Cold Feet: trackways and burrows in ice-marginal strata of the end-Ordovician glaciation (Table Mountain Group, South Africa)

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ABSTRACT

New observations from an outcrop of Upper Ordovician Table Mountain Group strata (Matjiesgoedkloof, Western Cape Province, South Africa) have revealed an unexpected ichnofauna, hosted within diamictites and sandstones that were deposited by a retreating low-latitude (c. 30°S) ice sheet during the Hirnantian glaciation. The locality provides a rare window onto animal-sediment interactions in an early Paleozoic ice-marginal shallow marine environment and contains a trace fossil community with a surprising ichnodiversity and ichnodisparity of burrows, trackways and trails (*Archaeonassa, Diplichnites, Heimdallia, Metaichna, ?Multina, Planolites, Protovirgularia, Skolithos*). Exceptional phenomena preserved in the strata include evidence for direct colonization of glacial diamictites by deep-burrowing *Heimdallia* infauna, and interactions between trackways and dropstones on substrates.

23   Observations from the newly-recognized outcrop dramatically expand our understanding of deep

24   time glacial habitats, demonstrating that deglaciating ice-margins had already been colonized by

25   the latest Ordovician. The freshwater influx that would have been associated with such settings

26   implies that faunal associations which were tolerant of brackish water were also established by

27   that time. The locality has further significance because it records the activity of a nearshore

28   animal community contemporaneous with the fauna of the nearby Soom Shale lägerstatte.

29   Combined, these reveal a paleoecological transect of the diverse marine life that inhabited cold-

30   climate, low-latitude shallow seas around the time of the end-Ordovician deglaciation.

31   **ICHNOLOGY OF GLACIAL ENVIRONMENTS**

32   Compared to other sedimentary systems, there is a less complete understanding of the

33   ichnology of ancient glacial environments (Buatois and Mángano, 2011; Netto et al., 2012;

34   Schatz et al., 2013); in part because glacial sedimentary formations are relatively uncommon,

35   and restricted in their stratigraphic distribution to a few ice-age intervals. Deep time case studies

36   imply that ancient glacial ichnofaunas were low diversity assemblages of diminutive, simple

37   trace fossils (e.g., Buatois et al., 2006; Jackson et al., 2016); explained with reference to

38   environmental stresses such as freshwater and sediment influx from melting glaciers, or frozen

39   substrates impeding infaunal burrowing (Buatois and Mángano, 2011; Netto et al., 2012;

40   Hasiotis et al., 2015). However, these characteristics contrast with the ichnological signatures of

41   modern near-glacial settings (Schatz et al., 2013), and it is possible that existing perspectives

42   have been skewed by paleoenvironmental and stratigraphic biases, and a limited suite of

43   Phanerozoic case studies. For example, ancient glacial ichnofaunas are chiefly reported from

44   fine-grained glacio-lacustrine rhythmites and fjord deposits (e.g., Buatois et al., 2006; Netto et

45   al., 2012), rather than ice-marginal diamictites or sandstones. Likewise, while there are multiple

46   case studies from Carboniferous and younger glaciogenic strata (see Netto et al., 2012), isolated

47   reports of end-Ordovician ichnofaunas are limited to periglacial facies (Kumpulainen et al.,

48   2006; Le Heron, 2010).

49   Here we shed light on animal-sediment interactions in one of Earth's earliest glacial

50   habitats; using new field evidence from an outcrop of the Late Ordovician Table Mountain

51   Group, Western Cape Province, South Africa.

52   **GLACIOGENIC STRATA AT MATJIESGOEDKLOOF**

53   The c. 4 km-thick lower Paleozoic Table Mountain Group, crops out throughout the Cape

54   Basin, and yields a number of direct and indirect signatures attesting to glacial influence (Figure

55   1) (Thamm and Johnson, 2006; Young et al., 2004; Turner et al., 2011). Most prominent

56   amongst the glacially-influenced units is the Pakhuis Formation: a succession of diamictites,

57   sandstones and rare mudrocks that reaches a maximum thickness of c. 80 meters in the basin

58   center, where it overlies glaciotectonically-deformed sandstones of the Peninsula Formation, and

59   thins northwards towards the basin margin, where it rests directly on glacially-carved pre-Cape

60   basement rocks (Blignault and Theron, 2010) (Figure 1C). The unit records glacio-marine

61   deposition by piedmont glaciers that descended southeastwards from a Gondwanan ice sheet

62   (Fig. 2), located at a paleolatitude of c. 30°S and isolated from the major south-polar end-

63   Ordovician ice sheet (Young et al., 2004; Blignault and Theron, 2010; Le Heron et al., 2018).

64   This study has recognized an outcrop of 11 meters of sandstones and glaciogenic

65   diamictites within the Table Mountain Group at the Matjiesgoedkloof farm (31° 38' 21" S; 18°

66   58' 51" E), close to the northern limit of the Pakhuis Formation's outcrop belt (Fig. 1A).

67   Although these strata have previously been mapped as belonging to the uppermost Peninsula

68   Formation (Council for Geoscience, 2001), multiple lines of stratigraphic and sedimentologic

69   evidence suggest that it may be more informative to consider them as constituent to the Pakhuis

70   Formation (Fig. 2B): 1) the strata rest directly on glacially-scoured pre-Cape basement of the late

71   Precambrian Vanrhynsdorp Group; 2) the strata directly underlie muddy diamictites (the "Kobe

72   Member": Rust and Theron, 1964), grading into siltstones of the Cedarberg Formation; and 3)

73   the strata contain multiple glacial sedimentary signatures (see further discussion in

74   Supplementary Information).

75   Evidence that the strata were directly deposited by glaciers (Fig. 2) include an

76   erosionally-fluted bedrock base to the succession, overlain by a 0.1-1.2 meter-thick, clast-

77   supported diamictite. Constituent clasts are striated, and consist of regional basement lithologies:

78   dominantly quartz, chert, banded ironstone, granodiorite and schist. The diamictite is overlain by

79   c. 10 meters of medium- to coarse-grained sandstones with pebble lags and long-axis-vertical,

80   sand-draped lonestones (dropstones). The sandstone is mostly flat-bedded but becomes trough

81   cross-bedded upwards. There is lateral variation within the outcrop: discontinuous thin (< 50 cm)

82   packages of reworked diamictite occur near the top of the succession.

83   Although end-Ordovician glaciogenic strata are frequently sandy (Le Heron et al., 2018),

84   the high sandstone content at this locality is unusual because overlying and adjacent Pakhuis

85   Formation strata in the vicinity of Matjiesgoedkloof consist of clay-rich tillite (Rust and Theron,

86   1964; Rust, 1981; Blignault and Theron, 2010). As the sandy facies 1) is of local extent only; 2)

87   directly overlies clast-supported diamictite (implying till deposits were not reworked by waves or

88   slumping); and 3) contains dropstones (indicating subaqueous deposition); a plausible

89   explanation is that it records deposition as a sub-glacially-sourced ice-contact fan, adjacent to a

90   tidewater glacier (e.g., Powell, 1981; Fig. 2C). Yet irrespective of precise depositional setting (or

91   regional stratigraphy), the unequivocal evidence that the strata were deposited by glaciers is

92   significant, because the diverse and disparate ichnofauna at multiple horizons within the outcrop

93   (Figs. 1B, 2C) is exceptional for an early Paleozoic glacial ichnofauna (Netto et al., 2012).

94   **TRACE FOSSILS OF THE GLACIOGENIC STRATA**

95   Trace fossils have previously been reported from the Matjiesgoedkloof locality (Rust,

96   1967; Anderson, 1975; Braddy and Almond, 1999; Braddy, 2001; Buatois and Mángano, 2011),

97   but the existing census of ichnofauna is incomplete and the glaciogenic nature of the trace-

98   bearing strata has not been recognized. We have identified 7 different ichnogenera at the

99   Matjiesgoedkloof outcrop, and 8 from the Pakhuis Formation in total. The ichnofauna includes

100   dense concentrations of *Heimdallia* and *Planolites*, in addition to isolated instances of the large

101   plug-shaped burrow *Metaichna*, *Skolithos* and a branching burrow system (?*Multina*). Multiple

102   examples of the arthropod trackway *Diplichnites* are present, in addition to two instances of the

103   trail *Archaeonassa*. A newly-identified specimen of *Protovirgularia*, previously collected from

104   the Pakhuis Formation, has been recognized by the present authors in the collections of the

105   Council for Geoscience (expanding the known trace fossils of the unit, though not directly

106   witnessed at the locality). Additionally, sedimentary features that may potentially record

107   microbial colonization of the glacial substrates are associated with the trace fossils and include

108   blister marks (Fig. 3A) and putative petee structures (see Appendix).

109   Three characteristics of this early glacial ichnoassemblage are significant:

110   1) The ichnodisparity is high relative to the ichnodiversity. The number of architectural designs

111   of trace fossils (Buatois et al., 2017) is equal to the number of ichnogenera in the succession

112   (Fig. 2C).

113   2) Multiple different organisms occupied the ice margin environment. The size differential

114   between the trace fossils at this location suggests multiple unique trace-maker organisms: for

115   example, the witnessed diameter of *Planolites* (< 2 mm) contrasts with that of *Metaichna* (up to

116   230 mm).

117   3) Organisms interacted with glaciogenic substrates. There is indisputable evidence that trace-

118   makers were directly occupying glaciogenic sediments very shortly after deposition (Fig. 3): the

119   largest *Metaichna* burrows can be seen within 20 cm vertically of the basal diamictite;

120   *Diplichnites* trackways divert around dropstone obstacles on the substrate; and *Heimdallia*

121   burrows can be seen penetrating to depths of 15 cm in the sandiest patches of the basal

122   diamictite.

123   **DISCUSSION: LIFE AT THE ICE MARGIN DURING THE LATE ORDOVICIAN**

124   The ichnological complexity of this 11-meter-thick outcrop is exceptional amongst

125   known early Paleozoic glaciogenic successions; yet significantly, it bears strong similarities with

126   the neoichnological character of modern ice margin settings (Schatz et al., 2013). Additionally,

127   whilst phenomena such as burrowed diamictites are extremely rare in the global glacial record,

128   they are not wholly without precedent: two other instances are known from the Pleistocene of

129   Alaska (Eyles et al., 1992) and Carboniferous of Argentina (Schatz et al., 2011). Given that there

130   are parallels with aspects of much younger and modern sediments, the Matjiesgoedkloof

131   succession should not be considered a paleoenvironmentally-exceptional glacial ichnofauna. The

132   simplest explanation is rather that it is a fortuitously-identified/preserved instance of a mundane,

133   low-latitude, near-glacial habitat during the Late Ordovician (its lack of precedence being an

134   artefact of a relatively low outcrop volume of similar strata globally).

135   Salinity dilution of marine waters through glacial melting has previously been considered

136   to be an environmental stress that resulted in low diversity or diminutive ichnofaunas in late

137   Paleozoic strata (Buatois et al., 2006; Jackson et al., 2016). However, the Matjiesgoedkloof

138   ichnofauna differs from expectations as it is similar to non-glacial shallow marine strata

139   elsewhere in the Table Mountain Group (Rust, 1967; Braddy and Almond, 1999), and some of its

140   most prominent ichnotaxa are archetypal constituents of other lower Paleozoic Gondwanan

141   sandy littoral environments in non-glacial settings (e.g., *Heimdallia* and *Diplichnites*: Shillito

142   and Davies, 2020). The similarities between the glacial Matjiesgoedkloof ichnofauna and its non-

143   glacial contemporaries resembles trends observed in modern settings, where comparable

144   ichnofauna occur in both arctic and temperate littoral settings and it is position on the high-low

145   tidewater transect that chiefly controls specific ichnoassemblages (Aitken et al., 1988).

146   A prominent characteristic of the Matjiesgoedkloof ichnofauna is its significant

147   ichnodisparity. This could indicate that it represents an early example of a community with

148   brackish water tolerance, as elevated ichnodisparity, relative to ichnodiversity, can be associated

149   with the initial colonization of new environments (Buatois et al., 2017). The variety of

150   architectural designs of trace fossils could reflect exploitation of locally-novel ecospace at the

151   outlet of a melting ice-sheet, but can also be seen in light of global evolutionary trends, as the

152   animal colonization of the land – and thus brackish and freshwater habitats – progressed through

153   the Ordovician and Silurian (Buatois et al., 2005; Shillito and Davies, 2019, 2020), with early

154   bursts of architectural diversification in trace fossils as new environmental niches were occupied

155   (Minter et al., 2017).

156   The Matjiesgoedkloof ichnofauna is also significant because of its relationship to the

157   Soom Shale lägerstatte (lower Cedarberg Formation: Fig. 1C). The Soom Shale Member

158   preserves skeletonized and soft-bodied fauna within very fine clastic outwash sediments

159   (containing occasional dropstones), deposited during a diachronous post-glacial marine

160   transgression as the Pakhuis ice-sheet receded northwards (e.g., Aldridge et al, 2001; Gabbott et

161 al., 2016). As the principal fossil site in the Soom Shale Member is at Keurbos farm (Gabbott et

162 al., 2016), 30 km south of Matjiesgoedkloof, deposition at the two sites was likely near-

163 contemporaneous (Fig. 2A). Together they provide a window onto a nearshore-offshore

164 paleoecological transect in a low-latitude. cold-water setting. The Soom Shale is unbioturbated,

165 due to dominantly anoxic and sometimes euxinic conditions, but yields an open-marine fauna of

166 vertebrates, arthropods, annelids, molluscs, brachiopods, algae, plankton, and problematica

167 (Gabbott et al., 2016). Moving closer to shore, the Matjiesgoedkloof ichnofauna indicates that

168 marine life also thrived where infaunal activity was not limited by anoxic or euxinic bottom

169 conditions. Speculatively, in the ice-contact fan setting, these may even have benefitted from a

170 localized 'life support bubble' in the form of well-oxygenated subglacial fluids (e.g., see Lechte

171 and Wallace, 2016). Here, in close proximity to the ice margin, diverse trace-makers likely

172 consisting of arthropods (e.g., *Diplichnites*), gastropods (e.g., *Archaeonassa*), vermiform

173 organisms (e.g., *Skolithos*) and bivalves (e.g., *Protovirgularia*) colonized and interacted with

174 glacial substrates.

175 **CONCLUSIONS**

176   Evidence from the Matjiesgoedkloof outcrop suggests that communities that could

177 tolerate ice-margin habitats, similar to those that exist today, had already evolved by the time of

178 the Hirnantian glaciation; the first significant ice-age to post-date the evolution of animal

179 motility. The ichnofauna demonstrates that ancient glacial ichnofaunas can exhibit high diversity

180 and disparity, despite perceived environmental stresses. Together with fossil-bearing strata

181 elsewhere in the Cape Basin (Soom Shale), the Matjiesgoedkloof ichnofauna provides an

182 unmatched window onto marine paleocommunities during the latest Ordovician glaciation:

183 demonstrating that preserved fossil and trace fossil diversity can be significant at basin- or

184 outcrop-scale, even against a global back-drop of major climate change and mass extinction.

185 **APPENDIX**

186 Further details and images showing the sedimentary and stratigraphic context of the trace fossils.

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279 **FIGURE CAPTIONS**

280 Figure 1. Geological context of trace-fossil-bearing strata at Matjiesgoedkloof. A: Location

281 relative to other outcrop of the Pakhuis Formation and Table Mountain Group in Western Cape

282 Province. B: Sedimentary log through the strata at Matjiesgoedkloof (KOBE/SOOM—Overlying

283 Kobe Mb and Soom Shale Mb; VRD GP—Underlying Vanrhynsdorp Gp). C: Cross-section

284 through Cape Basin along line A-A' (in A) showing regional stratigraphic relationships within

285 the Table Mountain Group; modified after Rust (1973). PIE—Piekenierskloof Fm; GFW—

286 Graafwater Fm; PEN—Peninsula Fm; CED—Cedarberg Fm (SS—Soom Shale Mb; DM—Disa

287 Mb); NAR—Nardouw Subgroup.

288 Figure 2. Paleoenvironmental reconstructions showing context of the ichnofaunal community. A:

289 Regional reconstruction as the South African ice sheet receded northwards. Matjiesgoedkloof

290 witnesses diamictite and sandstone deposition from the melting of sea-level piedmont glaciers at

291 the northern edge of the Cape Basin. Contemporaneously, marine siltstones (the Soom Shale) are

292 being deposited offshore to the south − including at fossil lägerstatte localities such as Keurbos.

293   B: Reconstruction of deposition of the strata at Matjiesgoedkloof, showing paleoenvironmental

294   context of sedimentary-stratigraphic phenomena witnessed at outcrop. C: Trace-fossils of the ice-

295   marginal sediments seen in B, showing architectural design (after Buatois et al., 2017),

296   commonness and preference for pro-glacial sandstone or diamictite substrates. *Protovirgularia*

297   was identified within a sample of Pakhuis Formation (locality unknown) in the collections of the

298   Council for Geoscience, Bellville Office.

299   Figure 3. Trace fossils within indisputably glaciogenic strata at Matjiesgoedkloof. A: *Skolithos*

300   and *Diplichnites* within pro-glacial sandstones, containing dropstones. *Diplichnites* (arthropod

301   walking trail) can be seen to divert around dropstone obstacle. B: Dense patches of *Heimdallia*

302   burrows internal to matrix-dominated parts of the basal polymict glacial diamictite that rests

303   directly on the glacially-scoured contact with the Ediacaran Vanrhynsdorp Group. C: Large (23-

304   cm-diameter) plug-shaped *Metaichna* burrow, 20 cm above the top of the basal diamictite,

305   penetrating a wave-rippled sand substrate (lack of crestline deflection implies *Metaichna* post-

306   dates ripple marks). Scale bar in all images is 20 cm.

307   [1]GSA Data Repository item 202Xxxx, further geological context and high resolution images of

308   the Matjiesgoedkloof ichnofauna, is available online at www.geosociety.org/pubs/ft20XX.htm,

309   or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140,
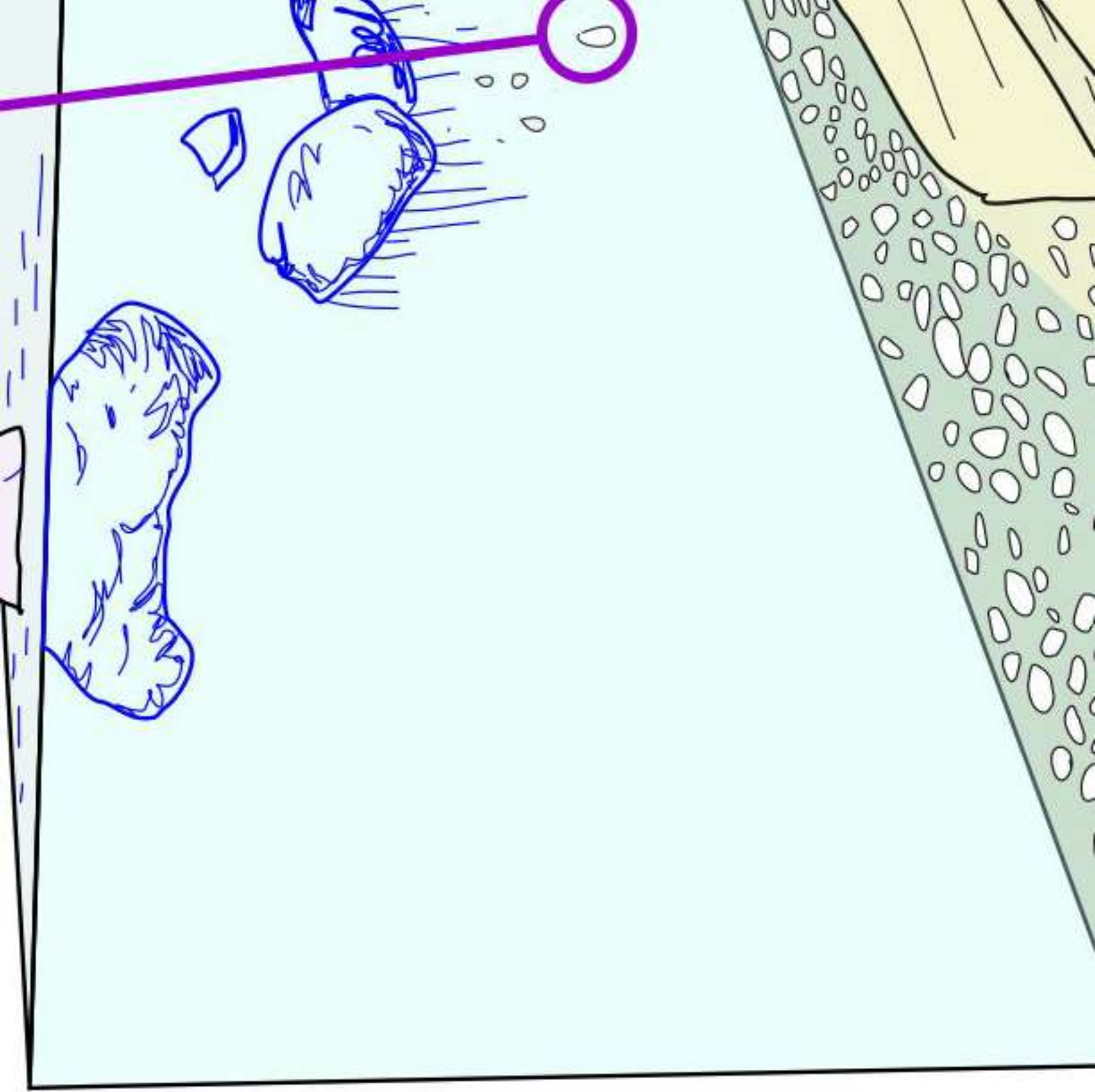
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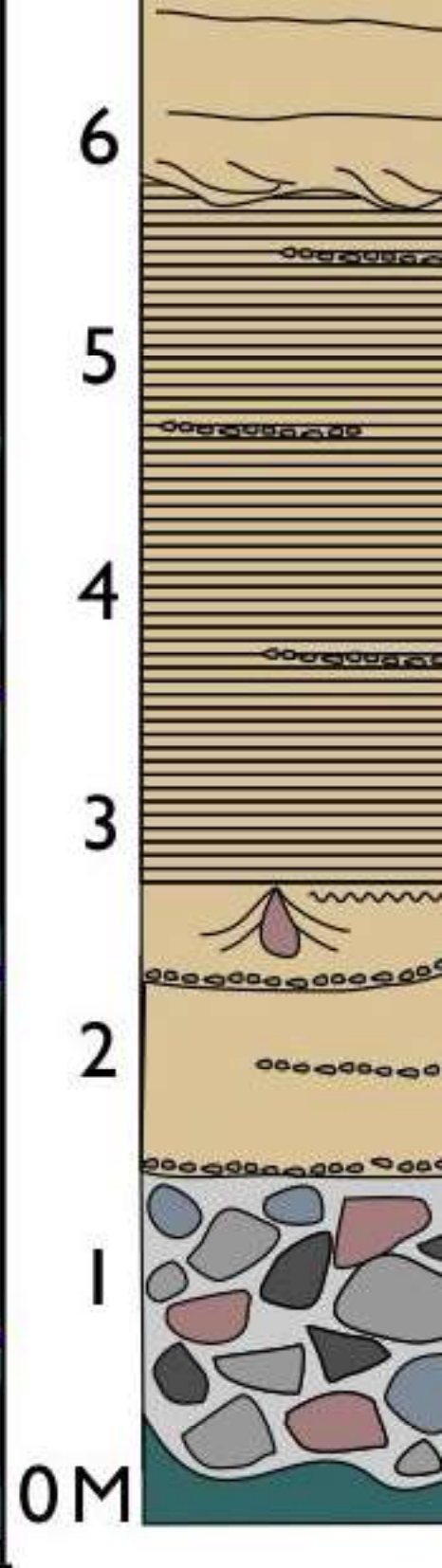
Trough cross-
bedding

Dropstone

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Cold Feet: trackways and burrows in ice-marginal strata of the end-Ordovician glaciation (Table Mountain Group, South Africa)

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STRATIGRAPHIC CONTEXT OF THE STRATA AT MATJESGOEDKLOOF

The succession exposed at Matjesgoedkloof has previously been mapped as Peninsula Formation (fluvial to shallow marine sandstones), resting unconformably on top of metamorphosed strata of the Ediacaran-Cambrian Vanrhynsdorp Group after work by Rust and Theron (1964) and Rust (1967, 1981) [Figure S1].

At Matjesgoedkloof, Rust and Theron (1964) and Rust (1967) noted that Peninsula Formation underlies rocks of the Pakhuis and Cedarberg formations. Here the Peninsula Formation was originally defined by two lithodemic units, a "basal conglomerate stage" and the overlying "lower sandstone stage" (Rust and Theron, 1964). The basal conglomerate stage was described as being usually less than a meter thick, poorly-sorted, polymict breccia conglomerate with clasts thought to have been derived from the basement and further afield. Rust and Theron (1964) noted that this basal conglomerate stage directly overlies the Vanrhynsdorp and Gifberg groups along an irregular undulating unconformity throughout most of the Kobe and Matzikamma mountains, disappearing north of Matjesgoedkloof. The lower sandstone stage was described as being a medium grained quartz arenite sandstone with thin conglomeratic beds and pebbly stringers in places (Rust and Theron, 1964). It was further noted by the authors that the lower sandstone stage characteristically pinches and swells in outcrop and has an irregular thickness when traced out along the Kobe Mountain, as such, the basal conglomerate stage too has an

irregular thickness with respect to the lower sandstone stage. The lower sandstone stage was further noted by the authors to disappear north of Matjiesgoedkloof.

Overlying this lithodemic succession, is a succession of lower muddy diamictites that progressively grade upwards into shales and mudrocks, the "shale-mudstone stage" of Rust and Theron (1964). The lowermost muddy diamictites were noted by Rust and Theron (1964) in the general Vanrhynsdorp area to comprise polished and well-faceted, striated extraclasts of jasper, chert and other metasedimentary rocks derived from the Nama Group. This characteristic diamictite was referred to later by Rust (1967) as the "Kobe diamictite" or the "Kobe member", the lowermost subdivison of the Pakhuis Formation, restricted to the northern most regions of the Cape Supergroup. In places north of Matjiesgoedkloof, the Kobe member was demonstrated to onlap the Vanrhyndorp and Gifberg groups directly (Rust and Theron, 1964). The shales and mudrocks which succeed these tillites would later be referred to as the Cedarberg Formation (Rust, 1967).

Further to these observations of the Peninsula, Pakhuis and Cedarberg formations, Rust and Theron (1964) further noted that there is a conspicuous (and relatively rapid) thinning of the Peninsula Formation in the area north of the towns of Klawer and Doringbos. The exact point to where they considered the Peninsula Formation (i.e. their basal conglomerate and lower sandstone stages) itself to pinch out was roughly determined to be around Matjiesgoedkloof which is currently shown on geological maps (Fig S1). North of Matjiesgoedkloof, the Pakhuis Formation (and in turn, the Cedarberg Formation) directly overlies the Vanrhynsdorp and Gifberg groups.

We interpret the "basal conglomerate and lower sandstone stages" of the Peninsula Formation identified by Rust and Theron (1964) and Rust (1967) to in fact be a succession of basal sandy

diamictite and related sandstone deposits of the Pakhuis Formation that accumulated within a glacial setting and not as a subaerial deflation/erosion surface as previously alluded to by Rust and Theron (1964) and Rust (1967). As noted by Rust and Theron (1964) and Rust (1967) this basal conglomerate of the Peninsula Formation is present in places in the northern extremities of the basin where the area of study is located. Given the poorly sorted polymict nature of extraclasts present in the lowermost portion of the stratigraphic succession and that some of these clasts are clearly striated it is reasonable to assume that this basal conglomerate is a diamictite and that it is glacial in origin. Since the outcrop area is located in the extreme northern limits of the basin it is further not unreasonable to assume that one would encounter sandier diamictites and associated ice margin outwash sandstones as proximal-most expressions in the glacial depositional system as interpreted in this study. We do admit that these deposits have not been extensively traced in the field study area and await further studies at a later date. If our thesis is correct, then one should predict more instances of similar facies and stacking trends, as observed in this study, to be present in places throughout the basin where ice-marginal sheets ablated, forming outwash fans.

As noted by Rust and Theron (1964), there is a conspicuous (and relatively rapid) thinning of the Peninsula Formation in the area north of the towns of Klawer and Doringbos. The exact point to where they considered the Peninsula Formation itself to pinch out was roughly determined to be around Matjiesgoedkloof. We noted that the northernmost extent of the Peninsula Formation, as a single tabular sandstone body, was observed to pinch out altogether in the Matzikamma Mountains at the northernmost extent of the Op-De-Berg Private Nature Reserve situated ~9.5 km due SE of Vanrhynsdorp and in the Kobe Mountains ~5 km due S of Matjiesgoedkloof. The succession observed in this study is thus disconnected from the main body of sandstones reliably

identified as the Peninsula Formation by a reasonable distance. We do admit that this is geographically close to where Rust and Theron (1964) place their northernmost limit of the Peninsula Formation and would perhaps have to researched at a further date. This relationship was observed both in the field, as well as with new high resolution satellite photography of the Matzikamma and Kobe mountains. It is interesting to note that the original geological maps were made before the advent of high resolution satellite photography and that the basis for the delineation of lithostratigraphic units was made on the basis of lithodemic principles. It is thus entirely reasonable that sandier equivalents of the Pakhuis Formation, as described in this study, could have been equated with the Peninsula Formation.

SEDIMENTARY CONTEXT

The unit comprises sandstones and diamictites deposited under the influence of a low-latitude ice-sheet during the end Ordovician ice age [Figure S2]. Diamictites rest directly on scoured Precambrian bedrock and reach a thickness of up to 1.2 metres [Figure S3-S5]. Clasts occur up to 35 cm diameter, are frequently striated and exhibit a wide range of sizes, shapes and BIF, chert, quartzite, granodiorite and schist lithologies. Other glacial structures include vertically-oriented and draped dropstones.

Trace fossils and glacial sedimentary structures are contemporaneous - trackways can be seen diverting around dropstones and *Heimdallia* burrows extend up to depths of 200 mm into glacial diamictite [Figures S6 and S7]

Figure S1 (overleaf): Simplified geological map of the field study area. Map created using 1:250, 000 geological data after 3118 Calvinia geological mapsheet (Council for Geoscience, 2001).
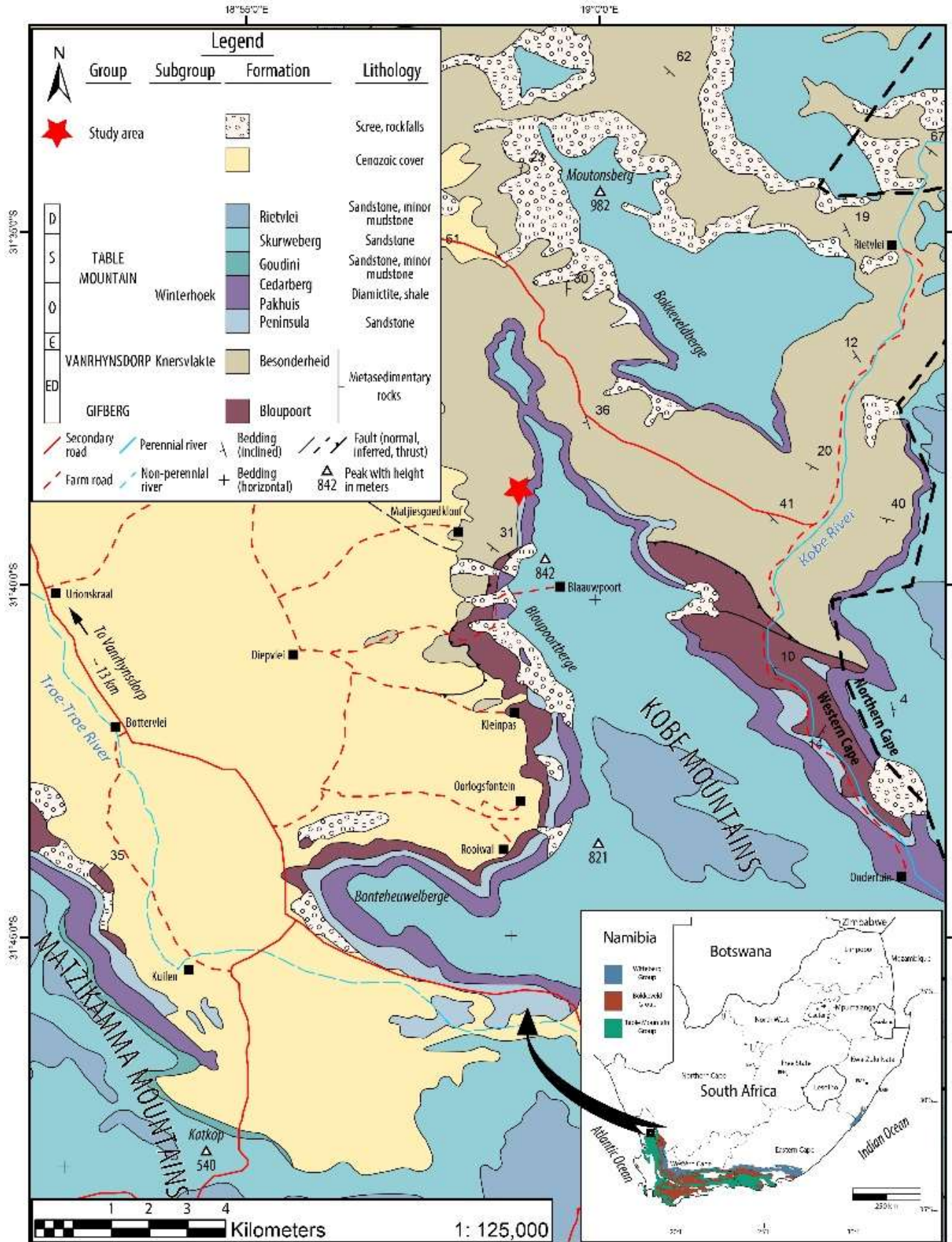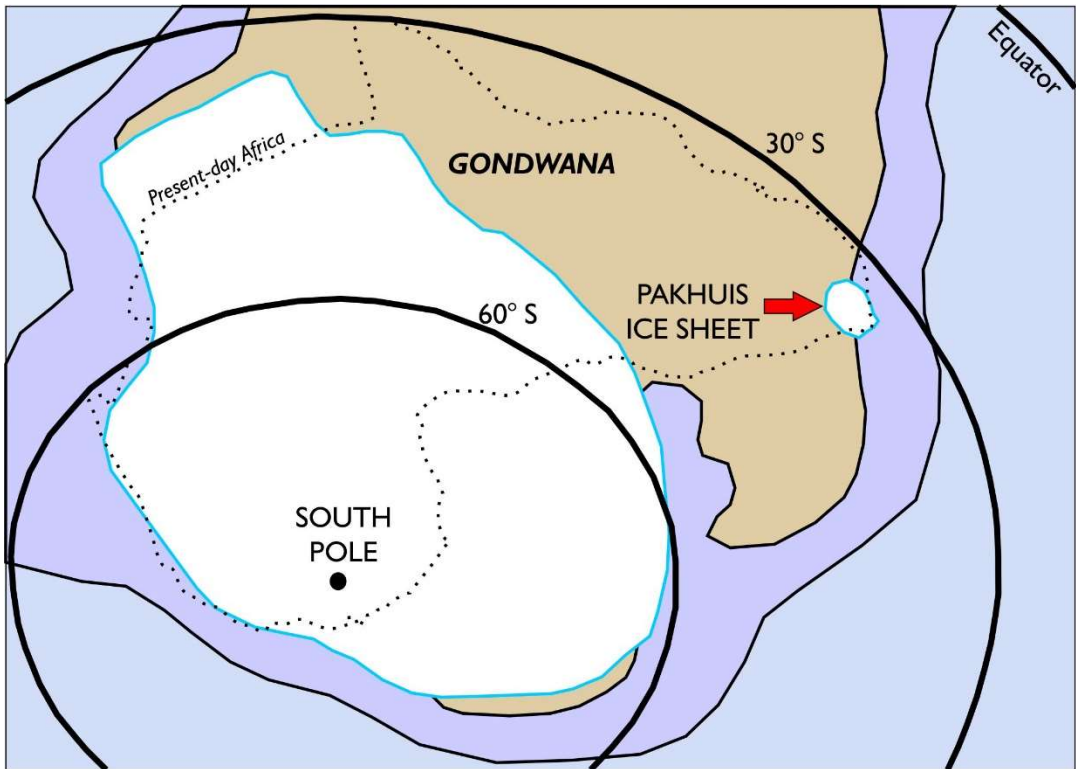
Figure S2. Location of the Pakhuis ice sheet relative to the main Hirnantian ice sheet (After Torsvik & Cocks, 2017).

Figure S3. Basal polymict diamictite with cobbles at Matjesgoedkloof.

Figure S4. Reworked diamictite within overlying sands

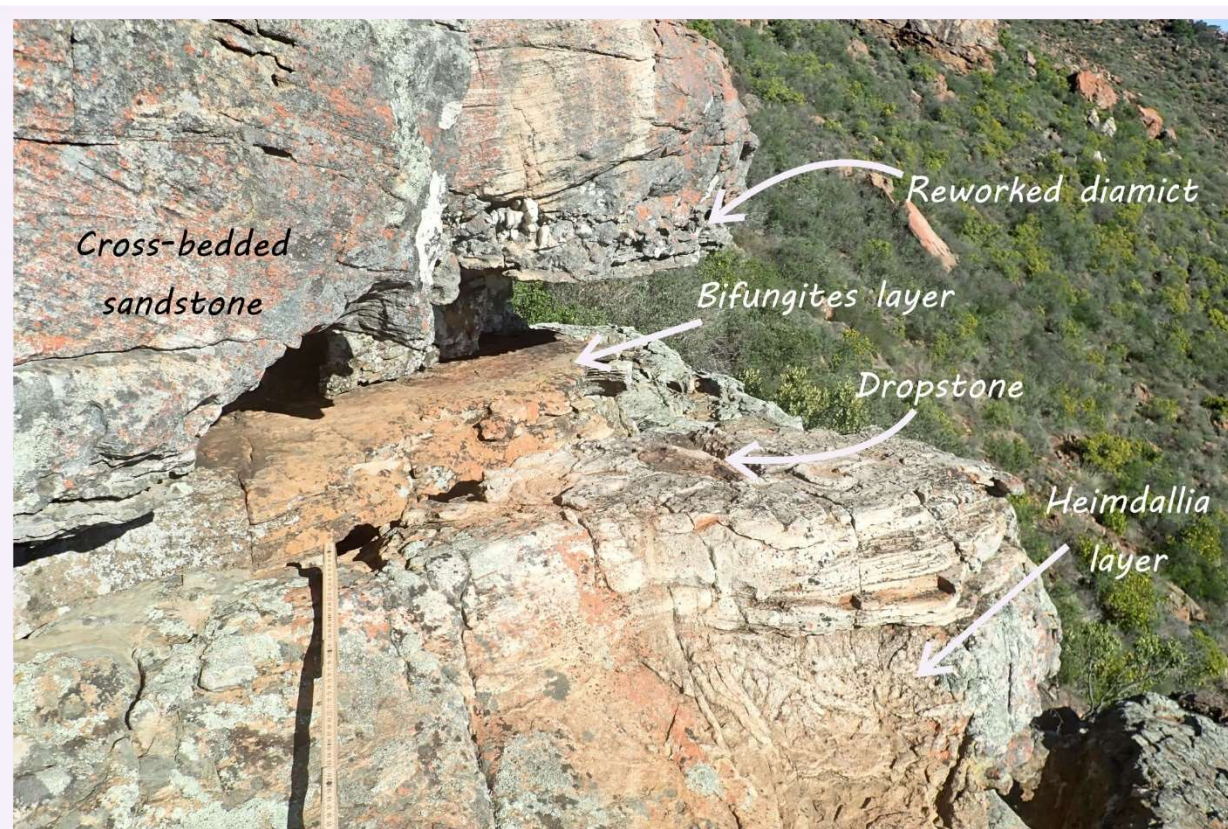*Figure S5. Location of stratigraphic log, showing basal diamictite.*

Figure S6. Trace fossil bearing strata are interspersed with glacial sediment, near top of section.
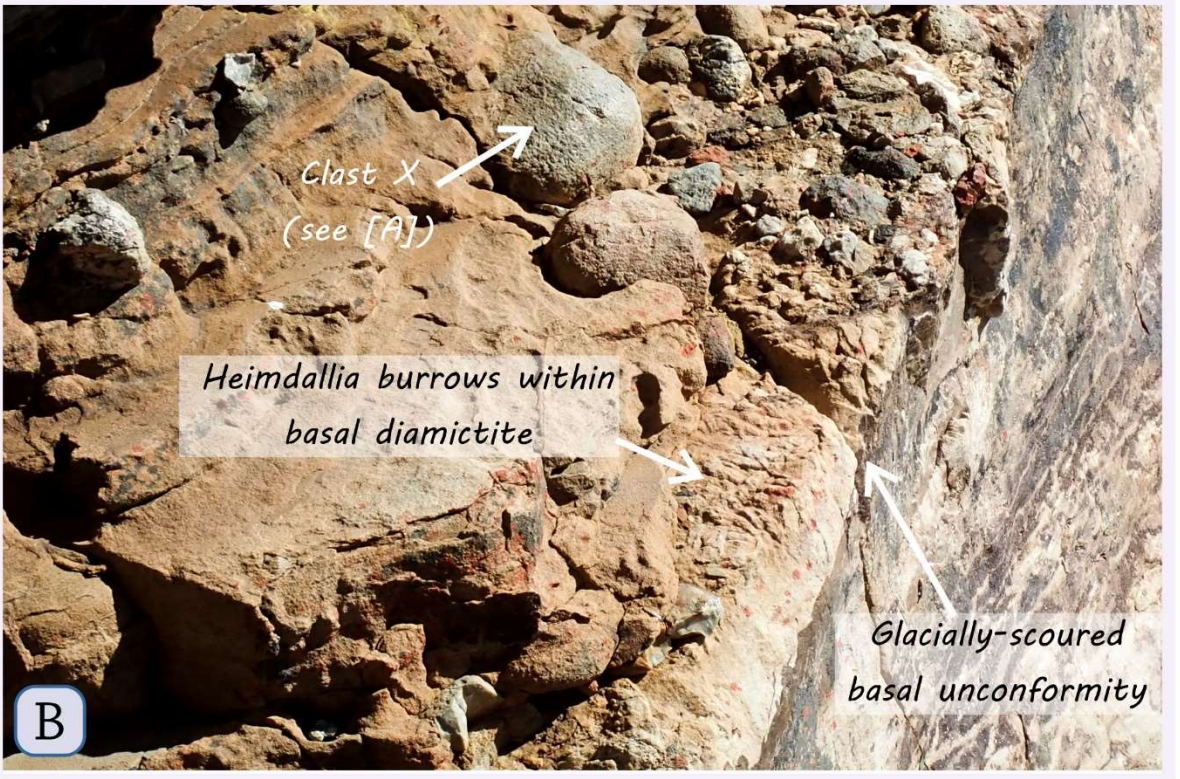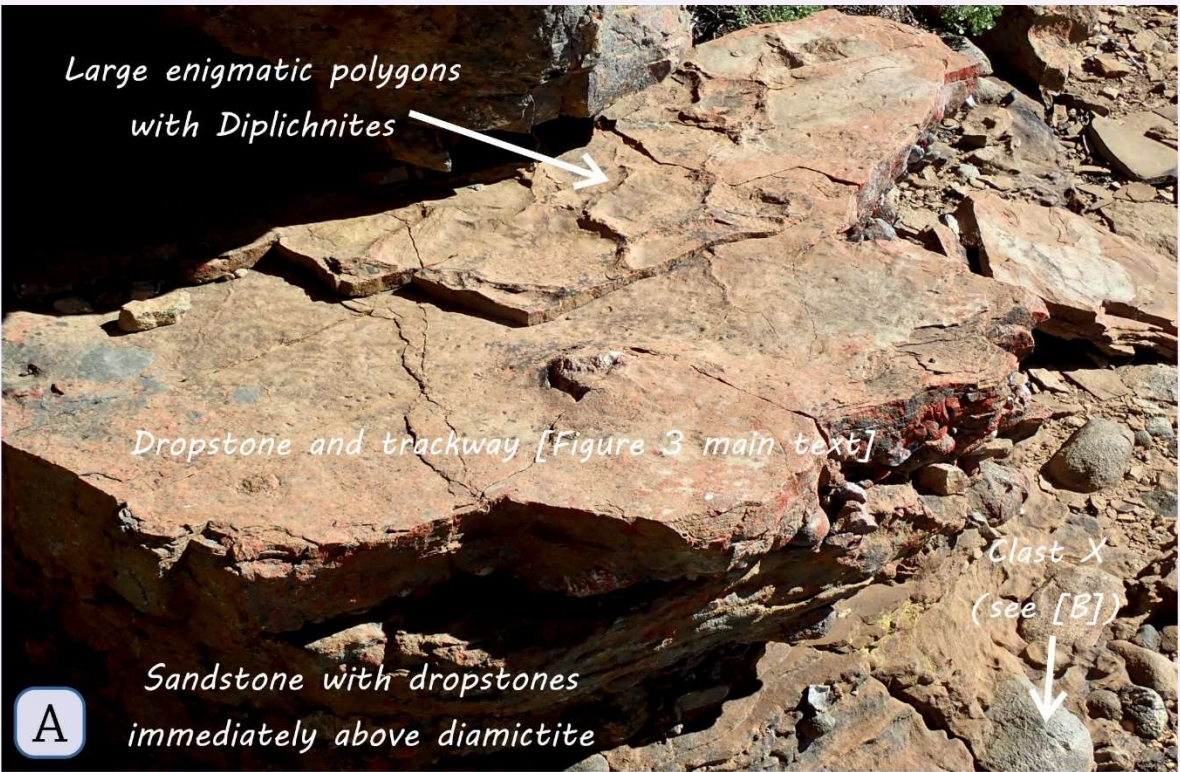
Figure S7. Detail of basal diamictite and relationship with trace fossils.

POSSIBLE MICROBIAL TEXTURES

Enigmatic polygonal surface features preserved in epirelief occur on some of the trace fossil surfaces [Figure S8]. These have resemblance to alpha- or gamma- petee structures (Reineck et al., 2000). The presence of trackways that cross the raised ridges indicates that they formed a true substrate at the time of deposition. Other possible microbial features include burst blister marks (see main text).
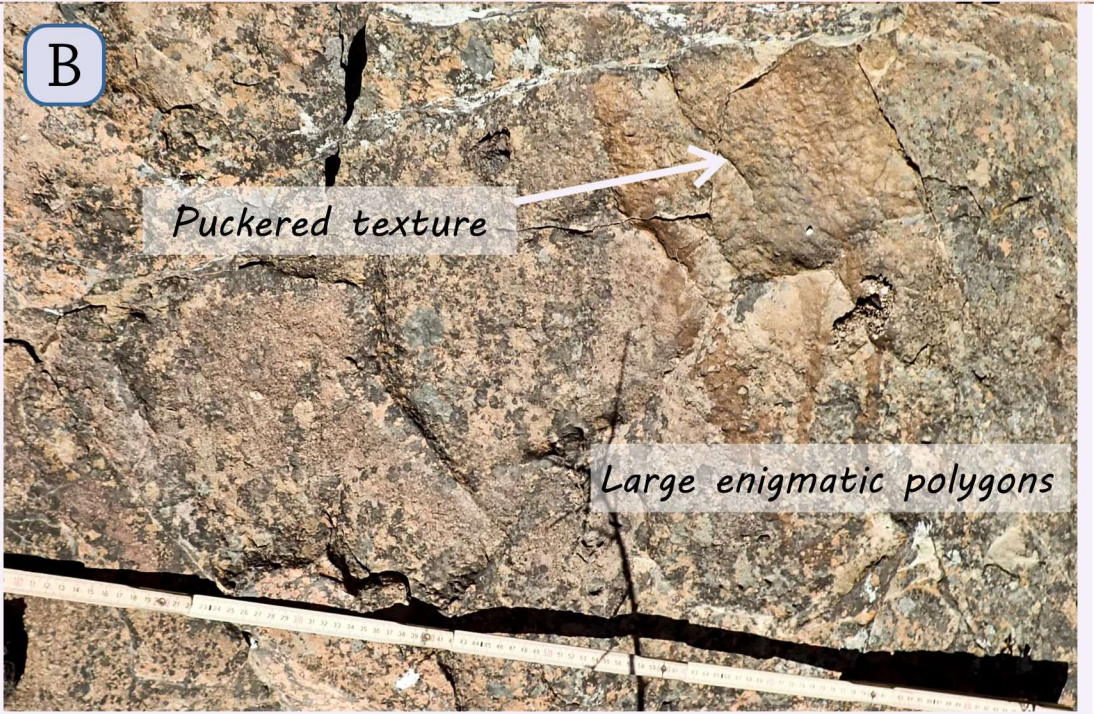
Figure S8. Enigmatic polygons that bear resemblance to petee structures (see also Fig. S5)

TRACE FOSSILS

Few trace fossils have previously been described from the Matjesgoedkloof locality, without recognizing the glaciogenic nature of the host sediment: Rust (1967) recognized three unnamed arthropod trackways; Anderson (1975) recorded "?*Petalichnus*" (here, *Diplichnites*) and *Metaichna*; Braddy and Almond (1999) recorded "*Palmichnium*" (here, *Diplichnites*), *Metaichna* and "horizontal burrows"; and Braddy (2001) recorded "*Metaichna*" with internal spreite (probably those traces here identified as *Heimdallia*).

An ichnotaxonomic list, detailing likely tracemakers, follows:

Archaeonassa

Two instances. Trails which consist of regular convex furrows, bounded on either side by low, narrow, subangular ridges. The furrows may be smooth or crossed laterally by rounded wrinkle marks (Fenton & Fenton, 1937). These trails are thought to typically have been produced by gastropod molluscs (Fenton & Fenton, 1937), although a wider variety of invertebrate tracemakers are possible (Buckman, 1994).

Fig. S9. Archaeonassa

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Diplichnites

Six instances, of variable dimensions (Figs. S10-S11). Symmetrical trackways, which consist of two rows of closely spaced imprints and no medial markings. The imprints are not connected to one another, although they may overlap, and may be elongate, ellipsoidal, or circular, and oriented oblique or perpendicular to the trace axis (Trewin & McNamara, 1994). *Diplichnites* is known to be produced by arthropods, and may be produced by many different classes including trilobites, myriapods, eurypterids, and xiphosurans (Radwanski & Roniewicz, 1963; Trewin & McNamara, 1994).

Fig. S10. Wide *Diplichnites* on polygon-bearing bedding plane

Fig. S11. Small Diplichnites, with Skolithos

Heimdallia

Burrows comprised of horizontally stacked vertically to sub-vertically oriented spreite, creating 'barriers' within the sediment. Burrows range from straight to tightly meandering, and typically occur in dense associations overprinting and cross-cutting one another. The infill of the burrows is compositionally the same as the surrounding sediment, and faint striations are occasionally visible on the burrow walls (Olivero et al., 2004). *Heimdallia* is thought to record a systematic feeding trace, although there is some uncertainty over the tracemaker. Both vermiform organisms and small crustaceans such as decapods have been considered, with the latter deemed most likely in coarse-grained, granular sedimentary rocks (Bradshaw, 1981). *Heimdallia* has previously been identified at this location (in the context of being noted for its restricted stratigraphic range from

Late Ordovician to Early Carboniferous: Buatois & Mángano, 2011: their Fig. 13.8; Mángano et al., 2012: their Fig. 2B).

Fig. S12. Multiple Heimdallia in sandy diamictite.

Fig. S13. Detail of looping form on bedding plane

Fig. S14. Heimdallia within diamictite

<div align="center">Metaichna</div>

A regular conical or hemispherical 'plug-shaped' burrow, oriented with the apex point directed stratigraphically downwards. There is typically no structure to the lining or core of the burrow, and the infill is typically coarser than the surrounding sediment (Anderson, 1975). The tracemaker of *Metaichna* is unknown.

Fig. S15. Metaichna (left of image) cross-cutting into Heimdallia

?*Multina*

An irregularly branching horizontal burrow network, where branches may cross each other to form irregular polygons. The individual burrow shafts are semi-ovular in cross section, with a straight to curved planform morphology. The infill may have indistinct transverse furrows but typically no other evidence of internal structure (Orłowski & Zylinska, 1996). Due to the weathered nature of this specimen it is possible it is a preservational variant of another ichnotaxon, although *Multina* is considered most likely. The trace is distinguished from *Heimdallia* due to the apparent branching, which is not known to occur in *Heimdallia* or other similar vertical spreiten trace fossils (Bradshaw, 1981; Olivero et al., 2004). *Multina* is thought to be an infaunal feeding trace, although the tracemaker is unknown (Zapata et al., 2017).

Fig.S17. ?Multina

Planolites

Unlined burrows with structureless infill which often differs from the surrounding sediment. These burrows are straight to slightly curved, with an approximately circular cross section and an absence of branching (Keighley & Pickerill, 1995). The burrows may record deposit feeding behavior or movement through the substrate, and are likely produced by vermiform organisms, although molluscan tracemakers are also possible (Keighley & Pickerill, 1995).

Fig. S18. Bedding planes with small Planolites and Diplichnites

?Protovirgularia

Small, straight to curved trails composed of a series of closely spaced, bilaterally symmetrical

chevronate ridges. The ridges are often connected along the midline by a continuous ridge or

furrow (Han & Pickerill, 1994). A range of possible tracemakers are thought to be responsible

for *Protovirgularia*, including arthropods, annelids, and bivalves, moving above or below the

surface of the sediment (Han & Pickerill, 1994).

Whilst the repeated chevronate pattern of this specimen most likely corresponds to

Protovirgularia, other ichnotaxa have been considered. As the chevrons appear to become

sharper towards the midline it is possible this trace is instead *Glaciichium*, an arthropod trackway

taxon known from similar depositional settings elsewhere (Uchman et al., 2008).

***Fig. S19.
Protovirgulara in
collections of
Council for
Geoscience,
Bellville***

Skolithos

Simple, unbranched vertical or near vertical tubes, frequently observed in dense concentrations. Burrows can be lined or unlined, with infill that is homogenous and typically the same as the surrounding sediment. When viewed in cross section on bedding surfaces, these burrows appear as raised circles which are not clearly directly associated with any other burrows (Schlirf & Uchman, 2005). Similar modern burrows are known to be produced by filter feeding polychaetes, but other tracemakers and life habits are possible (Curran & Frey, 1977).

Fig. S20. Burrow top of a 1 cm wide *Skolithos*

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