Ediacaran to early Cambrian weathering of the Kautokeino Greenstone Belt in Finnmark, northern Norway

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During exploration for copper and gold in the Bidjovagge area north of Kautokeino, northern Norway, in the Kautokeino Greenstone Belt, more than 20 holes were drilled through 10–20 m of Cambrian marine sandstones and shales, 5–8 m of lower Cambrian fluvial sandstones, and into the underlying Precambrian metamorphic basement, which appeared weathered. The drillholes start in marine Cambrian sedimentary rocks and continue with fluvial sandstones. The basal conglomerate of the fluvial sandstone is ‘floating’ in a 10 to 15 m-thick Ediacaran–early Cambrian saprolite. The weathering profile provides information about the environmental conditions in a particularly fascinating period of the Earth’s history, the late Ediacaran to early Cambrian. The fluvial sandstone between the basement and the marine sediments has protected the weathered basement from marine erosion. Newly formed clay minerals (kaolinite, smectite, illite and mixed layer minerals) can be found down to 10–15 m below the sub-Cambrian peneplain, and hematite can be found down to more than 100 m on faults and fractures.

One of the clay-rich samples from the saprolite profile yielded an age of 541 ± 6.8 Ma using the K–Ar method. This age confirms that the weathering process in the sub-Cambrian peneplain took place before the marine transgression in early Cambrian (i.e., at approximately 520 Ma) and also before the deposition of the fluvial sandstone. The types of clay minerals, such as kaolinite and smectite, support a model with a humid and warm climate in the Ediacaran with increasing oxygen content in the atmosphere in early Cambrian reaching a maximum at 520 Ma, based on Se/Co ratios in marine pyrite.

An abundance of hematite has been found precipitated in faults and fractures down to more than one hundred metres depth. It is suggested that this hematite was crystallised from iron-hydroxides. The hematite is clearly related to tectonic structures and is suggested to have formed at a later stage than the clay minerals.

The composition of the fluvial sandstone indicates movements of the shear zones in early Cambrian time related to the later stages of the Timanian collision (Arctida–Baltica) at around 540 Ma. Such a tectonic event can cause seismic pumping of oxygen-rich surface water deep into the basement and may explain the deep occurrences of hematite.


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Introduction

A major event in international geology is the weathering and peneplanation of the Precambrian basement and the marine transgression during early Cambrian time (Nielsen & Skovsbo, 2015). This is the period after the Varangerian ice age, ending at ~590 Ma, with high global CO$_2$ contents in the atmosphere (Schmitt, 1999) resulting in strong greenhouse effects. The early Cambrian marine transgression resulted in an increased supply of nutrients to the ocean and high organic production. There was a rapid increase in the oxygen content of the atmosphere from the end of the Ediacaran (approximately 4%) to the middle part of the early Cambrian (25% at around 525 Ma according to Large et al. (2019)).

High contents of CO$_2$ in the atmosphere gave a low pH of the rainwater, with high potential for chemical weathering (Liivamägi et al., 2014, 2015). During the Ediacaran and Cambrian there was no plant cover on land. The lack of vegetation promoted erosion and transport by wind, causing deposition of aeolian sediments in the sea areas. Aeolian sand and silt grains commonly have coatings of iron hydroxides containing nutrients like phosphorus, the supply of which to the sea resulted in higher organic activity (Drummond et al., 2015). This is seen by carbon-coating on some of the marine quartzites and the formation of, e.g., phosphorites (Bjørlykke et al., 2021).

In most areas along the Caledonian front in Norway (Figs. 1 & 2), the early Cambrian marine transgression has eroded the Ediacaran weathered profile (saprolite), with a few exceptions, as reported by Vogt (1967) and Gabrielsen et al. (2015). During the exploration for copper and gold in the Kautokeino area (Finnmark county), several holes were drilled through the autochthonous Cambrian sedimentary rocks and into a saprolite at the top of the sub-Cambrian peneplain in the Kautokeino Greenstone Belt at Bidjovagge. This study of the early Cambrian/Ediacaran weathering has been entirely dependent on access to these drillcores from the exploration programme (Fig. 3 and Table 1).

Figure 1. Simplified geological map of the investigated area, showing the Kautokeino Greenstone Belt KkGB and the Karasjokk Greenstone Belt KGB. (From: Torske & Bergh, 2004).
Figure 2. Detailed geological map of parts of the Bidjovagge area. The exploration area is marked with a grey rectangle. (Norw. Geol. Survey, 2020).

Figure 3. Map showing the exploration area in Bidjovagge, with all boreholes marked. The N-3000 profile is also marked.

Table 1. Exploration profiles N-3000, showing borehole (BH) distances from the main profiles, direction of the deviated boreholes, deviation of the boreholes (vertical = 90°), and total lengths of boreholes (m), i.e., ‘Drillers Depths’ (DD).

<table>
<thead>
<tr>
<th>BH No.</th>
<th>Profile No.</th>
<th>BH ID</th>
<th>BH distance from profile (m)</th>
<th>Geographical Direction</th>
<th>Deviation (vertical = 90)</th>
<th>Total length (DD) (m)</th>
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</thead>
<tbody>
<tr>
<td>Bh-1</td>
<td>N-3000</td>
<td>B</td>
<td>W-434.52</td>
<td>270</td>
<td>57</td>
<td>108</td>
</tr>
<tr>
<td>Bh-2</td>
<td>N-3000</td>
<td>C</td>
<td>W-434.50</td>
<td>270</td>
<td>70.5</td>
<td>114</td>
</tr>
<tr>
<td>Bh-3</td>
<td>N-3020</td>
<td>D</td>
<td>W-430</td>
<td>270</td>
<td>73</td>
<td>145</td>
</tr>
<tr>
<td>Bh-4</td>
<td>N-2980</td>
<td>D</td>
<td>W-423</td>
<td>270</td>
<td>68.6</td>
<td>132</td>
</tr>
<tr>
<td>Bh-5</td>
<td>N-3000</td>
<td>A</td>
<td>W-400</td>
<td>270</td>
<td>55</td>
<td>170</td>
</tr>
<tr>
<td>Bh-6</td>
<td>N-3020</td>
<td>A</td>
<td>W-400</td>
<td>270</td>
<td>66.4</td>
<td>165</td>
</tr>
<tr>
<td>Bh-7</td>
<td>N-3000</td>
<td>F</td>
<td>W-407</td>
<td>270</td>
<td>70</td>
<td>168</td>
</tr>
<tr>
<td>Bh-8</td>
<td>N-2980</td>
<td>C</td>
<td>W-385</td>
<td>270</td>
<td>60</td>
<td>156</td>
</tr>
</tbody>
</table>
The Ediacaran to early Cambrian, Timanian Orogeny (Arctida–Baltica collision; Kuznetsov 2006), as recorded in the eastern part of Varanger Peninsula (Roberts 1995, Gabrielsen et al. 2022), resulted in the upheaval and erosion of the Fennoscandian Shield in northern Norway (Andresen et al., 2014). The resulting network of faults and fractures from these tectonic events, affected the drainage pattern and therefore the intensity of meteoric weathering along these structural zones. Seismic pumping of surface and groundwater into these structures due to changes in the volume of water in fault-zones, may have influenced water-rock interactions in the basement and promoted oxidation of Fe$^{2+}$ to Fe$^{3+}$ (Muir-Wood & King, 1993; Olesen et al., 2004; Li et al., 2017; Bjørlykke et al., 2021).

Bedrock geology of the Kautokeino area

The Kautokeino Greenstone Belt with copper and gold ores

The Kautokeino Greenstone Belt (KkGB), which is part of the Svecokarelian orogen, is situated on the western side of the Archaean Jergul Gneiss dome (Figs. 1 & 2). It consists of volcanic rocks, diabase dykes, tuffites with biotite, black schists, carbonates of the Kvenvik Formation, and sandstones of the Caravarre Formation (Holmsen et al., 1957; Olesen & Sandstad, 1993; Bingen et al., 2016). A gabbro associated with the volcanic sequence in the KkGB has been dated (U-Pb, zircon) at 2137 ± 5 Ma (Bingen et al., 2016). The volcanites and tuffites are commonly altered by albitisation and scapolitization processes (Melezhik et al., 2015). The sodium alteration process preceded the ore formation and did not oxidise the graphitic schist (Ettner et al., 1993). Of special interest in relation to the weathering process is the elevated biotite content of the tuffites (Bjørlykke et al., 1987).

The KkGB belt was intruded by granodiorites during the Svecofennian orogeny, at 1865–1888 Ma (Bingen et al., 2016). There are two generations of mafic dykes in the Bidjovagge area. The earlier dykes have a high content of magnetite and are probably an important source of iron in the fault zones. Dykes of the second generation are light grey and albite rich (leucodiabase) and occur in the shear zones and are probably of the same age as the granodiorite (approx. 1.87 Ga).

The Bidjovagge ore deposit is related to Svecofennian, N–S-striking shear zones and belongs to the iron-oxide-copper-gold deposits (IOCG). The ore-forming fluid must have been highly oxidating, and the fluids have formed sharp oxidation fronts in the graphitic schists (Fig. 4). The formation of the ore can be divided into two main phases. The first phase is characterised by bornite, tellurides, some chalcocite and chalcopyrite, magnetite, davidite and gold, whereas chalcopyrite together with carbonates in open veins dominates the second phase (Fig. 5). The sulphide mineralisation may locally have influenced redox conditions in the mining area during the Ediacaran to Cambrian weathering.
Figure 4. Vertical section through the exploration area at Bidjovagge, with eight of the borehole trajectories indicated. Identification of hematite precipitation in the borehole cores are marked with “H”, and the positions of known copper-gold ores are shown (see colour guide).

Figure 5. A picture of a polished slab of the ore from Bidjovagge featuring characteristic distribution of ore-forming minerals in the albite rock. The first generation of copper minerals are bornite (black) and a later stage with chalcopyrite (yellow).
The sub-Cambrian peneplain and fluvial sandstones

The sub-Cambrian peneplain in central and east Finnmark has been studied in detail by Holtedahl (1932) and Føyn (1967), and they found that the peneplain changed from an uneven surface under the Varangerian tillites in the Varangerfjord to a flat surface beneath the early Cambrian marine sediments farther to the south and west. Føyn also found that the peneplain today dips at 2 to 3 degrees towards NW under Cambrian sedimentary rocks in Finnmark. The peneplain along the Caledonian front in west Finnmark and Troms (Fig. 1) has been studied by Holmsen (1956), Føyn (1967), Vogt (1967) and Bjarlykke et al. (1979) (Fig. 1) and commonly only the uppermost 1 metre of the basement shows signs of weathering.

The upper part of the weathering profile (saprolite) has probably been eroded by waves and tidal currents during the early Cambrian marine transgression over large areas of the Fennoscandian Shield.

There are exceptions to the erosion model and Vogt (1967) described a deep weathering zone in a Precambrian quartz-syenite at Ruogoava, close to Gjevdnevann, northern Troms. According to Vogt, the weathering of the quartz-syenite started 9 m under the conglomerate with the alteration of micas, and at 4 m depth below the conglomerate the feldspars become bleached. The uppermost half metre of the weathering zone consists of an unconsolidated yellow-green sediment, consisting of clay, kaolinite, quartz and feldspar. The lower part of the Cambrian conglomerate was cemented by hematite.

In the Bidjovagge area (Fig. 2) there is a saprolite development in the uppermost 5–15 metres of the Precambrian basement, under a fluvial sandstone (Fig. 4). The sandstone may have protected the altered basement from being eroded during the early Cambrian marine transgression. There is a gradual change downwards, from greenish-grey mudstone (saprolite) with no Precambrian structures, to ‘normal’ volcanosedimentary Precambrian rocks. Below the saprolite there is an extensive oxidation of iron-rich minerals. Hematite occurs in tectonic breccias with calcite and in veins with quartz down to more than 100 metres below the peneplain (Fig. 4).

Fluvial sandstone was deposited in the Bidjovagge area (Fig. 4) in a river valley of Cambrian age, which was probably related to the N–S oriented shear zone (Ciegnaljokka-Boagana lineament -- CBL) close to Bidjovagge. The fluvial sandstones are characterised by a quartz-feldspathic to arkosic composition, with coarse-grained reddish feldspar and quartz. Thin layers of greenish to greyish shales are interbedded with the sandstones. The fluvial sandstone starts with a conglomerate, deposited on the surface of weathered basement rocks (Fig. 6). Most pebbles are of well-rounded quartzites, with diameters of 1 to 2 cm. The fluvial sequence continues with a feldspathic sandstone of alternating red and grey colour (Fig. 7). Approximately 4–5 m above the basement there are benches of angular mixtites (Fig. 8). The source was probably the red granodiorite intrusion of the Råiseatnu Complex to the west, which indicates a short transport, and probably related to movements along the CBL-lineament. The Timanian orogeny, peaking at around 560-540 Ma in eastern Finnmark (Larionov et al., 2004, Andresen et al., 2014) probably caused movements along the fault zones and associated erosion of the Råiseatnu Complex.

From Carajavvri in the Caskias area (Fig. 1), Holmsen (1956, 1957) described a 2 m-thick basal conglomerate, which he interpreted to be a tillite. The rounded clasts of apparently local origin may alternatively indicate a fluvial reworking of a weathered basement and may be correlated with the fluvial sandstone at Bidjovagge. There are no outcrops of fluvial sandstones between Carajavvri and Bidjovagge and a connection between the two localities indicating a broad river valley is uncertain. The thickness of the fluvial sequence indicates a minimum difference in elevation of the sub-Cambrian peneplain in the order 15–20 m.
Figure 6. Basal-conglomerate at Bidjovagge, borehole N-324A, 55.4 m depth and 0.4 m below the subcambrian peneplain. The pebbles have sunk into the muddy saprolite. Diameter of all cores is ~5 cm.

Figure 7. Borehole 302-D, 33 to 41 m depth. The fluvial sandstone consists dominantly of quartz, with grey, green and reddish colours, and arkoses with less rounded feldspar grains and often a reddish matrix.

Figure 8. Close up on a mixtite facies in the fluvial sandstone. The poorly sorted material and angular fragments of reddish granitic composition indicate a very local source.
Marine Cambrian sandstones and shales

The early Cambrian marine sequence that was deposited onto the fluvial sandstones is part of the Dividal Group (Føyn 1967). At the base, there is also a grey, quartz-rich conglomerate with cobbles up to 20 cm in size. The conglomerate is overlain by a light, sometimes bluish quartzite, with a variable thickness, from 0.5 to 10 m. It is followed by alternating sandstones and a green to dark grey shale (Fig. 9). The upper part of the autochthonous sequence is composed of alternating red and green shales. The whole succession was deposited in a tidal/shallow-marine environment. Føyn (1967) suggested that some of the sand may have an aeolian origin.

The basal Cambrian beds at Bidjovagge can be correlated with the sections both at Averagge to the west (Vogt, 1967) and at Aksojokka to the east (Føyn, 1967). Nielsen & Skovsbo (2011, fig. 46) proposed to place the marine transgression in Averagge and Aksojokka to the Dominopolitan stage sequence, i.e., (LC1-5), which is chronostratigraphically at around 520 Ma (A.T. Nielsen, pers. comm., 2021).

The autochthonous early Cambrian sequence is bounded upwards by a major hiatus, the Hawke Bay event (Bjørlykke et al., 2021), which represents a regression and a break in the stratigraphic succession representing approximately 5–7 mill. yrs (Nielsen & Skovsbo, 2015). The break is marked by a conglomerate with phosphorite pebbles. The surface of the early Cambrian succession was probably oxidised and weathered during the Hawke Bay regression. However, at Bidjovagge, there are no signs of deep weathering related to this event. The conglomerate is overlain by the Middle Cambrian Alum Shale Formation.

The Caledonian nappes commonly cut the autochthonous sequence at the Alum Shale level or even lower in places, within lower Cambrian shales. It is difficult to estimate how far southeast the lower allochthonous nappes were thrusted; there is, however, reason to believe that the lowest nappe covered the entire Bidjovagge area. In front of the Caledonian nappes in the Kautokeino area there must have been folding and transport of parautochthonous sediments, similar to what can be seen in the Oslo area today.

Figure 9. Section through Lower Cambrian marine sandstones and shales.
The maximum burial/metamorphic temperature of the autochthonous sediments in Finnmark is uncertain. Data by Snäll (1988) and Bjørlykke et al. (2021) from the middle part of Sweden indicate a burial temperature of around 200–250°C. Rocks in the autochthon on Varanger Peninsula are in the upper diagenetic zone, indicating a maximum heating of about 200°C (Bevins et al., 1986). More data on the degradation of fossil remains are needed in order to establish a better burial history. The stability of the clay minerals at Bidjovagge (this paper) indicates a burial temperature lower than 150°C.

**Mineralogy, geochemistry and geochronology**

The petrographical, mineralogical and chemical analyses of this study are based on core material from the exploration drillholes in Bidjovagge. The samples were prepared for the various analytical purposes: thin-section studies on light microscope and SEM; mineralogy with X-ray diffraction (XRD), chemical analyses with X-ray fluorescence (XRF), and age determination with the K–Ar method. NGU’s standard procedures are followed for the various analytical methods and the results are included in the Electronic Supplement 1.

**Mineralogy of the Precambrian tuffites**

XRD analyses show that the mineral composition of the Precambrian tuffites in Bidjovagge is mainly biotite, biotite/chlorite mixed-layered minerals and chlorite. The mineral composition of the diabase is mainly amphibole, mica, plagioclase and chlorite. This is illustrated in Fig. 10A, with the composition of sample #195464 (tuffite from 62 m below the peneplain) and sample #132191 (diabase from 16 m below the peneplain). The chemical compositions of the same two samples are shown in Fig. 10B.

![Figure 10a. Mineral composition of one tuffite sample from borehole N316A at 62 m depth under the Precambrian peneplain and one diabase sample from borehole N320A at 16 m under the peneplain.](image)

![Figure 10b. Chemical composition of the same two samples as in Figure 10a, above](image)
The tuffite sample has higher values for ignition loss, potassium and magnesium due to high contents of biotite compared with the diabase. The diabase is characterised by higher sodium values than the tuffite, due to abundant albite, and a higher calcium content due to a high content of amphibole. This also illustrates that the strong hydrothermal Na–Ca exchange (albitisation) did not affect the amphibole in the area (Bjørlykke et al., 1987).

Mineralogy of the saprolite

The mineralogical composition of the saprolite zone is illustrated in Fig. 11. Four samples from four different boreholes were investigated, two samples from the top of the saprolite and two samples at one metre depth below the peneplain. Three of the four samples have illite as the dominant mineral while kaolinite dominates in the last sample, indicating that this sample has undergone an even stronger leaching. For this reason, it is a little strange to see that this sample contains plagioclase (albite). It is suggested that this plagioclase is derived from aeolian dust, deposited in the muddy saprolite. The kaolinite-rich sample also contains abundant hematite. This hematite formation must represent a later phase that took place after the oxygenation of the percolating meteoric water.

All four samples also contain significant amounts of hematite, derived from dissolution of iron-bearing silicate minerals (e.g., biotite, chlorite, amphibole) in the tuffite.

The mobilised ferrous iron was later oxidised by percolating meteoric water during the event of increased oxygen in the atmosphere, that peaked at around 525 Ma (early Cambrian). This oxidising event enabled the crystallisation of hematite, which is a later alteration of the original iron-hydroxides in the fracture system of the basement. Some of the iron may also be derived from oxidation of pyrite and magnetite in the parent rocks. The mineral compositions shown in Fig. 11 are vastly different from the non-weathered samples shown in Fig. 10A.

The mineralogical and chemical compositions of the two tuffite samples, one from 62 m below the peneplain and one from the saprolite, are illustrated in Fig. 12A, B. The saprolite sample is characterised by much lower values of MgO and Fe₂O₃ and much higher values of Al₂O₃ and TiO₂ compared with the deep sample (MgO is reduced from 16.2 to 3.6 wt.%). Most of the iron in the saprolite sample is contained in the hematite and pyrite.
Similar trends were described by Bjørlykke (1975) from tropical weathering of diabase in Uganda, with enrichment of TiO$_2$ and leaching of 90–100 wt.% of Na$_2$O, MgO and CaO. However, this weathering took place in tropical forests and soils, where abundant humic acids are complexing and mobilising ferric iron and other metallic components. In southern Sweden, a study of a deep-weathered profile in Precambrian gneiss showed abundant kaolinite and smectite, also indicating a tropical climate (Rueslåtten, 1985).

The data illustrated in Fig. 12B, show that the saprolite sample contains more K$_2$O than the non-weathered deep sample. This is due to the continuous leaching of potassium from the biotite-rich tuffite, and the absorption of this potassium by smectite to produce illite and an illite/smectite mixed-layered mineral. The effect of this illitisation can be traced down to approximately 20 m below the sub-Cambrian peneplain, where a smectite/chlorite mixed-layered mineral seems to be the stable phase.

**Clay alteration below the saprolite**

Three samples from borehole N300A are analysed to study the variation in mineral composition vs. depth (Fig. 13). One sample is from the top of the saprolite (0.1 m depth) and the other two are from 17 m and 23 m below the peneplain. The sample from the saprolite zone displays a similar composition to those shown in Fig. 11, with illite, illite/smectite mixed-layered mineral, chlorite and kaolinite, in addition to hematite, calcite, plagioclase and amphibole. The plagioclase and amphibole are
suggested to be remnants of diabase, derived by deposition of aeolian dust. The deepest sample, from 23 m below the peneplain, is dominated by precipitated products from the weathering above, crystallised as hematite, calcite and quartz. Some amphibole indicates that the parent rock is diabase.

The sample from 17 m depth (Fig. 13) is composed mainly of amphibole and plagioclase, i.e., diabase, but it also contains some hematite and quartz. The supply of potassium from the weathering of tuffite has illitised smectite and a smectite/chlorite mixed-layered mineral, to produce illite, illite/smectite and illite/chlorite mixed-layered minerals, as seen at 17 m depth. However, this sample also contains the smectite/chlorite mixed-layered mineral, like the sample from 23 m depth, indicating that the smectite/chlorite mixed-layered mineral was the stable clay mineral at depths of 20 m and more. The preservation of smectite and smectitic mixed-layered minerals in the weathering zone indicates that the maximum burial temperature was below 150°C. This is confirmed by Bjørlykke (1994), who stated that kaolinite will recrystallise to illite at temperatures in the range 120 to 140°C, provided that there is a source of potassium. The most important source of potassium during the formation of the saprolite was biotite, and it is believed that this is the source of potassium for the high content of illite and illite/smectite mixed-layered mineral in the saprolite. The reason why kaolinite is still present in the saprolite must then be that the temperature never exceeded 150°C.

**Hematite formation**

The formation of hematite is the dominant alteration feature seen in the drillcores from the weathering zone associated with the Precambrian peneplain. Hematite occurs mainly in faults and breccias of all rock types and is seen from the upper saprolite and down to more than 100 metres below the peneplain (Fig. 4).

Three kinds of hematite precipitation features are recognised: Type 1) hematite filling fractures/veins up to 2 cm wide, in tuffite and diabase; Type 2) scattered spots of hematite, randomly distributed in tuffite due to oxidation of pyrite and magnetite; and Type 3) thin laminae of vein-filling hematite in tuffites. The alteration is controlled by the drainage system, i.e., breccias/fault zones, fractures and the composition of the host rock.

Type 1 hematite is shown in Fig. 14 (borehole N302D at 16 m below the peneplain). The vein is cutting through the diabase at nearly right angles to the oriented amphibole minerals. The felsic minerals are
mainly plagioclase, whilst the greenish to greyish earthy material is secondarily formed clay minerals consisting of smectite/chlorite- and illite/chlorite-mixed-layered minerals. The thin quartz streak that is cutting through the hematite must have formed at a later stage.

Figure 14. Sample 198366, borehole N302D at -16 m depth. A vein in diabase filled with hematite is cutting through the oriented amphibole minerals at nearly right angle. A thin quartz vein is cutting through the hematite filling.

Figure 15. Sample 198367, borehole N280D at 0.1 m depth. A random distribution of hematite aggregates is seen in this saprolite sample of weathered diabase. The hematite aggregates and plagioclase particles" float" in a matrix of structureless clay, consisting of in-situ formed chlorite.
Type 2 hematite from the upper part of the saprolite zone in borehole N280D (sample #198367) displays a random distribution of hematite aggregates that have crystallised in situ (Fig. 15). The light particles (<0.5 mm) in the picture are albite and the earthy material is chlorite clay, formed in situ. The albite particles and hematite aggregates are ‘floating’ in the clay material. The compositions of the clays formed in this saprolite zone are different from those formed in the saprolite developed in tuffite. Thin streaks of quartz are cutting through the hematite aggregates in both samples, interpreted to be the last phase of alteration.

Type 3, vein-filling hematite from 46.3 m below the peneplain, is shown in Fig. 16A (borehole N288C). The approximately 1 cm-thick vein is cutting through the tuffite. The adjacent host rock is commonly bleached, indicating migration of iron from the host rock to the vein. The vein is filled with needle-shaped hematite and quartz (Fig. 16B).

The other weathering products that are precipitated below the peneplain are quartz and calcite. This is illustrated in Fig. 17, with precipitation of these minerals in veins at 13 m depth under the peneplain in borehole N292B. The calcite is easily recognised by its twin planes and the quartz by its undulose extinction under crossed nicols. The quartz minerals show no clearly defined crystal surfaces, indicating an initial precipitation as opal which later re-crystallised as quartz. A thin vein filled with quartz is cutting through the calcite crystal.

In borehole N-302D, a Cu-rich mineralisation was intersected with bornite, chalcocite and malachite at a depth of 38 metres below the peneplain. Bornite is not unusual in the primary ore mineralisation, whilst the presence of chalcocite and malachite and the lack of chalcopyrite indicate that an oxidation process has altered the primary ore. There are no clay minerals in the Cu-rich sample.

Figure 16a. The schist is bleached at the contact of the vein. The fracture is now filled with hematite. The width of the thin section is ~2 cm.
Figure 16b. SEM micrograph of needle-shaped hematite (sample #128071). Scale bar (left) is 100 microns.

Figure 17. Sample 198355, borehole N292B at -13 m depth. Calcite is easily identified by its twin stripes and quartz by its undulating behaviour (crossed Nichols). A thin quartz vein cuts across calcite.
K–Ar dating of weathered tuffite

A sample (#129077) representing the saprolite zone in borehole N-288C was selected for K–Ar dating. The sampling depth was 0.9 m below the sub-Cambrian peneplain (referred to as DP). Diffractograms of both randomly oriented and treated oriented specimens with identified mineral phases are shown in Fig. 18. Note that these scans were performed on bulk sample material, while the <6 µm fraction of the sample is used for the K-Ar analysis, because this fraction contains mainly kaolinite and illite-smectite mixed-layer mineral, i.e., clay minerals formed in this ancient weathering process. The main source of potassium in the K–Ar analyses is the illite/smectite mixed-layered mineral.

The <6 µm fraction of the sample is used for the analysis, because this fraction contains mainly kaolinite and an illite-smectite mixed-layer mineral, i.e., clay minerals that formed during this ancient weathering process. The main source of potassium in the K–Ar analyses is the illite/smectite mixed-layered mineral. The potassium-argon (K–Ar) dating method is based upon the relative numbers of atoms of the radioactive potassium isotope $^{40}$K and the stable daughter element, $^{40}$Ar, that were accumulated after crystallisation of the clay minerals in the saprolite. In the conventional technique, which was applied in this study, K and $^{40}$Ar concentrations are measured separately.

The analyses in the laboratory followed the standard procedures of the Geological Survey of Norway. The samples were packed in molybdenum foil and degassed at 1400°C for 20 minutes, followed by spiking with a known amount of pure $^{38}$Ar. Spiked gas was purified using a combination of a titanium sublimation pump and SAES ST-101 getter cartridges, and analysed on an IsotopX NGX multi-collector noble gas mass spectrometer. Mass discrimination was corrected for by using an online air-filled pipette with atmospheric composition. K was determined by dissolving the Li-tetraborate fluxed sample in HNO$_3$, spiked with Rh as an internal standard and analysed on a PerkinElmer 7100DV ICP-OES. A detection limit (LOD) of 0.004% K is obtained with ICP-OES. Ages were calculated using the decay constants of Steiger & Jäger (1977) and the results of the analyses are given in Table 2.
Discordant ages may occur in weathering profiles, meaning that one mineral geochronometer is different from the age given by another geochronometer mineral (Villa & Hanchar, 2017). This can typically occur when remnants of the parent rock in a weathering profile contain potassium-bearing minerals (like mica and K-feldspar), which have higher ages than the clay minerals formed during the weathering process (like illite or illitic mixed-layered minerals). To minimise this problem, the fraction <6 microns is chosen for the K–Ar analyses, because the mineral composition of this fraction of the saprolite is completely different from the precursor, tuffite and diabase, and contains no preserved precursor K-rich minerals. The potassium contained in the newly formed dioctahedral clay minerals is sourced from dissolved biotite (and phlogopite) in the parent rocks.

The analysis gave an age of 541.8 ± 6.8 Ma (Table 2), confirming that the weathering process took place around the transition from the Ediacaran to the early Cambrian. In Scandinavia, this period was characterised by weathering processes that are considered to be associated with the formation of the peneplain.

Discussion

Chemical weathering on the Fennoscandian Shield of Baltica took place in the Ediacaran (Liivamägi et al., 2014) after the Varangerian glaciation, and this was a period with a high content of CO₂ in the atmosphere (3000–5000 ppm) (Schmitt, 1999). Ediacaran saprolites from the East Baltic states (Liivamägi et al., 2015) show that kaolinisation probably took place in a warm and humid greenhouse climate at high latitudes. Baltica was moving from 60°S to 30°S during the Ediacaran (Li et al., 2013; Meert, 2014)). The Baltic paleosols are developed on various lithologies, from amphibolites, metagabbros to gneissic rocks. The residue from the weathering can be more than ten metres thick, composed of kaolinite (60%), Fe-oxyhydroxides and residual quartz. This is a minimum thickness on account of erosion by water and wind before and during the marine transgression.

Based on Se/Co ratios in marine pyrite, Large et al. (2019) concluded that the atmosphere during the Ediacaran had a low O₂ content (4–6%). The global marine transgressions in the early Cambrian resulted in an increased supply of nutrients to the ocean, e.g., from P- and Fe-bearing mineral coatings, resulting in a high organic production and a rapidly increasing concentration of oxygen in the atmosphere, reaching a maximum of around 25% at 525 Ma (Large et al., 2019). After 525 Ma, there was a sharp drop in the oxygen content in the atmosphere to around 10%.

During the marine transgressions in early Cambrian time the saprolite became an important source of nutrients for organic production in the shallow sea, such as quartz grains coated with iron-hydroxides which has a large capacity to adsorb phosphorus and metal nutrients. Iron-hydroxides are unstable in a marine environment, and adsorbed elements were released to the sea. Increased organic production resulted in higher O₂ and lower CO₂ contents in the atmosphere. This is in agreement with the cyclicity in the composition of the atmosphere described by Large et al. (2019). They proposed that the atmospheric oxygen content peaked at around 525 Ma followed by a rapid reduction afterwards.

Table 2. K–Ar dating of the saprolite sample #129077 from Bidjovagge. The sample is a core sample from borehole 288C at a depth of 39.7 m (‘Drillers Depth’). This depth corresponds to 0.9 m below the surface of the Precambrian peneplane (‘DP’). The fraction <6 µm was selected for dating because of its high content of secondary formed clay minerals.

<table>
<thead>
<tr>
<th>Sample #129077</th>
<th>⁴⁰Ar* (%)</th>
<th>⁴⁰Ar* (%)</th>
<th>K (wt.%)</th>
<th>Age (Ma)</th>
<th>σ (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bidjovagge 37.9 m &lt;6 µm</td>
<td>5.0702E-09</td>
<td>0.34</td>
<td>97.0</td>
<td>4.641</td>
<td>1.2</td>
</tr>
</tbody>
</table>
which may reflect a colder climate due to the low CO\textsubscript{2} concentration in the atmosphere and in rainwater. This may have slowed down the weathering process at the end of the early Cambrian. There are no signs of deep weathering during this major regression at the boundary between the early and middle Cambrian (Hawke Bay event), neither in Bidjovagge nor in the lead-zinc mine at Vassbo (Bjørlykke et al., 2021).

**Formation of clay minerals**

Kaolinite occurs mainly in the upper 5 m of the weathered Precambrian bedrock (Fig. 19), and is explained as due to the high concentrations of CO\textsubscript{2} and low concentration of oxygen in the Ediacaran atmosphere. This greenhouse effect resulted in an increased rate of precipitation of rainwater with a high content of carbonic acid. The acidic and oxygen-poor precipitation led to weathering of the bedrock and efficient leaching of the dissolved components in the weathering zone. This is especially important for the leaching of dissolved ferrous iron hydroxides which would otherwise have hampered the crystallisation of kaolinite (Lewis & Schwertmann, 1979).

The K–Ar age of 541.8 ± 6.8 Ma obtained from the kaolinite-rich saprolite sample places the weathering at around the transition from Ediacaran to Cambrian, which is at the beginning of several transgressions and regressions on the peneplain of the Fennoscandian Shield. This is at the end of a period with high CO\textsubscript{2} concentrations in the atmosphere, and before the period with a rapid increase in oxygen (Schmitt, 1999; Large et al., 2019).

The main clay mineral found at depths between 15 and 30 metres below the peneplain is the smectite/chlorite mixed-layered mineral. This is explained by the abundant leaching of magnesium that facilitated the formation of brucite layers in the crystal lattice of chlorite. This, in addition to aluminium, silica and calcium, was leached from the saprolite and sourced the crystallisation of smectite. The octahedral layers in chlorite are formed at a pH above 8 (Phillips et al., 1977), which dictates that most of the acidity of the infiltrating meteoric water was consumed in the saprolite zone itself, at least for large periods of time. Meteoric weathering and formation of clay minerals continued below the saprolite zone, down to depths of more than thirty metres. Furthermore, the mobilised weathering products leached from the saprolite have precipitated at various depths, according to their specific solubilities. That is why quartz, calcite and hematite are found enriched in the interval from 20 to 30 metres below the saprolite.

![Figure 19. Average mineral composition of samples taken at various depths in the boreholes at the exploration area of Bidjovagge. Composition is given in weight-% (XRD). The upper part represents the saprolite zone, developed in the Precambrian peneplain. The yellow curve marks the content of clay minerals, which has a maximum in the saprolite zone, while hematite, calcite and quartz show a maximum in the interval 20 to 30 meters below the peneplain.](image-url)
These processes are clearly different from hydrothermal and diagenetic alterations, where newly formed minerals (like clay minerals) commonly replace the minerals in the parent rocks, in situ. They are also different from veins filled with hematite, which can be seen down to depths of more than 100 metres.

The formation of thick pure quartzites during the early Cambrian transgression (Nielsen & Skovsbo, 2011) was probably also a product of chemical weathering during the transition from the Ediacaran to the early Cambrian. The iron-hydroxide coating with absorbed phosphorus on quartz grains supplied nutrients to the beach environment, which may have resulted in algal blooming (Bjørlykke et al., 2021). The bluish quartzite acquired its colour from a carbon layer on the grains (Vogt, 1924).

**Formation of hematite**

Below the saprolite, the weathering is most pronounced along fractures, breccias and veins, which is explained by the fact that these zones constitute the dominant hydraulic conduits in the basement. Fillings of hematite aggregates commonly seen in these fractures and veins dominate the visible signs of weathering in the Precambrian basement below the saprolite zone and can be observed in drillcores down to more than one hundred metres below the peneplain (Fig. 4).

It is suggested that the hematite was formed from dewatering of iron-hydroxides and -oxyhydroxides (di- and trivalent) which had precipitated in the fault and fracture system. Because of the low solubility of ferric oxyhydroxides, it is suggested that the oxidation and formation of the hematite took place close to the site where it is found in the rocks today (Schwertmann & Murad, 1983; Schwertmann et al., 1999).

The formation of hematite is illustrated in Fig. 16A, which shows a vein filled with hematite and quartz. A sharp boundary is seen in the host rock close to the vein, indicating leaching of (ferrous) iron that later oxidised and precipitated onto the hematite. This may be related to diffusion of iron from the host rock to larger crystals in the vein.

The petrographic studies indicate that the hematite formation took place at a later stage than the formation of kaolinite, probably during the period from 540 Ma to 520 Ma, before the marine transgression stopped the weathering process. This period was also characterised by a rapid increase in the content of oxygen in the atmosphere, which peaked at 525 Ma (Large et al., 2019).

The rapid increase in oxygen in the atmosphere of the early Cambrian, as well as seismic activity in the fault zone, led to infiltration of more oxidised water deep into the Precambrian basement. Bacterial activity probably also contributed to this oxidation process. The initially high contents of sulphides in the rocks indicate an environment favourable for bacterial oxidation processes. Ferrihydrite is commonly associated with bacteria (Gallionella and Lepthorix) which obtain their energy from the oxidation reaction, $\text{Fe}^{2+} + \text{H}^+ \rightarrow \text{Fe}^{3+} + e^-$ (Scott & Pain, 2009).

Biotite is commonly the first mineral to dissolve in a weathering zone, due to an initial leaching of potassium that creates an imbalance in the electrical charge of the crystal lattice. This imbalance is commonly compensated by oxidation of ferrous iron in the octahedral layers (Goodfellow et al., 2016). However, at Bidjovagge, this oxidation was probably not taking place in the initial weathering period, due to the low oxidation level of the pore water. Still, the biotite was dissolved, and the ferrous iron was mobilised and leached downwards with the percolating, poorly oxidated, meteoric water. Similar dissolution reactions took place for chlorite and amphibole.
Hematite found at depths of more than a hundred metres below the peneplain demonstrates deep percolation of oxidised water. This is supposed to be a result of the increased oxygen content in the atmosphere in the early Cambrian combined with seismic pumping due to tectonic activity along the main shear zones. These processes also promoted oxidation of sulphides, like pyrite, resulting in the formation of sulphuric acid and the crystallisation of ferric iron-hydroxides (e.g., ferrihydrite) in fractures and veins. The formation of iron-oxyhydroxides increased the volume of the iron minerals, causing a swelling effect. However, ferrihydrite is unstable and subsequently recrystallised to needle-shaped hematite in the veins, which resulted in a significant volume reduction. The microporosity associated with the growth habit of the needle-shaped hematite aggregates is seen to be clogged by quartz (Fig. 16B) and calcite.

Calcite occurs mainly together with hematite in breccias and fault zones, but is also found in the saprolite. This must be a late formation, and perhaps formed during the marine transgression. Carbonate beds occur in the Kautokeino Group in the western anticlinal structures (Fig. 2). The calcium content in the volcanic host rock varies considerably, from less than 1 wt.% to 10 wt.%. The calcium ions in the leachate were balanced mainly with bicarbonate (HCO$_3^-$) which was later converted to carbonate (CO$_3^{2-}$) for the precipitation of calcite. This takes place when the pH reaches ~8.2 (as in seawater).

Both the alteration from ferrihydrite to hematite and the precipitation of calcite indicate an increased pH of the pore water. The maximum oxygen content in the atmosphere occurred at around 525 Ma and was causing oxidation of the iron-hydroxides. This was followed by the marine transgression at around 520 Ma. The recrystallisation of iron-oxyhydroxides to hematite and the precipitation of quartz and calcite were probably promoted by the early Cambrian marine transgression, which led to a higher pH in the porewater of the weathering profile. Veins with calcite and quartz cross-cutting hematite may be related to Cambrian movements in the shear-zones close to Bidjovagge.

Conclusions

Drillcores from the Cu–Au exploration at Bidjovagge in Kautokeino allowed us to sample material from the entire succession of autochthonous marine sediments and fluvial sandstones deposited in the early Cambrian; and the drillholes continue deep into the weathered Precambrian basement. A 6–8 m-thick fluvial sandstone was discovered between the basement and the Cambrian marine sediments. This fluvial sandstone may have protected the underlying weathered basement from erosion during the early Cambrian transgression.

Mixtites in the alluvial sandstone show that the Svecofennian shear zones were reactivated in the early Cambrian during the later stages of the Timanian Orogeny. Tectonic movements may have caused seismic pumping of meteoric water in the faults and fractures, resulting in deeper infiltration of the meteoric water and oxidation of sulphides and ferrous iron down to depths of more than one hundred metres below the peneplain.

The weathering process at Bidjovagge can be summarised as follows:

- The Ediacaran period, following the Varangerian glaciation, was characterised by a warm and humid climate with high contents of carbon-dioxide (4000–5000 ppm) in the atmosphere. The resulting low-pH rainwater caused strong weathering of the Precambrian basement rocks and the formation of secondary minerals, such as kaolinite. Saprolites more than 10 metres thick can be found in Bidjovagge and are also recorded at many places in the eastern Baltic states.
Minerals formed by the weathering process are smectite, kaolinite, illite, an illite/smectite mixed-layered mineral and a smectite/chlorite mixed-layered mineral, in addition to hematite, calcite and quartz. Crystallisation of these minerals took place at various depths below the peneplain, according to their specific solubilities, leaching characteristics, and the pH and Eh conditions.

A K–Ar dating of the saprolite (<6 micron fraction) containing mainly kaolinite, smectite and the illite/smectite mixed-layered mineral gave an age of 541 ± 6.8 Ma, i.e., late Ediacaran to early Cambrian. Most of the potassium in the sample was associated with the illite/smectite mixed-layered mineral, which may be younger (less stable) than the kaolinite.

The change of the atmosphere from a ‘greenhouse’ rich in CO2 to an increasing oxygen content which peaked at 525 Ma can be observed by changes in the mineral assemblage from the weathering phase, with dissolution of basement rocks, formation of clay minerals (e.g., kaolinite) and leaching of base cations, silica and iron-hydroxides.

In addition, the early Cambrian marine transgression took place at around 520 Ma, and the saline marine water with a pH of around 8.2 and increasing oxygen saturation changed the chemistry of the water in the saprolite and in the fault breccias. The higher pH led to precipitation of calcite, and the oxygenation led to crystallization of hematite from iron-oxyhydroxides. Quartz was precipitated in the microporosity associated with the formation of hematite.

The K–Ar age of around 542 Ma and the preservation of kaolinite, smectite and smectitic mixed-layered minerals in the weathering zone indicate that the maximum burial temperature never exceeded 150°C in the Bidjovagge area.

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