Brainard Sund
Sirius Passet
Ice cap
C
J.P. Koch Fjord
5 km
B


42°10´W
82°48´N
Postglacial deposits
Polkorridoren Group (Frigg Fjord Mudstones)
Slope
Mudstone
Sandstone
Mudstone
Transitional Buen Formation
Shelf
Buen Formation (with basal sandstone)
Portfjeld Formation
Locality 6
Locality 4
Locality 3
Locality 2
Locality 1
Locality 5
1 km
Basic dyke
Thrust
Normal fault (tick on downthrow side)
Horizontal bedding
Dip, strike
Younging direction
C

with dense assemblages of microburrows are reminiscent of the three dimensionally preserved burrow assemblages often seen on large arthropods at Locality 1 (Peel 2010b), but one example is also known from Locality 2 (Fig. 4I). One slab preserves dark, circular, spots up to 11 mm in diameter with a fine radial texture reminiscent of the sponge *Choia* but individual spicules have not been recognised.

Locality 6

The juxtaposition of the vertical escarpment composed of dolostones of the Portfjeld Formation and dark silicilcastic sediments with debris beds containing dolostone talus blocks at this locality was described in detail by Ineson & Peel (2011, fig. 5). Black pyritic mudstones close to the contact (GGU collection 340109) yielded a single external mould of a transversely ornamented tube comparable with *Hyolithellus tenuis* Missarzhevsky *in* Rozanov & Missarzhevsky (1966), as illustrated by Vasilieva (1998, pl. 2, figs 16, 17; Fig. 4N) from the Tommotian (early Cambrian) of Siberia. Vasilieva (1998, table 4) recorded the species mainly from the Tommotian and Atdabanian of Siberia, but stated that it ranges into the early Botoman along the Lena River. *Hyolithellus* was described from the middle part of the Buen Formation in southern Peary Land, North Greenland by Skovsted & Peel (2011) in strata yielding *Mesolenellus hyperboreus* (Poulsen, 1974), indicative of the *Olenellus* Zone and thus younger than the Sirius Passet Lagerstätte (*Nevadella* Zone).

Discussion

Sediments at Localities 1, 3 and 4 appear to form a contiguous structural unit juxtaposed against the escarpment of the Portfjeld Formation but the precise stratigraphic position of Localities 3 and 4 relative to Locality 1 is not known. Examination of the contact between the vertical face of the Portfjeld Formation and the Transitional Buen Formation at Locality 6 suggests that the contact between these two units at Localities 1, 3 and 4 is also essentially a stratigraphic contact, although minor structural displacement may have taken place, as described at Locality 6 (Ineson & Peel 2011).

As noted by Ineson & Peel (2011, caption to fig. 3), the nature of the dolostone inliers of Portfjeld Formation between Localities 2 and 4 is uncertain (Figs 1C, 2). They may represent pinnacles of dolostone in the degraded escarpment margin or olistoliths that have detached from the scarp face. Their bedding, however, appears to be comparable to that seen in the main Portfjeld Formation outcrop immediately to the south indicating that substantial rotation or tumbling similar to the tumbled blocks at Locality 6 (Ineson & Peel 2011, fig. 5), has not taken place. Equally, their apparent separation from the main Portfjeld Formation outcrop may result from minor faulting parallel to the escarpment margin.

There is no faunal similarity between Localities 1 and 6 and their relative positions within the Transitional Buen Formation cannot be determined. Locality 6, has not yielded any fossils characteristic of the lagerstätte, nor remains of poorly skeletonized metazoans.

Locality 2 occurs at a higher structural level than the outcrops at Locality 1. It lies on the hanging wall of a south-easterly directed thrust which oversteps the fossiliferous succession exposed at Locality 1 to eventually lie in contact with pale dolostones of the Portfjeld Formation (Ineson & Peel 2011; Figs 1C, 2). Given the similarity between the faunas of the two localities, it is not unreasonable to assume that strata at Locality 2 represent a structural repetition of the fossiliferous beds at Locality 1. It cannot be discounted, however, that they represent a different horizon and thus extend the stratigraphic range of the lagerstätte.

Locality 5 lies some 300 m west of Locality 1. Local stratal dips (Fig. 1C) indicate that it lies at a significantly higher structural level than the other fossiliferous localities but its precise stratigraphic position relative to these cannot be ascertained due to southerly directed thrusting. The thrust sheets have their origin distal to the scarp face and the other fossil-yielding localities, downslope towards the transition into the deeper water Polkorridoren Group.

Extent of the Sirius Passet Lagerstätte

It is unlikely that the Sirius Passet Lagerstätte is stratigraphically restricted to just the 8.5 m interval exposed by chance at Locality 1, but there is no evidence that the biota preserved at Localities 1–4 has an extensive biostratigraphic range. The trilobite *Buenellus higginsi* occurs at all of these four localities and no marked differences in the composition of the assemblages have been noted, although only a few specimens were found at each of Localities 3 and 4. Faunas preserved at Localities 5 and 6 probably represent other stratigraphic horizons and their stratigraphic positions relative to the lagerstätte are unknown.

The geological setting of the Sirius Passet Lagerstätte within mudstones of the Transitional Buen Formation deposited immediately offshore of the steep scarp face of the carbonate platform succession of the Portfjeld Formation is remarkably similar to the middle Cambrian Burgess Shale Lagerstätte of British Columbia where shales of the Burgess Shale Formation abut

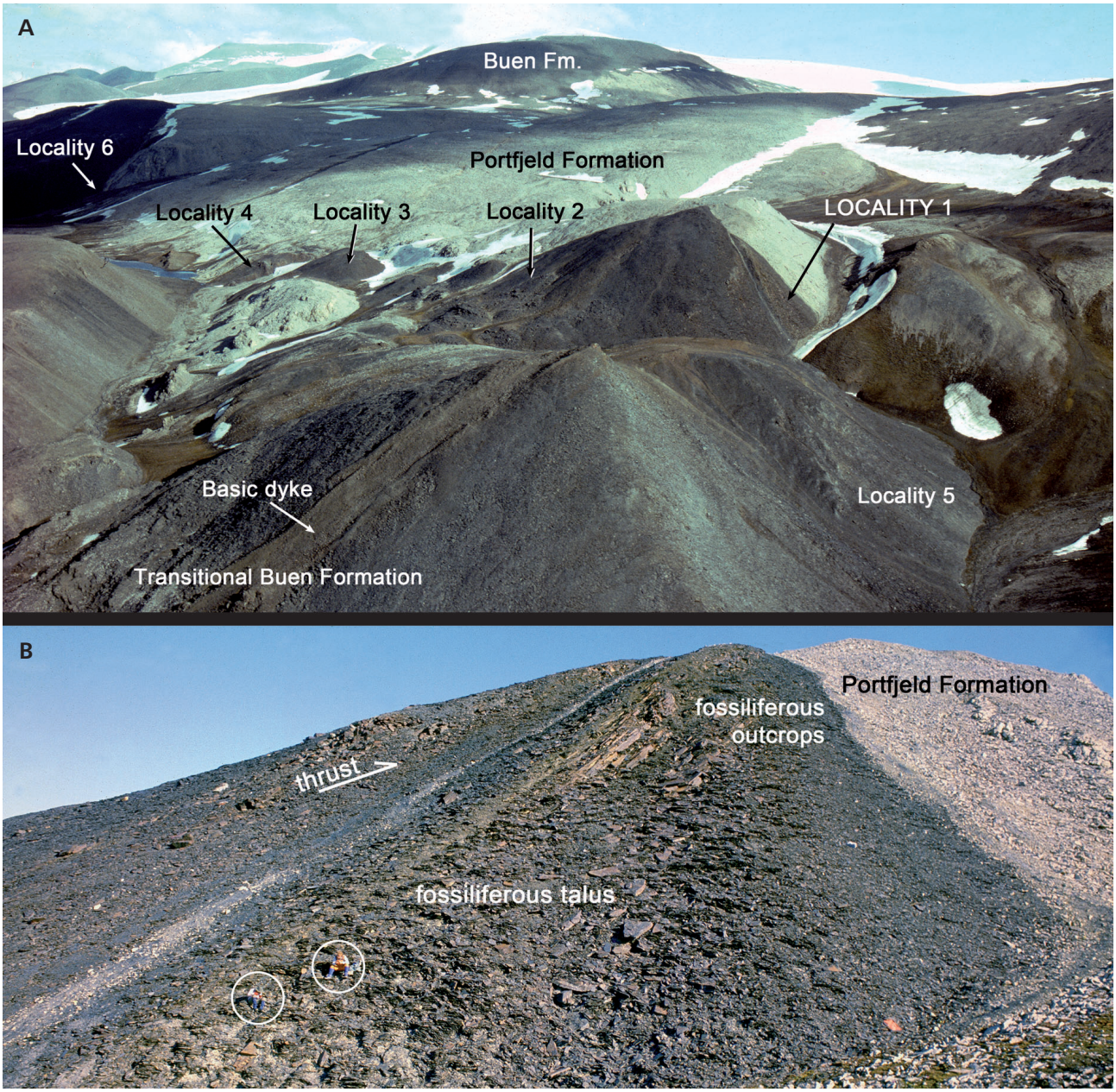


Figure 2. A – southern side of Sirius Passet identifying localities mentioned in the text and located on Fig. 1C. • B – Locality 1, the principal source of fossil from the Sirius Passet Lagerstätte, viewed from the south (right in Fig. 1A). Dark mudstones of the Transitional Buen Formation abut against the outer scarp slope of the Portfjeld Formation; the vertical contact appears low angle due to the obliquity of the photograph. Note circled figures for scale.

against the carbonate escarpment of the Cathedral Formation (Fletcher & Collins 1998, 2009; Ineson & Peel 2011). Both these lagerstätten differ in terms of geological setting from the Emu Bay Shale Lagerstätte (Cambrian Series 2, Stage 4) of Kangaroo Island, South Australia, which was deposited in a more nearshore environment (Gehling *et al*. 2011).

In the classic area of the Burgess Shale Lagerstätte in Yoho and Kootenay National Parks in British Columbia, the Cathedral Formation scarp can be followed or inferred for almost 200 km from Wapta Mountain south-east through Prospectors Valley to The Monarch and numerous fossiliferous localities are scattered along its length (Fletcher & Collins 2009, fig. 1). This is in strong contrast to the currently known geographical distribution of the Sirius Passet Lagerstätte which is limited to the small area encompassing Localities 1-4, a distance of less than 1 km. This distribution may extend to the south-west of Locality 1

	LOCALITY 1	LOCALITY 2	LOCALITY 3	LOCALITY 4	LOCALITY 5	LOCALITY 6
Aaveqaspis inesoni	●	○				
Archaeocyatha spp.	●	●				
Buenaspis forteyi	●	●				
Buenellus higginsi	●	●	●			
Campanamuta mantoni	●	○				
Chalazoscolex pharkus	●					
Choia hindei	●	●				
Choia sp.	●	●	●		○	
Hadronax augustus	●					
Halkieria evangelista	●	●		●		
Hyolithellus cf. *tenuis*						●
Hyolithid sp.	●	●				
Isoxys volucris	●	●	●	●	●	
Isoxys sp.	●					
Kerygmachela kierkegaardi	●	●				
Kiisortoqia soperi	●	○				
Kleptothule rasmusseni	●					
Oodigera peeli	●					
Orthothecid sp.	●	●				
Pambdelurion whittingtoni	●	●				
Paulоterminus spinodorsalis	●	○				
Phragmochaeta canicularis	●					
Siriocaris trollae	●	○				
Sirilorica carlsbergi	●					
Sirilorica pustulosa	●					
Tamisiocaris borealis	●					
Trapezovitus sp.	●					
Undescribed arthropod sp. 1	●	●	●			
Undescribed arthropod sp. 2	●	●				
Xystoscolex boreogyrus	●					
Other undescribed arthropod spp.	●	●				
Horizontal burrows	●	●			●	
Micro-burrows	●	●			●	

Figure 3. Fossils from the Transitional Buen Formation (early Cambrian), Sirius Passet, North Greenland. For discussion of localities see accompanying text. Filled circles, positive identifications; open circles, tentative identifications.

but fossiliferous strata have not been recognised in the generally poorly exposed area. To the north-east of Locality 4 the Transitional Buen Formation is thrust over the Portfjeld Formation, overstepping the fossiliferous mudstones that abut the scarp face (Fig. 1C). While exposing the scarp face and juxtaposed slope sediments, the small structural window at Locality 6 does not yield specially preserved fossils referable to the lagerstätte.

Helicopter reconnaissance in 1994, following the outcrop of the Portfjeld Formation north-east towards Brainard Sund (Fig. 1B), confirmed that thrusts transport metamorphosed siliclastic sediments of the Polkorridoren Group southwards onto the Portfjeld Formation along the southern side of Sirius Passet; outcrops of the escarpment face were not found. While fossiliferous outcrops of the Buen Formation are present to the south-west, across J.P. Koch Fjord in north-east Freuchen Land (Fig. 1B), they yield a later early Cambrian assemblage in which the sponges *Choia hindei* (Dawson, 1896) and *Vauxia*? *gracilenta* Walcott, 1920 are associated with *Olenellus* sp. and the trilobite *Alacephalus*? *davisi* Lane & Rushton, 1992 in beds now known to occur in the upper part of the formation, and not within the Sirius Passet Lagerstätte (Rigby 1986, Peel & Ineson 2011). It is noteworthy that Rigby (1986) also identified *C. hindei* in the first fossils collected from the Sirius Passet Lagerstätte, prior to the recognition of the lagerstätte (Peel & Ineson 2011), although in that assemblage it is associated with the nevadiid trilobite *Buenellus higginsi*.

Outcrops of the Portfjeld Formation occur as scattered inliers in deformed terranes along the northern coast of Greenland as far as northern Wulff Land, some 150 km to the west (Fig. 1A). They lie in close proximity to the inferred east-west trending margin between the southern carbonate platform and deeper water carbonate and siliciclastic sediments of the deep-water trough to the north (Higgins *et al.* 1991, Ineson & Peel 2011) but the presence of a steepened, scarp margin has not been demonstrated in these more western outcrops. Further west, the Portfjeld Formation is recognised as the Ella Bay Formation of north-eastern Ellesmere Island, Canada, with overlying siliciclastic sediments of the Ellesmere Group being equivalent to the Buen Formation (Long 1989, Dewing *et al.* 2004).

To the east, the platform margin extends more than 300 km, along the southern margin of Frederick E. Hyde Fjord into the G.B. Schley Ford area of easternmost Peary Land (Fig. 1A). While fossils have also been described in this area from the upper Buen Formation (*cf.* Blaker & Peel 1997, Ineson & Peel 1997, van der Stijl & Mosher 1998), geological settings and fossil assemblages comparable to that of the Sirius Passet Lagerstätte have not been recognised.

Thus, the Sirius Passet Lagerstätte is an unusual deposit not only in terms of the special preservation of its remarkable fauna, but also on account of its chance preservation and exposure along just a 1 km sector of the 500 km long, tectonized northern margin of the Portfjeld Formation carbonate platform in North Greenland.

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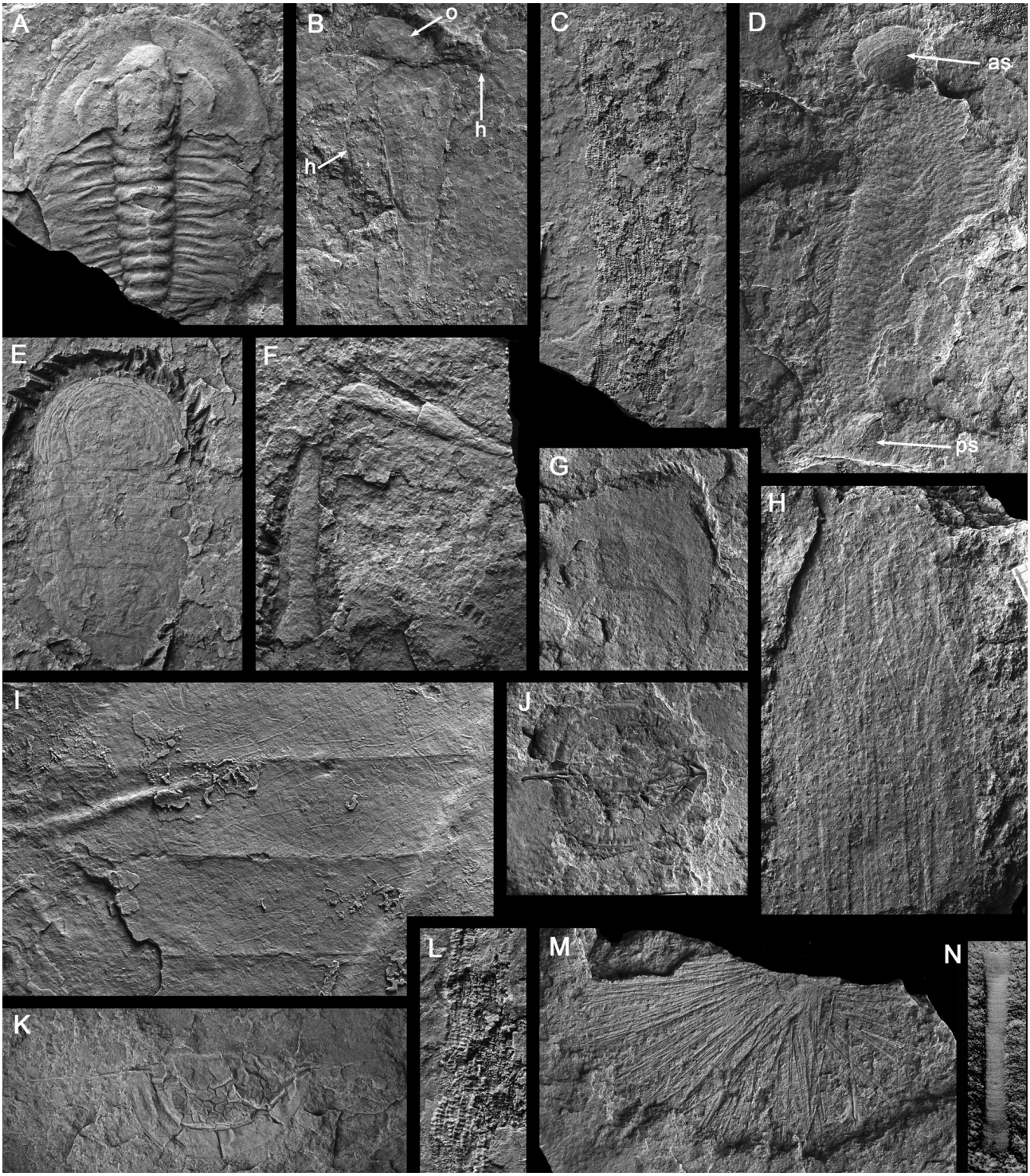

Figure 4. Fossils from Locality 2 (A–M; GGU collection 340112) and Locality 6 (N; GGU collection 340109), Transitional Buen Formation (early Cambrian), Sirius Passet, North Greenland. • A – *Buenellus higginsi*, MGUH 29690, × 2.4. • B – hyolithid with operculum (o) and helens (h), MGUH 29691, × 3. • C, L – archaeocyathan, crushed, lateral view, MGUH 29692, × 2.4 (C), with detail (L, × 4). • D – *Halkieria evangelista*, external mould showing anterior (as) and posterior shields (ps), MGUH 29693, × 2. • E – *Buenaspis forteyi*, MGUH 29694, × 3. • F – orthothecid hyoliths, MGUH 29695 and MGUH 29696, × 2. • G – *Aaveqaspis*(?), poorly preserved head shield MGUH 29697 × 1.5. • H – *Sirilorica carlsbergi*, lateral view of crushed lorica, MGUH 29698, × 2. • I – area of arthropod thorax with four articulated tergites showing a dense ichnofauna of microburrows, MGUH 29699, × 2.5. • J, K – *Isoxys volucris* with conjoined valves spread open (J, MGUH 29700, × 1.5) and in lateral view showing long spines (K, MGUH 29701, × 1.5). • M – *Choia* sp., MGUH 29702, × 2. • N – *Hyolithellus* cf. *tenuis* Missarzhevsky, 1966, MGUH 29703, × 6.

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