Evidence of permafrost in the Paleoproterozoic (c. 1.9 Ga) of Central Sweden

Jef Vandenberghe1 | Gerrit Kuipers2 | Frank F. Beunk1 | Keewook Yi3 | Frederik M. van der Wateren4

1Faculty of Science (Department of Earth Sciences), Vrije Universiteit, Amsterdam, the Netherlands
2Stroom 171, Assen, the Netherlands
3Division of Earth and Environmental Sciences, Korean Basic Science Institute, Ochang, South Korea
4Cas Oorthuyskade 23, Amsterdam, the Netherlands

Correspondence
Jef Vandenberghe, Vrije Universiteit, Faculty of Science (Department of Earth Sciences), De Boelelaan 1085, 1081 HV Amsterdam, the Netherlands.
Email: jef.vandenberghe@vu.nl

Abstract
This paper reports on an ice-wedge pseudomorph that formed and is preserved in metavolcanic host material that was later transformed to metamorphic solid bedrock. It has been dated to 1,895 ± 5 Ma by U–Pb geochronology of zircon in the bedrock, an Early Proterozoic age. Detailed observation of the deformation structures of the wedge points to an ice-wedge pseudomorph based on typical downbending around the wedge and vertical lamination in the inner part of the wedge due to slumping into the wedge after the ice melted, along with a few remains of lateral pressure structures (such as folds and upturned strata) in the adjacent host sediment. The interpretation of the wedge structure as an ice-wedge pseudomorph confirms previous work on this topic. This ice-wedge pseudomorph demonstrates for the first time the existence of permafrost at c. 1.9 Ga. It indicates that permafrost and associated conditions were present in lowlands at low latitude at discrete time intervals early in Earth’s history. Although some caution should be applied, mean annual air temperature appears to have been slightly below the freezing point at that time.

KEYWORDS
Central Sweden, early Proterozoic, ice-wedge cast, paleo-permafrost

1 INTRODUCTION

Specific landforms and sediment–structural perturbations have long been used for the recognition of former permafrost conditions (e.g., 1–5). The application of permafrost indicators—for instance ice-wedge pseudomorphs, sand wedges, and pingo remnants—may be very helpful in the reconstruction of former climatic conditions (e.g., 6–12 and references therein). Permafrost reconstructions are usually limited to the Quaternary or even to the last ice age (Weichselian, Wisconsinan stage) (e.g., 10,13–15). However, their application to a much larger time span may be envisaged given that the presence of cold climatic conditions prevailed in much earlier periods, as shown since Wegener.16 Evidence for pre-Quaternary cold conditions at various degrees of intensity has mainly been derived from the remnants of glacial sediments and landforms, for example in late Paleozoic times.17 In addition, the presence of (glaciogenic) loess in the Paleozoic has been reported.18 The hypothesis of very cold climatic conditions resulting in the formation of large ice sheets and frozen oceans during the Cryogenian period of the Neoproterozoic era (c. 720–635 Ma) has been debated for some time (references in 19,20). In this context, the concept of a “Snowball Earth” has been introduced,21,22 but critically discussed. However, although evidence for pre-Quaternary permafrost is rare, periglacial phenomena from the end-Cryogenian, in the form of cryogenic (sand) wedges, are widespread (references in 23–25). Paleosurface temperature reconstructions are often missing or vague, although the latter authors24 reliably derived indicative temperatures for the Cryogenian.

Prominent, global (?) ice ages occurred occasionally at different times during the Proterozoic but are conspicuously absent during a long Paleoproterozoic–Mesoproterozoic temperate interval (c. 2.3 Ga...
to 750 Ma\textsuperscript{26}, known as the “Proterozoic glacial gap.”\textsuperscript{22} However, the recent report of an ice-wedge pseudomorph and related periglacial structures\textsuperscript{27} in a c. 1.9 Ga lithified bedrock of the volcano-sedimentary Bergslagen Group (BG\textsuperscript{28}) in the Svecofennian orogen of the Fennoscandian Shield in Sweden suggests an as yet little known ice age during that supposed “glacial gap”, prior to the Cryogenian period. After the initial report,\textsuperscript{27} further work was carried out to better understand the significance of these periglacial features as to their thermal processes and the permafrost conditions under which they developed and to better constrain their age through radiometric dating. Here, this ancient ice-wedge pseudomorph and its environmental implications are discussed in detail, in particular evidence derived from this feature for the existence of permafrost. To our knowledge, the presence of early Proterozoic ice-wedge pseudomorphs elsewhere has been suggested previously, but based on rather vague photographs.\textsuperscript{29} The suggestion of ice-age conditions at low latitude and low elevation\textsuperscript{30,31} at c. 1.9 Ga should stimulate more detailed discussion of the periglacial features involved and their environmental implications.

2 \hspace{1cm} \textbf{GEOLOGICAL SETTING}

The BG forms a predominantly felsic metavolcanic to siliciclastic suite in the Svecofennian orogen of south-central Sweden (Figure 1). The Group has been dated in different, widespread locations to approximately 1.91–1.89 Ga.\textsuperscript{32} Shallow marine deposition prevailed, as witnessed by a variety of sedimentological, mineralogical and geochemical details, such as the occurrence of wave-base sediments and (stromatolitic) limestone,\textsuperscript{28} but occasionally subaerial conditions prevailed (for references see \textsuperscript{28,33}). Throughout Bergslagen the BG is accompanied by a synvolcanic intrusive suite of “older” granites, diorites, and gabbros (GDG suite\textsuperscript{32}). Petrographical details are given in Supporting Information nr 2. Bergslagen is

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Geology of the Ställdalen area, redrawn after Van Dongen (1986),\textsuperscript{36} showing supracrustal rocks of the Berglagen group folded into a tight to isoclinal, subvertically plunging anticline in the lower left and a syncline in the upper right (arrowed, dashed axial planes). The location of the ice wedge cast [RT90 coordinates 6642553/1449751] is indicated. Key: 1–5 = various metavolcanic formations; 6 = agglomerates and metagreywackes; 7 = phyllites and mica schists (1 to 7 in order of stratigraphic younging); 8 = metabasic flows, dykes and sills; 9 = various skarns: light and dark blue; 10 = Ställdalen granite (GDG-suite); 11 = fault zone. Coordinates refer to the Swedish RT90 net (kilometer-scale). The formation carrying the ice-wedge cast (2 on the map) is 1,675 m thick. The maximum exposed thickness of the BG in the map area is 8,750 m. Inset: geology of the Fennoscandian shield, with location of the main map indicated. Cross hatched: Archean; light gray: Paleoproterozoic Svecofennian orogen; black: Mesoproterozoic intrusions; diagonally hatched: Mesoproterozoic Sveconorwegian orogen; medium gray: Caledonian orogen; dark gray: Phanerozoic platform.}
\end{figure}
part of the accretional continental margin of the Columbia (or Nuna)-supercontinent (e.g., 34,35). Beunk and Kuipers28 interpreted Bergslagen as a micro-continental accreted block within the Svecofennian orogen. Fennoscandia during the period under study was situated in the tropical zone, as evidenced by paleomagnetic studies.30

The map area of Figure 1 was subject to Svecofennian amphibolite facies peak metamorphism. Although metamorphism and deformation tend to obliterate primary rock textures, preservation of even the finest sedimentary structures under high-grade conditions is often remarkably successful, particularly in non-reactive lithologies such as quartz-sandstones and felsic volcanics lacking penetrative shearing (e.g., 37-39).

3 | ICE-WEDGE PSEUDOMORPH AND ASSOCIATED DEFORMATIONS IN THE STUDIED SECTION

The most prominent feature in the described section is the wedge structure depicted in Figure 2. The wedge structure clearly cuts through the stratification while the layers of the bedded strata are sharply truncated at the sides of the wedge. It consists of two main parts: an internal part which substantiates the original wedge (a), and an external part consisting of micro-folds and occasional micro-faults (b). In its lower part the wedge form (a) is typified by sediment lamination parallel to the wedge margins (a1) and thus mimicking the wedge form (indicated in Figure 2). In the upper part of the wedge, the

![Figure 2](image-url)

**FIGURE 2** Field photographs of the ice-wedge pseudomorph in thin bedded metavolcanic sediments near Ställdalen (Figure 1). Associated with the wedge deformation are vertical laminations in the wedge fill a1 (black lines, shown schematically in Figure 4.), the homogenized infill a2 at the top of the wedge, the generally bent layering of host sediments next to the wedge (b, red lines), micro-downfaulting towards the inner pseudomorph (pink lines) and micro-folding in the host material next to the wedge (blue lines). Note the cryoturbation structure in the upper left corner that is older than the wedge (black dashed lines). Minor thrust faults are not marked. Zircon sample Bk1336 was taken from the top of the outcrop. More details on the petrographic composition are given in Supporting Information nr 2. Hammer shaft is c. 35 cm long. The outcrop surface is dipping at c. 10°, the bedding dips at 75° to N55E, and the outcrop surface is nearly at a right angle to the stratification (only ~5° oblique). Modified after photographs by Kuipers et al.27 [Colour figure can be viewed at wileyonlinelibrary.com]
Parallel lamination (a1) is only present near the wedge side, while the innermost part (a2) shows a much more homogenized structure. In the external part of the deformation (b) (directly adjacent to the wedge) micro-folds are preserved (see also Figure 3). Locally, subtle upturned strata are seen abutting the margin of the wedge structure (Figure 2). Micro-thrust faults and an occasional normal fault occur at greater distance from the wedge; they are not marked on the section of Figure 2 as they are probably not related to the wedge formation. Such faults, which are discontinuous and of limited length, are synsedimentary and widespread in the formation. Their origin is uncertain, but they might be the result of expansion/contraction during freeze/thaw cycles.

The combined wedge and surrounding deformation structures bear strong similarities to ice-wedge pseudomorphs, commonly known from deposits of Quaternary permafrost areas. This suggests that the (internal) wedge structure represents the fill of a thermal contraction crack after thawing of the ice that originally filled the wedge. The successive filling phases of the wedge are depicted schematically in Figure 4. The laminated structure (a1) is caused by the gliding of thawed muddy sediment from the surface thawed layer (“active layer”) into the void between still intact ice and the original wedge margin. The latter void gradually thickened during progressive thaw, leaving more space to be filled by muddy sediment and thus resulting in the parallel lamination of the wedge fill (a1). The relatively thick, homogenized fill at the top of the wedge (a2) is the result of more slump-like filling of the gap that formed at the top of the ice body during thawing. Thermal contraction cracking typically occurs in a polygonal network, but the small size of the exposure and poor outcrop conditions due to the presence of dense vegetation cover prevented the detection of such a pattern here.

Disappearance of the wedge ice caused conditions for subsidence in the sediments near the original wedge. This resulted in downward folding of thawed sediment along the wedge and occasional normal faulting in the still frozen sediment. Local upward bending (“upturning”) and small folds in the adjacent host sediments were caused by lateral pressure exerted during ice-wedge growth. Upward bending of the strata is exceptional as it was superseded later on by the effects of subsidence. Such a succession with compressional structures, such as micro-folds, and the later development of pressure-releasing features during ice-wedge melting, such as slump structures and normal faults, is similar to the structures caused by the

**FIGURE 3** Detail of left upper quadrant of Figure 2. Micro-folds near the (left) side of the wedge are probably due to lateral pressure exerted by the growing ice in the wedge. In contrast, the deformations at the top of the section have a considerably larger amplitude (50–60 cm) caused by periglacial loading (cryoturbations). The latter cryoturbations are clearly older than the former epigenetic ice wedge [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 4** Schematic representation of successive phases of wedge filling. F3 and F4 represent filling by homogenized a2-sediment, while F1 and F2 represent filling by laminated a1-sediment [Colour figure can be viewed at wileyonlinelibrary.com]
successive growth and decay of lenses of ground ice.\textsuperscript{41} These structures pre-dated Svecofennian deformation and metamorphism. The wedge structure and related deformation features were truncated by later erosion given that the original thawed surface layer ("active layer") is not present or, at least, is not exposed.

In addition, relatively large-scale deformation structures are notable (left of the wedge in Figure 2). Their amplitude is 50–60 cm as visible in the section, but this is a minimum size as their tops are not exposed or have been subsequently eroded (Figure 3). They seem to be unrelated to any Svecofennian tectonic deformation. These deformation structures are synsedimentary and thus older than the wedge which is epigenetic; this indicates they are not associated with the wedge. They closely resemble periglacial loadcasts\textsuperscript{42} and thus may most probably be interpreted as cryoturbations formed relatively shortly before but during the same time period as the ice wedge (\textsuperscript{43,44} and references there in). Small-scale cryoturbations were also noted by Kuipers et al.\textsuperscript{23}

A final remark must be made regarding the availability of information. Although the described section is of limited size, it contains very important information on permafrost occurrence and periglacial conditions at the time of deposition. In the surrounding region there are many outcrops of similar size and equivalent strata, although without reliable stratigraphic links to the main section in Figure 2. Many show cryoturbations similar to those shown in Figures 2 and 3, but none of these sections shows wedges.\textsuperscript{26} One illustration of cryoturbations from the work of Van Dongen \textsuperscript{36} in the present area and near the study site is presented in Supplementary Information Figure S1.

Alternatively, wedge structures as described here have sometimes been interpreted as tension cracks, for example as a result of seismic shaking (e.g., \textsuperscript{45,46}). They may occasionally share the downward synformal sedimentary infilling seen with ice-wedge pseudomorphs and can be deceptively similar to them. However, seismic wedges lack the compressional structural features derived from lateral expansion of a growing ice wedge, in contrast to the wedge structure described herein. Moreover, seismites are generally characterized by upward injection of fluidized sediment into pre-existing cracks, forming clastic dykes, often with upward splitting vents and mud (sand) boils at their top.\textsuperscript{47} In addition, seismic dykes and pipes are generally of equal width from bottom to top, which contrasts clearly with the cone shape of ice wedges and ice-wedge casts in cross-section as visible in Figure 2 (tapering downward). Other typical features of seismic extrusion in the form of extrusion pipes and sand volcanoes have not been observed in these strata. Although we cannot theoretically exclude a seismic origin for the structures under discussion, a periglacial origin of the deformations described in Figure 2 is consistent with the form and structural characteristics of present-day growing and degrading ice wedges.\textsuperscript{40} Finally, to stress this similarity, a photo from a vertical section of a typical ice-wedge pseudomorph of late Quaternary age from the eastern Netherlands is presented, showing the vertical lamination of the down-folded wedge fill and the down-faulted adjacent sediment (Figure 5).

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image}
\caption{For comparison, (part of) an ice-wedge pseudomorph in fluvo-eolian sediments at Borne (eastern Netherlands) probably of Weichselian Late Pleniglacial age. Note the rather thin central infill of the former wedge surrounded by a wider zone of downbending and downfaulted sediments. Length of hammer is c. 35 cm. Photo courtesy of ANWB, the Netherlands.}
\end{figure}

4 | ZIRCON U–PB AGE DETERMINATION

4.1 | Samples and analytical methods

We collected one rock sample (Bk1336) adjacent to and near the wedge top (Figure 2), and a second sample (Bk1337) c. 1.5 m stratigraphically higher. The rocks are oligoclase-bearing biotite quartzites exhibiting millimeter- to centimeter-scale microscopic modal banding in colour index, and a relict foliation expressed by greenish-brown biotites.

Zircons were concentrated at VU University, Amsterdam, by magnetic and centrifugal heavy liquid separations, followed by hand picking. Both samples delivered euhedral, bipyramidal, colorless, transparent and crystal clear 60–90 μm zircon grain size fractions. They were embedded in resin, polished, and imaged by backscattered electron and cathode luminescence microscopy, using a JEOL JSM-6610LV scanning electron microscope at KBSI in Seoul, Korea. Selected spots were U–Th–Pb isotopically analyzed by secondary ion mass spectrometry, using the SHRIMP-IIe instrument housed at the Korean Basic Science Institute, and the 1,099 Ma FC1 zircon standard.\textsuperscript{48} Analytical procedures followed routine guidelines.\textsuperscript{49} Data
reduction followed the user’s manual of Ludwig\textsuperscript{50,51} and was plotted subsequently.\textsuperscript{52}

4.2 | Geochronological results

The \(^{207}\text{Pb}/^{206}\text{Pb}\) zircon ages in sample Bk1336 cluster mostly between 1.88 and 1.91 Ga, which conform to the known age range of the BG.\textsuperscript{32} Results from Bk1337 also peak in the range 1.89–1.91 Ga (Figure 6). Both samples contain some additional, near-concordant, older, inherited grains, somewhat older than the dominant range, c. 1.92 Ga, up to 1.97 and 2.35 Ga. Eight concordant spots in Bk1336 define a weighted, \(^{204}\text{Pb}\)-corrected \(^{207}\text{Pb}/^{206}\text{Pb}\) age of 1895 ± 5 Ma (95% confidence) with a low mean squared weighted deviation (MSWD) of 0.23.\textsuperscript{52}

Sample Bk1336, taken from the rock adjacent to the wedge, therefore antedates wedge formation. Sample Bk1337 was taken stratigraphically higher in sediment overlying the wedge, inferring an age that postdates wedge formation. However, the obtained zircon ages are similar or overlap within confidence limits. This means that there is no resolvable time gap between wedge formation and the overlying sediments, giving a wedge formation age of between 1.89 and 1.90 Ga.

5 | PALEOCLIMATIC IMPLICATIONS

There is a primary relationship between air temperature and the presence of permafrost as seen from modern permafrost regions.\textsuperscript{3,6} However, this relationship in the past may have been slightly different from the modern analogs.\textsuperscript{53,54} In addition, modern temperatures at the southernmost permafrost boundary—reflecting the maximum temperatures for permafrost development—vary for different regions as reported in the literature. For instance, for the southern limit of discontinuous permafrost, variable values have been reported. For example, this limit approximates the \(-1^\circ\text{C MAAT (mean annual air temperature) isotherm in North America}\textsuperscript{7,55}\) whereas in Russia the MAAT of \(-4^\circ\text{C}\) is used to define the southernmost limit of permafrost\textsuperscript{56} and in China\textsuperscript{57} the MAAT of \(-3\) to \(-1^\circ\text{C}\) is assumed. Moreover, local conditions of vegetation cover, snow thickness and topography also determine the permafrost extent. To cope with these uncertainties, an error bar of ±2°C relative to the MAAT limits seems realistic.\textsuperscript{14,58} In conclusion, a conservative maximum MAAT of \(-2^\circ\text{C}\) may be assumed, or maximum 0°C for the mean annual temperature of the soil (MAST) in the (local) presence of permafrost. However, ice wedges are not typical for local permafrost, although they are common in continuous permafrost.\textsuperscript{3,6} In the latter case, the reconstructed temperatures may have been a few degrees lower.\textsuperscript{55,56}

FIGURE 6  Age histograms for \(^{207}\text{Pb}/^{206}\text{Pb}\) zircon spot ages ≤6% discordant of samples Bk1336 and Bk1337, for the age range 1870–1926 Ma, in 4-Ma age bins
the interpreted temperatures are considerably higher than the previously supposed −20°C during the Cryogenian. 22 In this respect, Ewing et al. 24 argued that lateral pressure structures in the (frozen) host sediment near to the wedge, as evidenced in the present case by occasional micro-folds, require sufficiently “warm” temperatures to enable ductile deformation (i.e., close to 0°C), although seasonal freezing might have caused the brittle, broadly synsedimentary faults. In addition, using the value of max. MAAT of −2°C for the Orosirian Period of the Paleoproterozoic Era requires additional caution because of different conditions compared with the Quaternary, particularly the 15% lower solar insolation values and higher atmospheric CO₂ content. 59

The present and previous observations and interpretations of the volcano-sedimentary facies of the BG indicate a hitherto poorly known, nearshore lowland environment with cold conditions at low latitude. 108 The observed ice-wedge pseudomorph indicates that the sediments into which it formed must have been exposed subaerially for a lengthy period. The structures in Bergslagen indicate permafrost environments at low latitude, suggesting the existence of intermittent arctic conditions during this period, within the c. 1.4 Ga long “Proterozoic glacial gap.” 22 For comparison, the development of permafrost in this region is about 100 Ma earlier than the terrestrial subglacial and glaciofluvial phenomena from the c. 1.8 Ga old King Leopold glaciation in the Kimberley basin in northern Australia. 60 Potential causes of these Precambrian permafrost conditions are beyond the scope of discussion for this paper, but might be related to explosive volcanism, a preponderance of land masses at low latitudes raising Earth’s albedo, and lower solar insolation, or their combined effects. Regardless, the identified ice-wedge pseudomorph at 1.8–1.9 Ga contradicts the idea of a continuous terrestrial ice sheet as already proposed for the younger “Cryogenian.” 24

6 | CONCLUSIONS

An ice-wedge pseudomorph was formed and is preserved in metamorphic metavolcanic solid bedrock. Its age has been determined at c. 1895 ± 5 Ma by U–Pb analysis of the zircons in the bedrock, that is in the Orosirian (Paleoproterozoic).

Detailed observation of the deformation structures of the wedge indicates an ice-wedge pseudomorph based on the characteristic down-folding at the wedge sides and the vertical lamination in the inner part of the wedge due to subsidence and slumping into the wedge after the wedge-ice melted, and the few remains of lateral pressure (micro-folding) in the host sediment. Interpretation of this wedge structure as an ice-wedge pseudomorph confirms previous work on this feature. 27

The ice-wedge pseudomorph points indicate now the former existence of permafrost at 1.8–1.9 Ga. It shows that permafrost (conditions) has (have) been present at discrete time intervals early in Earth’s history. This is about 1 Ga older than previously demonstrated at c. 720–635 Ma, that is during the Cryogenian (Neoproterozoic era). Presumably, MAAT was slightly below the freezing point at that time.

ACKNOWLEDGEMENTS

G.K., F.F.B. and F.M.vdW. acknowledge funding for fieldwork and laboratory costs from the Dutch Dr. Schürmann Foundation for Precambrian research (www.dr-schurmannfonds.nl). The ANWB is thanked for allowing the use of the photograph in Figure 5. The authors are very grateful for the constructive comments provided by Anthony M. Spencer and Cunhai Gao and two anonymous reviewers.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available on request.

ORCID

Jef Vandenberghe https://orcid.org/0000-0001-9910-1319

REFERENCES

1. Cailleux A, Guilhauc A, Tricart J. Phénomènes pergiglaicaires d’âge prémésumé Würm. Cartes des phénomènes pergiglaicaires quaternaires en France. Carte Géologique Détaillee de la France. Mémoires 1956: 1–34, Planches 111.
2. Black RF. Periglacial features indicative of permafrost: ice and soil wedges. Quatern Res. 1976;6(1):3-26.
3. French HM. The periglacial environment. 1st ed. London, UK: Longman; 1976.
4. Velichko AA. Paleogeography of Europe during the Last One Hundred Thousand Years. Moscow, Russia: Nauka; 1982 (Atlas monograph in Russian with abstracts and legends in English).
5. Van Vliet-Lanoë B. Dynamics and extent of the Weichselian permafrost in Western Europe (substage 5E to stage 1). Quat Int. 1989;314: 109-113.
6. Péwé TL. Paleoclimatic significance of fossil ice wedges. Blü Volgglac. 1966:15:65-73.
7. Brown RJE. The relation between mean annual air temperature and ground temperature in the permafrost regions of Canada. In: Permafrost (International Conference Proceedings). National Research Council of Canada: Publication 1287. Washington, DC: National Academy of Sciences; 1966:241-246.
8. Karte J. Räumliche Abgrenzung und regionale Differenzierung des Periglazials. Bochumer Geogr Arbeiten. 1979:35:1-211.
9. Washburn AL. Permafrost features as evidence of climatic change. Earth Sci Rev. 1980;15(4):327-402.
10. Vandenberghe J, Pissart A. Permafrost changes in Europe during the last glacial. Permafr Periglac Proc. 1993;4(2):121-135.
11. Huijzer AS, Isarin RFB. The reconstruction of past climates using multi-proxy evidence: an example of the Weichselian Pleniglacial in northwestern and Central Europe. Quat Sci Rev. 1997;16(6):513-533.
12. Vandenberghe J, Coope GR, Kasse C. Quantitative reconstructions of palaeoclimates during the last interglacial-glacial in western and Central Europe: an introduction. J Quat Sci. 1998;13(5):361-366.
13. Vandenberghe J. Permafrost during the Pleistocene in northwest and central Europe. In: Paepe R, Melnikov V, eds. Permafrost Response on Economic Development, Environmental Security and Natural Resources. Dordrecht, the Netherlands: Kluwer; 2001:185-194.
14. Vandenberghe J, Lowe J, Coope GR, Litt T, Zöller L. Climatic and environmental variability in the Mid-Latitude Europe sector during the last interglacial-glacial cycle. In: Battarbee R, Gasse F, Stickley C, eds.
Past Climate Variability through Europe and AfricaPEPPII Conf Proc. Dordrecht, the Netherlands: Kluwer; 2004:393-416.

Vandenbergh et al. J. French HM, Gorbonov A, et al. The last permafrost maximum (LPM) map of the northern hemisphere: permafrost extent and mean annual air temperatures, 25–17 ka BP. Boreas. 2014;43(3):652-666.

Wegener A. Die Entstehung der Kontinente und Ozeane. Viertel. umgelagerte Auflage. Braunschweig, Germany: F. Vieweg & Sohn Akt.-Ges.; 1929.

Soreghan G, Soreghan M, Hamilton M. Origin and significance of loess in late Paleozoic western Pangaea: a record of tropical cold? Palaeoecol Palaeoclim Palaeoecol. 2008;268(3–4):234-259.

Soreghan G, Soreghan M, Poulsen C, et al. Anomalously cold in the Pangaean tropics. Geology. 2008;36(8):659-662.

Harland WB. Origins and assessment of snowball earth hypotheses. Geol Mag. 2007;144(4):633-642.

Arnaud E, Halverson GP, Shields-Zhou G. The geological record of Neoproterozoic glaciations. London, UK: Geological Society of London; 2011.

Hoffmann PA. Neoproterozoic snowball earth. Science. 1998;28:1342-1346.

Hoffman PF, Schrag DP. The snowball earth hypothesis: testing the limits of global change. Tern Nov. 2002;14(3-4):129-145.

Williams GE. Precambrian permafrost horizons as indicators of palaeoclimate. Precambrian Res. 1986;32(2-3):233-242.

Ewing R, Eisenman I, Lamb M, Poplick L, Maloof A, Fischer W. New constraints on equatorial temperatures during a late Neoproterozoic snowball earth glaciation. Earth Planet Sci Lett. 2014;406:110-122.

Hambrey MJ, Harland WB. Earth pre-Pleistocene glacial record. Cambridge, UK: Cambridge University Press; 1981.

Eyles N. Glacio-epochs and the supercontinent cycle after ~3.0 Ga: tectonic boundary conditions for glaciation. Palaeogeogr Palaeoclim Palaeoecol. 2008;258(1-2):89-129.

Kuipers G, Beunck FF, Van der Wateren FM. Periglacial evidence for a 1.91–1.89 Ga old glacial period at low latitude, Central Sweden. Geol Today. 2013;29(6):218-221.

Kuipers G, Beunck FF, Van der Wateren FM. Periglacial evidence for a 1.91–1.89 Ga old glacial period at low latitude, Central Sweden. Geol Today. 2013;29(6):218-221.

Kuipers G, Beunck FF, Van der Wateren FM. Periglacial evidence for a 1.91–1.89 Ga old glacial period at low latitude, Central Sweden. Geol Today. 2013;29(6):218-221.

Rodriguez-Lopez JP, Brigitte Van Vliet-Lanoë B, Lopez-Martinez J, Martin-Garcia R. Scouring by rafted ice and cryogenic patterned ground preserved in a Palaeoproterozoic equatorial proglacial lagoon succession, eastern India, Nuna supercontinent. Mar Pet Geol. 2021;123:104766.

Kuipers G, Beunck FF, Van der Wateren FM. The Paleoproterozoic Gryttynan Field in the Svecofennian Orogen, west Bergslagen, Central Sweden: structure, stratigraphy and age. Norweg J Geol. 2018;98(3):333-357. https://doi.org/10.17850/njg98-3-05

Kuipers G, Beunck FF, Valbracht PJ. Early Palaeoproterozoic continental shelfies from western Bergslagen, Central Sweden: III. Geodynamic inferences. Precambrian Res. 1991;52(3-4):231-243.

Allen RL, Lundström I, Ripa M, Simeonov A, Christoffersen H. Facies analysis of a 1.9 Ga continental margin, back-arc, felsic caldera province with diverse Zn-Pb-Ag-(Cu-Au) sulfide and Fe oxide deposits, Bergslagen region, Sweden. Econ Geol. 1996;91(6):979-1008.

Van Dongen J. Geology of the Stöldalen area. MSc thesis, Universiteit van Amsterdam, The Netherlands; 1986:1-132.

Roep TB, Linthout K. Precambrian storm wave-base deposits of early Proterozoic age (1.9 Ga), preserved in andalusite-cordierite-rich granofels and quartzite (Råmsberg area, Värmland, Sweden). Sed Geol. 1989;61(3-4):239-251.

Le Heron DP, Tofaif S, Vandyk T, Ali DO. A diamictite dichotomy: glacial conveyer belts and olistostromes in the Neoproterozoic of Death Valley, California, USA. Geology. 2017;45(1):51-54.

Sultan L, Pinski-Buland A. Depositional environments at a Palaeoproterozoic continental margin, Västervik Basin, SE Sweden. Precambrian Res. 2006;145(3-4):243-271.

Vandenbergh et al. J. Ice-wedge casts and involutions as permafrost indicators and their stratigraphic position in the Weichselian. Proc 4th Int Conf Permafr. Fairbanks. 1983:1298–1302.

Bertran P, Andrieux B, Bateman M, Font M, Mouchel K, Sicilia D. Features caused by ground ice growth and decay in Late Pleistocene fluvial deposits, Paris Basin, France. Geomorphology. 2018;310:84-101.

Van Loon AJ, Pisarska-Jarmoñy Z, Woronko B. Sedimentological distinction in glacial sediments between load casts induced by periglacial processes from those induced by seismic shocks. Geol Quart. 2020;64(3). https://doi.org/10.7306/gq.1546

Vandenbergh et al. J. Earth-ice wedge casts and involutions as permafrost indicators and their stratigraphic position in the Weichselian. Proc 4th Int Conf Permafr. Fairbanks. 1983:1298–1302.

Vandenbergh et al. J. Cryoturbations. In: Clark MJ, ed. Advances in Periglacial Geomorphology. Chichester, UK: John Wiley and Sons; 1988:179-198.

Montenat C, Barrier P, d’Estevou PO, Hilbsch C. Seismites: an attempt at critical analysis and classification. Sediment Geol. 2007;196(1-4):5-30.

Mazumder R, Rodríguez-López JP, Arima M, Van Loon AJ. Palaeoproterozoic seismites (fine-grained facies of the Chalabasa formation, East India) and their soft-sediment defomation structures. Geol Soc Lond Spec Publ. 2009;323(1):301-318.

Audemard AF, de Santos F. Survey of liquefaction structures induced by recent moderate earthquakes. Bull Int Assoc Engin Geol. 1991;44:1-5-16.

Francis JB, Millar JD. Precise U-Pb ages of Duluth complex and related mafic intrusions, northeastern Minnesota: geochemical insights to physical, petrogenetic, paleomagnetic, and tektomagnatic processes associated with the 1.1 Ga midcontinent rift system. J Geophys Res. 1993;98:13997-14013.

Choi M, Cheong W, Ernst WG, Yi K, Kim J. SHRIMP U-Pb ages of detrital zircons in metasedimentary rocks of the central Opchen fold-thrust belt, Korea: evidence for tectonic assembly of Palaeozoic sedimentary protoliths. J Asian Earth Sci. 2013;63:234-249.

Ludwig KR. User’s manual for Isoplot 3.6: a geochronological toolkit for Microsoft excel. Berkeley Geochronology Center Special Publication 2008:1-77.

Ludwig KR. SQUID 2: a user’s manual. Berkeley Geochronology Center Special Publication 2009 2.1-100.

Kuipers G, Beunck FF, Van der Wateren FM. A 1.9 Ga glacial sedimentary facies association at low palaeolatitude from the Gryttynan field, Bergslagen Sweden [Submitted].

French HM. The periglacial environment. 3rd ed. Chichester, UK: Wiley; 2007.

Murton J, Kolstrup E. Ice-wedge casts as indicators of palaeoclimate. Geology 1997;25(2):155-170.

Brown RE. The distribution of permafrost and its relation to air temperature in Canada and the USSR. Arct. 1960;13:163-177.

Romanovskii NN. Distribution of recently active ice and soil wedges in the USSR. In: Church M, Slamyaker O, eds. Field and theory:
Lectures in geocryology. Vancouver, Canada: University of British Columbia Press; 1985:154-165.

57. Zhao L, Jin H, Li C, et al. The extent of permafrost in China during the local last glacial maximum (LLGM). Boreas. 2014;43(3):688-698.

58. Van Huissteden J, Vandenberghe J, Pollard D. Palaeotemperature reconstructions of the European permafrost zone during marine oxygen isotope stage 3 compared with climate model results. J Quat Sci. 2003;18(5):453-464.

59. Feulner G. The faint young sun problem. Rev Geophys. 2012;50(2):1-29.

60. Williams GE. Subglacial meltwater channels and glaciofluvial deposits in the Kimberley Basin, Western Australia: 1.8 Ga low-latitude glaciation coeval with continental assembly. J Geol Soc Lond. 2005;162(1):111-124.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Vandenberghe J, Kuipers G, Beunk FF, Yi K, van der Wateren FM. Evidence of permafrost in the Paleoproterozoic (c. 1.9 Ga) of Central Sweden. Permafrost and Periglac Process. 2021;32:169–177. https://doi.org/10.1002/ppp.2094