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Unusual features caused by lightning impact in West Greenland

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Abstract – Two lightning impacts are described from an area near the Inland Ice in West Greenland. The first lightning blasted an outcrop of metacherts. It subsequently split into two branches, which traversed rock outcrops and boulders, leaving behind two white almost straight lines, 30 m and 14 m long, respectively, where all lichens and plants were burned away. On the white lines the upper few millimetres of the traversed boulders were melted to a glass which subsequently peeled off by thermal expansion to leave a rough surface. Magnetic investigation of an amphibolite boulder found on the white line showed that a strong electric current indeed traversed the boulder. A few years later a second lightning impacted on a mountaintop close to the first impact. The second lightning left a trail on the rock surface covered by a thin layer of glass. The glass displays spectacular colours ranging from metallic blue to red, yellow and green.

Keywords: lightning, magnetization, fulgurite, Greenland, iron formation.

1. Introduction

The most common geological features produced by lightning impact are fulgurites. These are tubes of fused sand particles found in sand or other loose sediments, a few centimetres across and up to many metres long. They are fragile and break easily into small fragments (Pye, 1982). Occasionally lightning hits rock surfaces to produce rock fulgurites. These are glassy surfaces, often with magnetic anomalies caused by remagnetization of rocks by strong electric currents produced by the lightning (Frenzel & Stähle, 1982; Frenzel, Irouschek-Zumthor & Stähle, 1989).

Major blasting and shattering of rock outcrops by lightning strikes is rarely observed. Barnett (1908) describes a blasted outcrop on Leucite Hill in Wyoming, ascribed to lightning. Several angular blocks were ejected from the outcrop. Barnett (1908) also presents an eyewitness description of a lightning event in Maine, which blasted and shattered an outcrop from which blocks up to 1 m in diameter were ejected. A major lightning impact in Sweden blasted a crater-like hole in rocky ground 2 m in diameter and 0.75 cm deep, and dislodged blocks up to $\sim$500 kg (Muller Hildebrand *in* Malan, 1963, p. 164). Reasons for the scarcity of recorded blasts by lightning strikes may include lack of sufficient energy, as well as the difficulty in distinguishing effects from man-made explosions.

Greenland is an unlikely region in which to find the results of lightning impacts. In Nuuk, the capital of Greenland, about 150 km southwest of the area dealt with in this paper, lightning occurs on average once every two years. At Kangerdlussuaq, an airport close to the Inland Ice about 150 km north of the present area, lightning occurs once every five years (Cappelen *et al.* 2000). Füllekrug *et al.* (2002) report only one lightning event in Greenland in their inventory of intense lightning events.

This paper describes two lightning impact features in West Greenland. The first impact took place in late 1996 or early 1997. The second lightning struck in late 2002 or early 2003 less than two kilometres from the first lightning impact. The two impact features are described in the order they took place.

2. Setting

The features are found in an area close to the Inland Ice about 150 km northeast of Nuuk. The location is 65.169° N, 49.825° W, at an altitude of 950 m. The area is dominated by gently rolling hills, mostly with fresh outcrops of rocks. The bedrock consists mainly of amphibolites, metacherts and banded iron formation. There are extensive fields of well-rounded boulders ranging up to 1 m in diameter. The majority of glacial boulders are gneisses and amphibolites. Soil is present only locally and then only as small patches, mostly less than a few centimetres thick. The climate is high arctic with permafrost. Vegetation is sparse and consists of lichens, heather (*Cassiope*), and birch scrub, which is never more than 10 cm high. A steady wind blowing off the Inland Ice keeps the daily humidity down at low levels.

Most rock surfaces are well rounded due to glacial abrasion. They are also fresh, since very little chemical weathering takes place under these arctic conditions.

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Figure 1. Gneiss boulder traversed by the white line. Scale 10 cm.

3. First lightning impact

The first lightning strike described in this article impacted in a fairly flat area of boulder fields and scattered outcrops. Two almost straight white lines, 30 m and 14 m respectively, traversing boulder fields and rock outcrops, are the most prominent features. The angle between the two lines is 100°. The two lines meet on an outcrop of metachert, which has been blasted and strongly shattered. The blasting has a triangular surface outline 1 × 1 × 1.5 m in size and is 1 m deep. All blocks are angular and most of them are still located at the blasting site. However, a few angular blocks, weighing about 30 kg each, have been ejected several metres out of the pit.

The white line is seen on boulders (Fig. 1), on pebbles and on rock outcrop. Along the line all lichens have been burned off. The surface of the white line on boulders and rock is rough compared to their surface adjacent to the white line.

Samples were collected from gneiss boulders traversed by a white line (Fig. 1). The samples have been investigated in a scanning electron microscope (SEM). Samples from the normal smooth surface of the gneiss boulder show that the surface has been ground and polished during glacial transportation. Samples from the rough surface of the boulder on the white line show that all fractures are completely fresh and have not been rounded or smoothed at all.

4. Magnetic investigations

In palaeomagnetic investigations of rocks exposed at the Earth's surface, unwanted magnetic effects on the remanent magnetization induced by a lightning strike are common and may be quite disturbing for magnetic surveys (e.g. Dunlop & Õzdemir, 1997). For palaeomagnetic studies a number of individually oriented samples are typically collected from each of several sites (Butler, 1992) and, to avoid lightning effects, sampling at each site is spread over several metres of the exposed surface to make sure that at most only one or two samples may have been affected by a lightning strike. To avoid a local disturbance, a quick survey by a compass may be useful before sampling. For the same reason, sampling of rock exposures in peaks is usually avoided, as lightning strikes tend to concentrate on such peaks at an uneven surface.

Figure 2. Amphibolite boulder with trace of the first lightning. Fourteen samples have been drilled out of the boulder along a line perpendicular to the EW-oriented trace of the lightning. The figures on the tape indicate sampling sites along an NS-oriented profile. Sample 1 is the northernmost sample. Length of drilling profile is about 40 cm.

In order to test the hypothesis that the white lines and the blasting at the first impact site indeed were caused by lightning, one boulder of amphibolite with the trace of the white line was collected. A short profile composed of 14 2.5 cm cores was drilled vertically across the white line, the length of the profile being about 0.4 m (Fig. 2, with drilled cores). The spacing between each core was 3 cm, and from each core one specimen was later cut in the laboratory and magnetically investigated.

To test the magnetic properties, two specimens were treated in a stepwise increasing DC field up to 1.5 Tesla, and the induced isothermal remanent magnetization (IRM) was measured (Fig. 3). The IRM saturates around 0.3 T, indicating that the dominant carrier of magnetic remanence is magnetite. From 14 specimens the mean of the magnetic susceptibility was 10^{-3} SI, and the mean of the natural remanent magnetism (NRM) intensity was 66 mA/m.

From each core the remanent magnetization of one specimen was measured in a fluxgate spinner magnetometer and by standard treatment (e.g. Butler, 1992), stepwise demagnetized in alternating magnetic fields up to 50 mT. The coercivity and hence magnetic

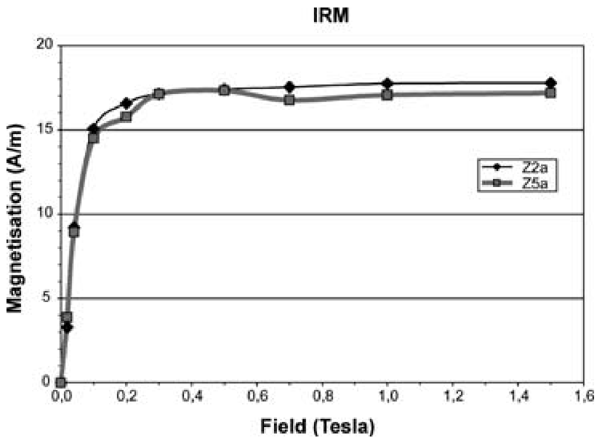

Figure 3. Induced IRM (isothermal remanent magnetization) in two specimens treated in a stepwise increasing DC field up to 1.5 T (Tesla). The IRM saturates around 0.3 T, thus indicating that the dominant carrier of magnetic remanence is magnetite.

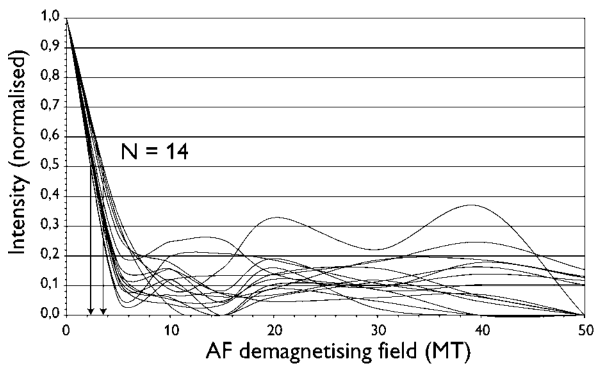

Figure 4. Decay of the remanent magnetization intensity by AF-demagnetization. The m.d.f. (median destructive fields) are between 2 and 4 mT.

stability of the NRM was found to be very low, the median destructive fields being between 2 and 4 mT (Fig. 4). The direction of the well-clustering initial NRM had a mean direction being (Dm, Im) = (313°, 34°), with the fisher parameters (R, k, a_{95}) = (13.59, 31, 7.2°), N = 14.

From the stepwise demagnetization data, characteristic remanent directions were finally determined by the linefind procedure in the IAPD program (Torsvik *et al.* 2000) using a minimum of three consecutive demagnetization steps. All characteristic directional results are illustrated in Figure 5. The stereogram shows two directional clusters. One is directed to the northwest with a down-dip direction equivalent to the initial NRM, whereas an approximately opposite direction, equivalent to a much more scattered southeast component, is also seen.

Due to the very low coercivity of the northwest direction, we interpret this characteristic direction as a recent lightning-induced IRM direction, while the more scattered southeast direction (Dm, Im) = (142°, 14°) with fisher parameters (R, k, a_{95}) = (8.61, 2.2, 35°), N = 15, is likely the product of a much older,

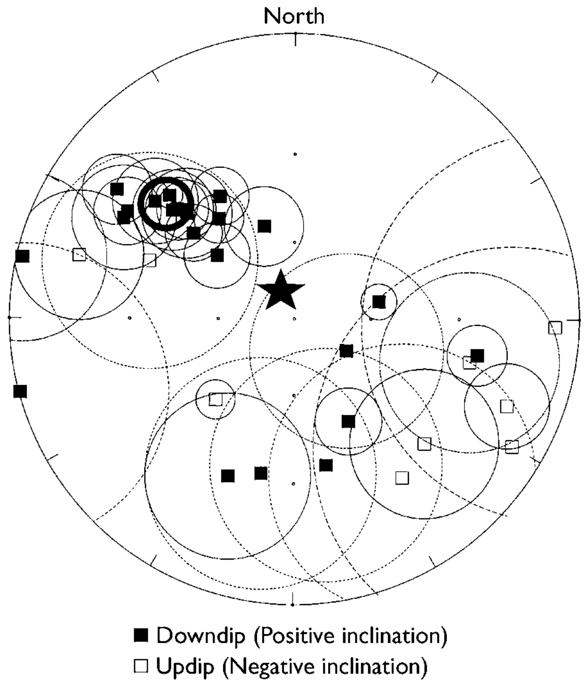

Figure 5. Stereogram of characteristic remanent directions. Two clusters are found: one NW down-dip (initial NRM) and another SE (partly up-dip and more scattered, likely older). Black star indicates the present day direction of the geomagnetic field at the site.

presumably Precambrian, remanence. The reason why the old southeast direction is so scattered may be partly the low stability of the magnetic carriers in the rock, and partly the demagnetizing influence from the strong overprint of the lightning-induced IRM.

5. Second lightning impact

The second lightning strike impacted on a mountaintop about 2 km from the first. The mountaintop consists of banded iron formation with alternating bands of metachert and magnetite. After impact the lightning travelled down along a vertical slope for several metres (Fig. 6), leaving an approximately 30 cm wide track where lichens have been burned off. The track exhibits bright colours ranging from metallic blue to red and yellow. The track is completely smooth.

Samples of the smooth track and the rock next to the track have been investigated in SEM. Samples from the smooth surface on the track show no grains but glass domains with curved boundaries. Samples from the surface next to the lightning track show mineral grains. A thin-section of the smooth surface was prepared as seen on Figure 7. The glassy surface is clearly seen on the lightning track.

6. Discussion

In case of the second lightning strike the explanation is straightforward. Lightning impacted on a mountaintop

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Figure 6. Rock fulgurite from second lightning impact. Hammer handle is 50 cm long.

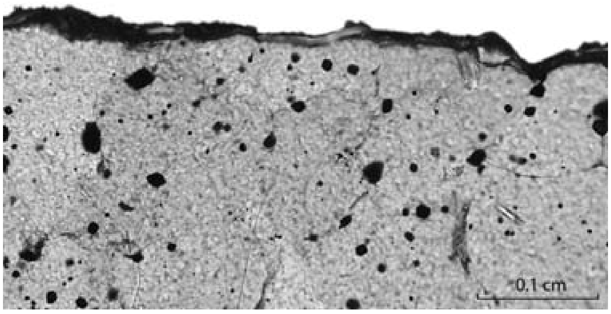

Figure 7. Thin-section of the rock surface under the track at the second lightning impact. The thin layer of glass is clearly visible on the surface.

and travelled several metres down a steep slope. All lichens on the track burned off and the rock melted. Upon cooling the track was covered with a thin layer of glass with spectacular colours. The glass will presumably soon peel off.

The features created by the first lightning impact are more complex. It is obvious that the lightning hit and blasted an outcrop of metacherts. Subsequently the lightning split into two branches that crossed a boulder field leaving a white track on boulders and burning off lichens.

Where evidence of lightning strikes is preserved, it is usually as fulgurites or rock fulgurites. However, blasting and shattering by lightning is also sometimes observed (Barnett, 1908; Malan, 1963). The suggested mechanism is best described by Malan (1963, pp. 163–4): 'When a lightning flash is incident on rocky soil the electric current tends to follow interstices between the rock or cracks which are filled with moist soil. Rocks may be split asunder or thrown aside with explosive violence.'

Can lightning have the necessary energy to blast and shatter outcropping rocks? The force of the blast at the first lightning strike is estimated to be equivalent to about 300 g of dynamite with an energy of 1.5×10^6 Joule, yielding a gas volume of ~ 270 litres. Lightning has energies in the range 1×10^4 to 5×10^5 Joule per metre with temperatures up to 30 000 °K (MacGorman & Rust, 1998). Lightning currents range from 10 to 40 kA (MacGorman & Rust, 1998) with extreme values of 250 kA (Berger, Anderson & Kröninger, 1975). If lightning impacts on an outcrop with abundant cracks and fractures, the strong currents will cause moisture in the cracks to evaporate instantaneously.

In the following simple calculation it is assumed that the impacting lightning had a temperature of 4000 °K, which is not unrealistic considering measured temperatures in lightning are up to 30 000 °K. According to the ideal gas equation, almost 2000 litres of gas will be produced from 0.1 litre of water or ice. However, at temperatures above ~ 3500–4000 °K, the water molecules will dissociate into atoms. According to Dalton's law of partial pressure the total volume of gas produced at 4000 °K will then be close to 4000 litres. It is thus reasonable to assume that lightning can possess sufficient energy to produce the degree of blasting and shattering of the extent observed at the first lightning impact site.

When the first lightning traversed the boulder fields, the boulders were strongly heated, whereby the rock surfaces melted along the narrow track. Upon cooling a glass was formed. Due to later thermal expansion and weathering, the glass cover has fallen off leaving the very fresh rock surface seen on the white track (Fig. 1).

7. When did lightning produce these features?

It is usually impossible to estimate the timing of a lightning impact unless it is actually observed. In the present case, however, it is possible to give a reliable estimate. In 1995 many geologists worked in the area where the first lightning impacted. In 1996 the lines were observed. It can thus be estimated that the first lightning impacted late 1995 or early 1996.

The second impact was on a mountaintop where the first author worked in 2002. At that time there was no trace of lightning. Next summer the rock fulgurite was observed. The lightning thus impacted late 2002 or early 2003.

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