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 Matjiesgoedkloof, 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 Matjiesgoedkloof. 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.

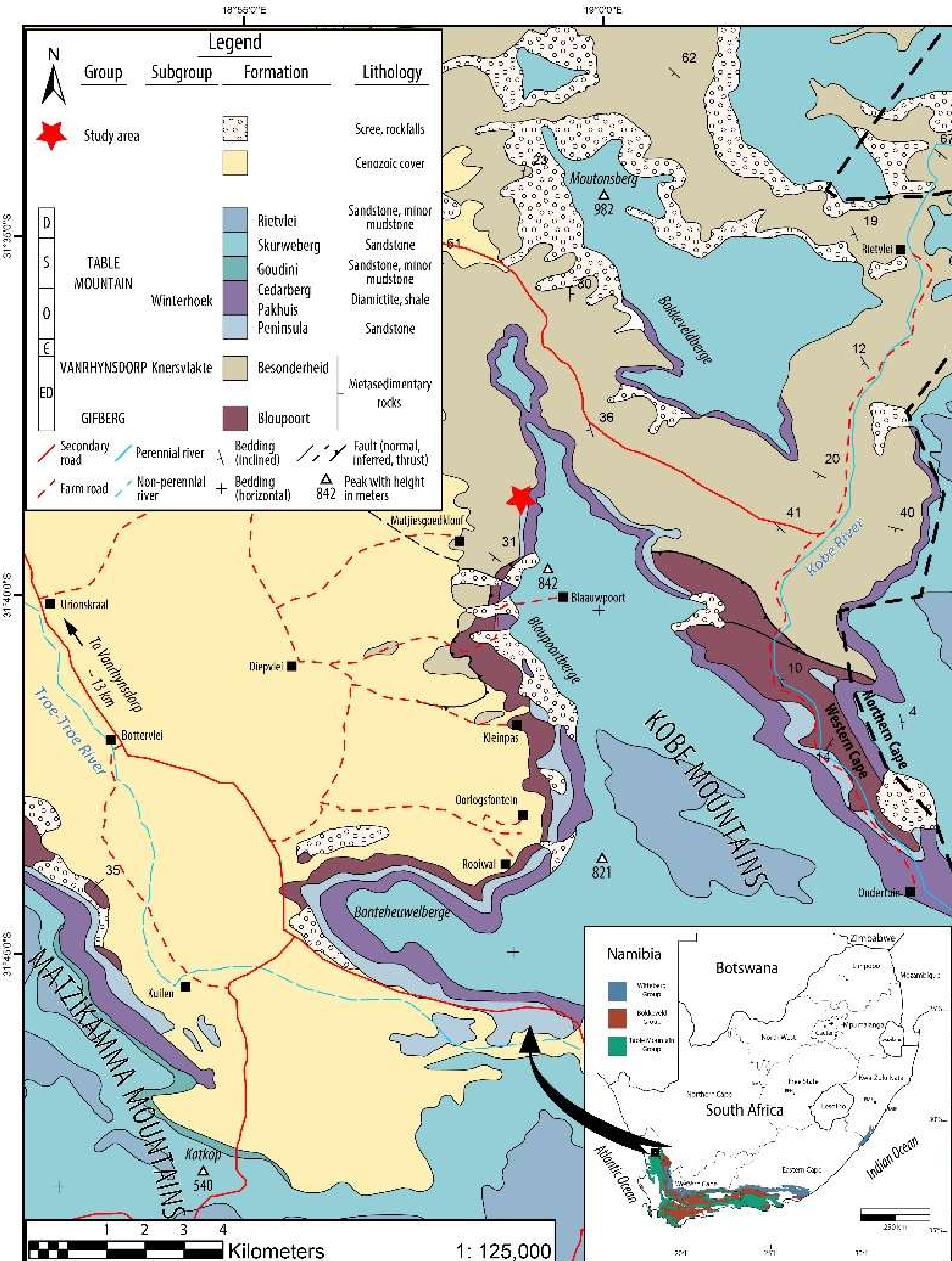
As noted by Rust and Theron (1964), there is a conspicuous (and relatively rapid) thinning of the Peninsula Formation in the area north of the towns of Klawer and Doringbos. The exact point to where they considered the Peninsula Formation itself to pinch out was roughly determined to be around Matjiesgoedkloof. 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).



Legend
Group
Subgroup
Formation
Lithology
Study area
Scree, rockfalls
Cenozoic cover
TABLE MOUNTAIN
Winterhoek
Rietvlei
Skurweberg
Goudini
Cedarberg
Pakhuis
Peninsula
Sandstone, minor mudstone
Sandstone
Sandstone, minor mudstone
Diamictite, shale
Sandstone
VANRHYNSDORP
Knersvlakte
Besonderheid
Metasedimentary rocks
GIFBERG
Bloupoort
Secondary road
Perennial river
Bedding (inclined)
Fault (normal, inferred, thrust)
Farm road
Non-perennial river
Bedding (horizontal)
Peak with height in meters
Moutonsberg
Bokkeveldberge
Rietvlei
Kobe River
Matjiesgoedkloof
Blaauwpoort
Bloupoortberge
Urionskraal
To Vanrhynsdorp ~13 km
Troe-Troe River
Diepvlei
Botterviei
Kleinpas
KOBE MOUNTAINS
Western Cape
Northern Cape
Oorlogsfontein
Rooival
Bonteheuwelberge
Onderfontein
MATZIKAMMA MOUNTAINS
Kuilen
Kotkop
Kilometers
1: 125,000
Namibia
Botswana
South Africa
Atlantic Ocean
Indian Ocean

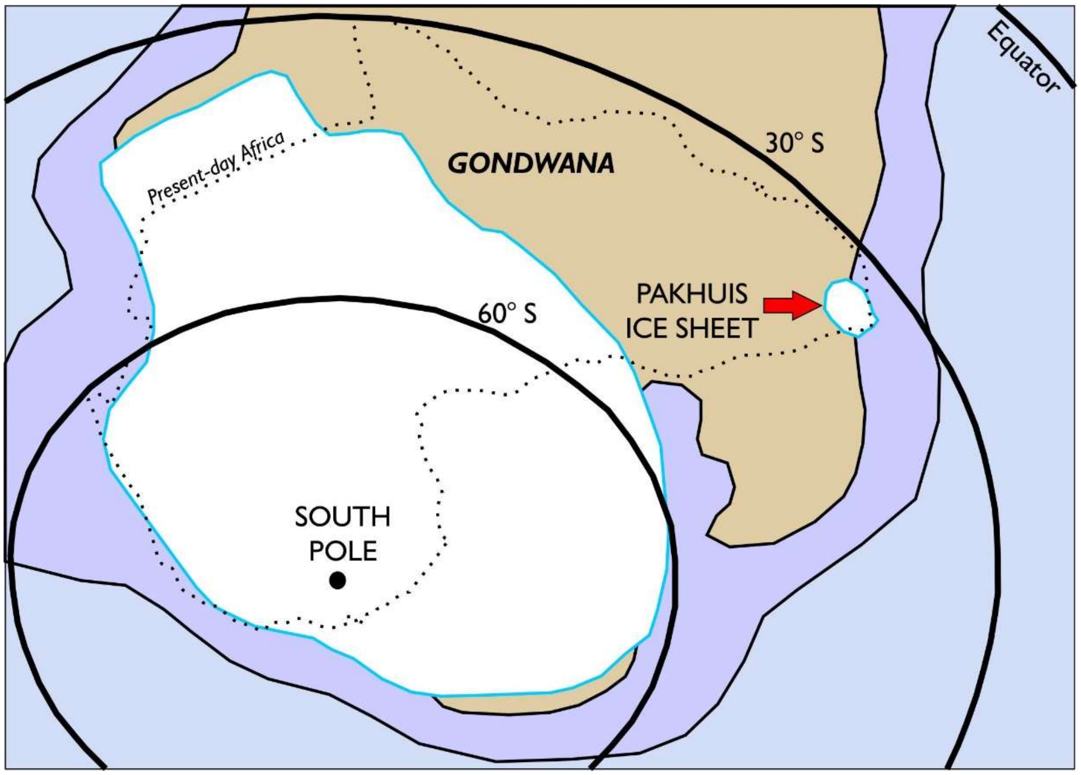


Figure S2. Location of the Pakhuis ice sheet relative to the main Hirnantian ice sheet (After Torsvik & Cocks, 2017).

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.

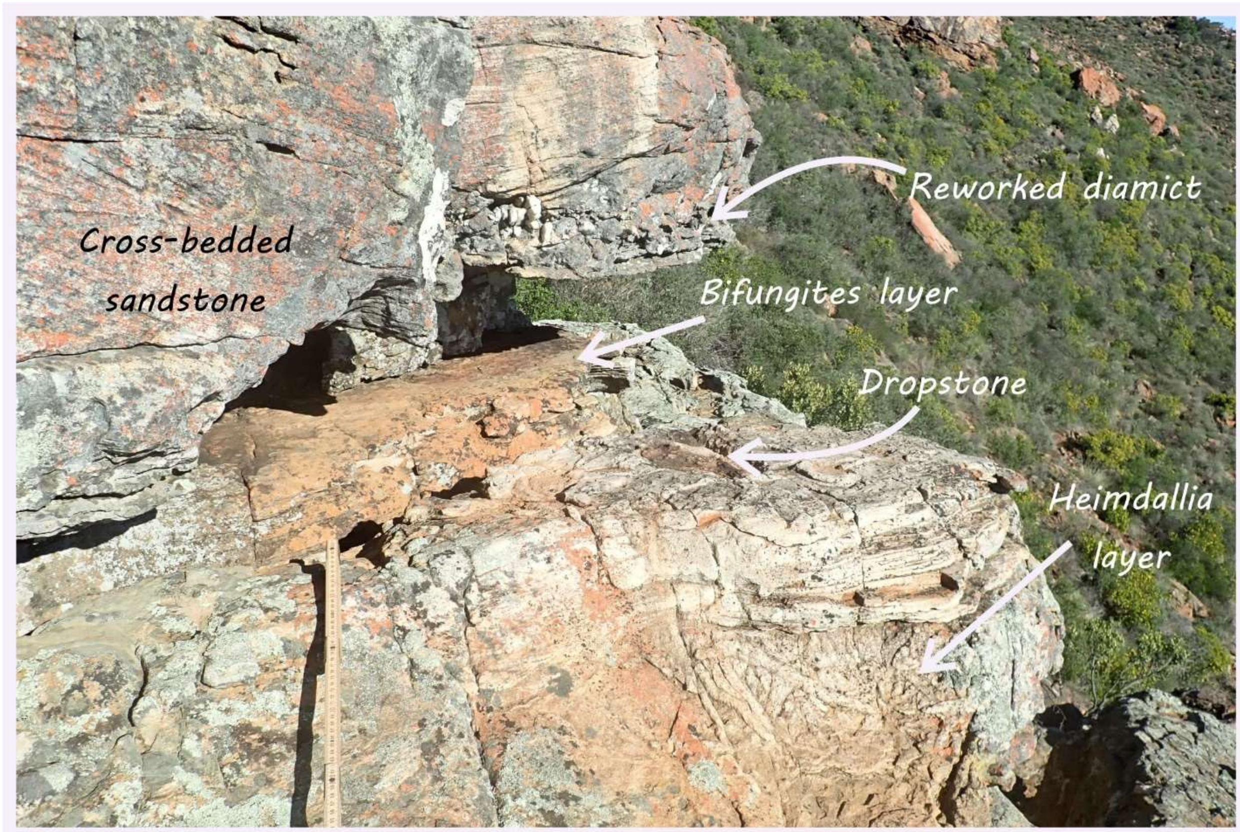


Figure S6. Trace fossil bearing strata are interspersed with glacial sediment, near top of section.

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).

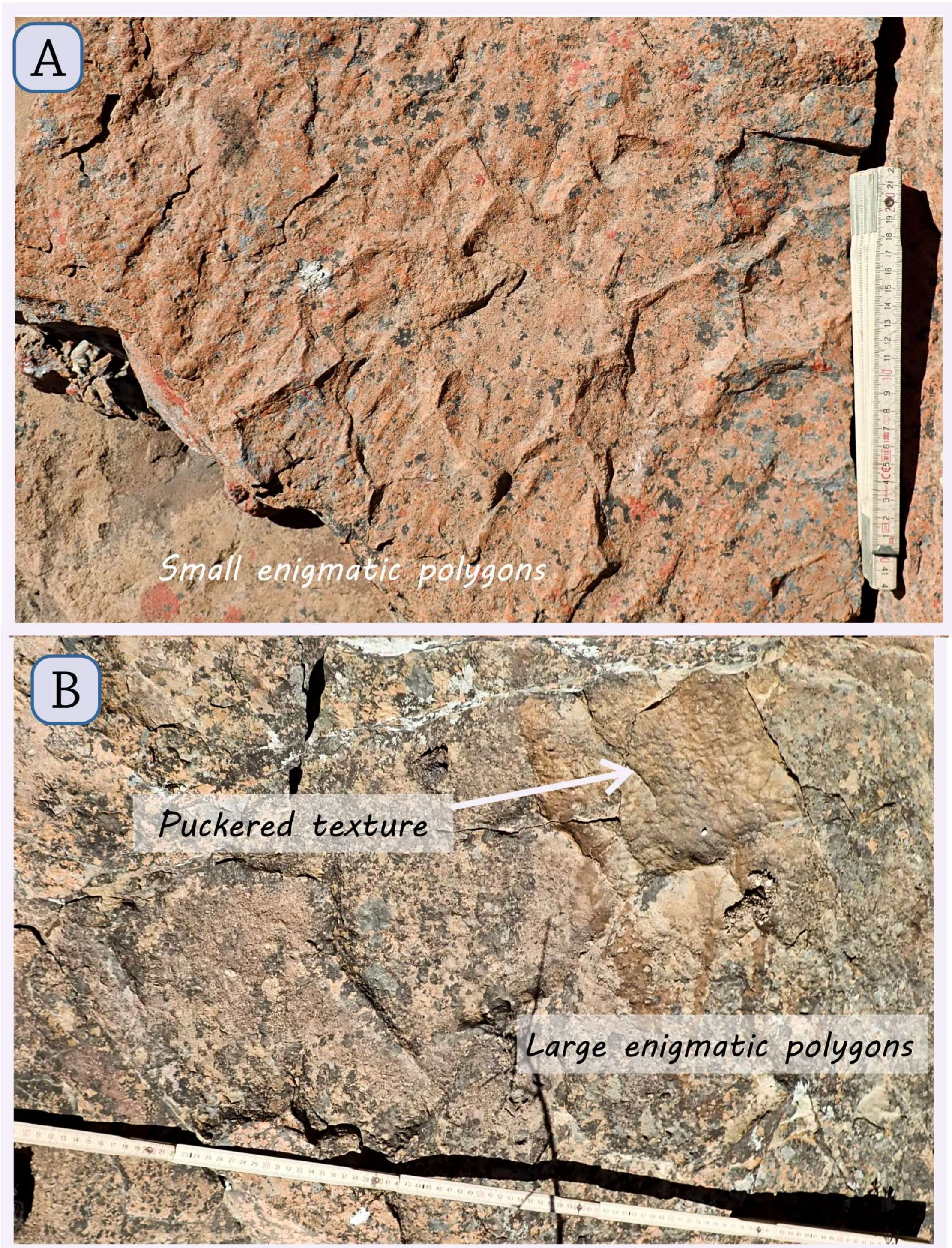


Figure S8. Enigmatic polygons that bear resemblance to petee structures (see also Fig. S5)

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).

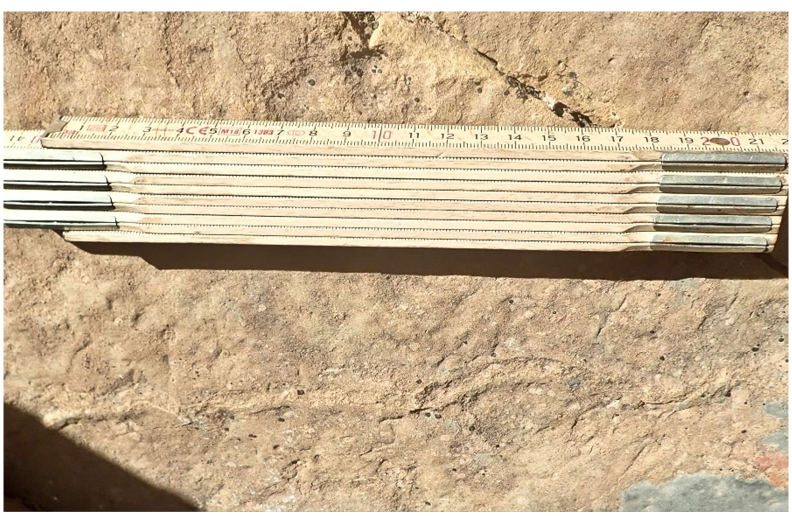


Fig. S9. Archaeonassa

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

Metaichna

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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