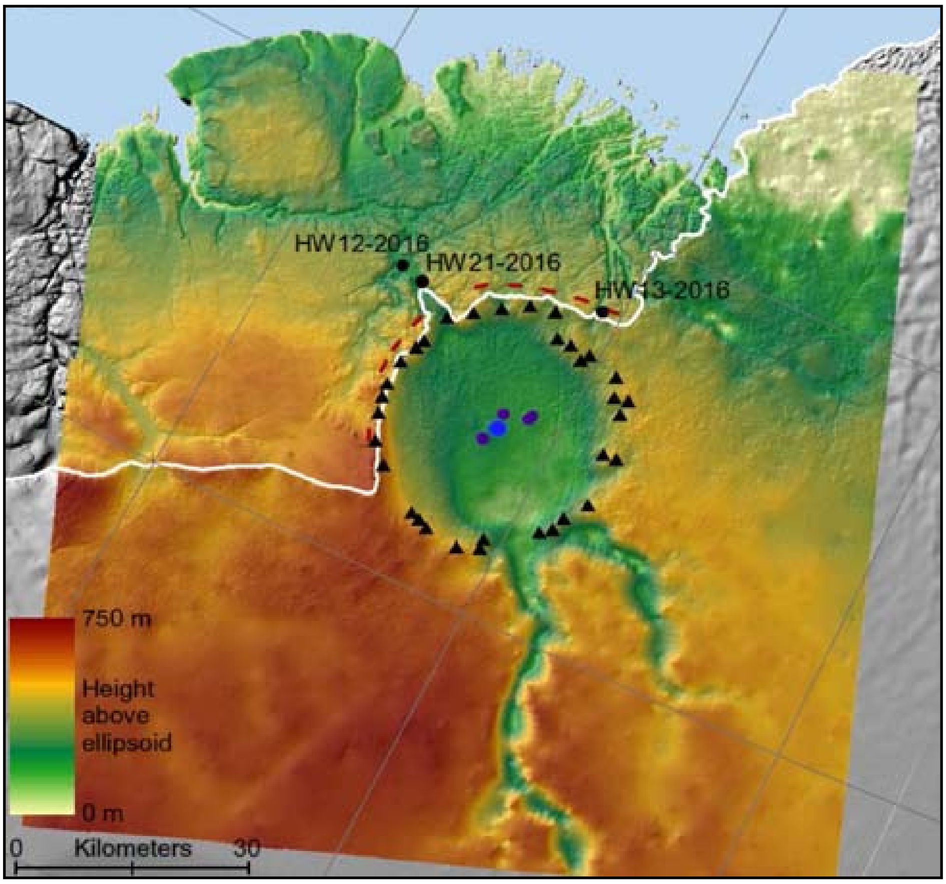
GEOBROWSER

Update on the Greenland meteorite

In *Geobrowser* for 2018 we highlighted research suggesting that the chain-reaction of events culminating in the sudden Younger Dryas cooling at about 12,900 years BP could have been triggered by a major meteorite impact or airburst. Intriguingly, an article published in November the same year (and brought to our attention by Peter Worsley), has the potential to pinpoint one possible source of this anomalous climatic change. Airborne radar imaging previously conducted, but only recently reported on by Kjaer *et al. (Science Advances, 4 (11), 2018 DOI: 10.1126/sciadv.aar8173)*, has revealed the presence of an impact crater, 31 km across, close to the northern margin of the Greenland ice sheet. The crater lies beneath the Hiawatha Glacier and is ranked among the 25 largest impact structures yet found on Earth. Sediments draining from the glacier include glass and shocked quartz: their chemistry features high contents of Ni, Co and platinum-group elements not found in local bedrock. All these findings suggest that the Hiawatha meteorite was made of iron, was about 1500 m in diameter, and penetrated to a depth of 7 km, melting around 20 km^3 of target rock. The event is thought to have produced several other iron meteorites in this part of Greenland, the largest being the 20-tonne Agpalilik meteorite, found on an ice-free slope in 1963.

Kjaer *et al*. were careful not to discuss a possible Younger Dryas linkage because, as yet, the age of the Hiawatha impact has not been precisely constrained. Their radiostratigraphic survey did show that the crater contains an upper layer of Holocene ice (i.e. younger than 11,700 BP), which elsewhere rests on debris correlated with the Younger Dryas stadial. Within the crater this Holocene ice rests on two further layers correlated with ice from the Last Glacial Period (LGP), extending back to about 115,000 BP, but this older material is evidently neither complete nor conformable across the entire crater, suggesting a *'...transient that strongly affected ice flow after most of the LGP ice was deposited'*. In their discussion of factors causing this anomalous radiostratigraphy, the authors do not rule out the possibility that hydrothermal activity following the impact could have melted, vaporized, and excavated ice for some time afterwards, thus affecting local ice-flowage. While cautioning that meteorite-derived ejecta has not been identified in the four deep cores through LGP ice in central and northern Greenland, they did not discuss the platinum anomalies and combustion aerosols found in certain of the ice-core layers (reported in *Geobrowser* for 2018). According to Wolbach *et al. (Journal of Geology, 2018, v.126/2*), these layers could be evidence for a meteorite strike during the youngest part of the LGP, at between about 12,836 and 12,815 cal BP – immediately before the onset of the Younger Dryas stadial.

So as far as the Hiawatha meteorite is concerned, the only evidence is that it must have impacted some time during the Pleistocene. But given its dimension,



Bed topography at the Hiawatha Glacier, near the northwest coast of Greenland; based on airborne radar sounding from 1997 to 2014 NASA data and 2016 Alfred Wegener Institute data (from Kjaer et al., 2018).

which on the Broomfield Hazard Scale is well over the 600 m diameter needed to cause destruction on a global scale (*Space.com; November 2014*), it must have had significant environmental consequences. It seems plausible that one of the several Pleistocene glacial/interglacial periods would have been affected, with the anomalous Younger Dryas being an attractive candidate. But more investigation is needed, which may include a search for further craters and perhaps drilling of the Hiawatha feature, so at the moment we can only 'watch this space'.

A geological 'Lost City of Atlantis'

In Greek mythology Atlantis, the 'island of Atlas', was named after one of Poseidon's sons and is mentioned as far back as Plato's *Timaeus and Critias*, written at around 360-330 BC. The legend holds that the island and its city foundered beneath the sea in one day, a particularly dramatic scenario that has inspired many books, films and TV documentaries. Most notoriously, the Atlantis fable was actually made a cornerstone of Himmler's crazed Nazi theories concerning the origin of the Aryan race and its importance to supposed Germanic superiority.

One of the Lost City's most recent resurrections is purely geological, and was inspired by a discovery made in December 2000 during a National Science Foundation expedition to the Mid-Atlantic Ridge. In a new survey, reported by Kelley *et al*. (*Oceanography, 2005, v.18, No. 3*), a remarkable submerged world of at least 30 gothic-like towers rising up to 60 m above the sea-floor is revealed. These structures surmount the 'Atlantis Massif', a fault-bounded 4000-m-high mountain composed of mantle peridotite. The towers are hydrothermal chimneys, predominantly composed of the carbonate minerals aragonite and calcite ($CaCO_3$) but with lesser amounts of brucite ($Mg(OH)_2$). Unlike the situation in black smoker vents, there are no sulphide or sulphate minerals, and no silica gangues, because the highest temperature of the venting hydrothermal fluids is only 91°C.

The minerals of the chimneys do not require magmatic heat to form: they are believed to have originated from exothermic serpentinization reactions between percolating seawater and the olivines and pyroxenes in the underlying mantle peridotites. This process produces low-temperature, highly alkaline fluids that are rich in calcium, methane and hydrogen. In fact the reactions produce 10 to 100 times more hydrogen and methane than a typical black smoker system found along mid-ocean ridges. When vented, these warm, nutrient-rich fluids host concentrations of microbes, such as archaea. The animal life attracted to the carbonate vent margins shows a diversity that is as high or higher than that of black smoker systems along the Mid-Atlantic Ridge (Kelley et al., 2005), with invertebrates such as snails, bivalves, annelid worms, crustaceans and ostracods among the specimens found. There has been plenty of time for evolutionary adaptations, since strontium, carbon and oxygen isotope data and radiocarbon ages document at least 30,000 years of hydrothermal activity, making the 'Lost City' older than known black smoker vents by at least two orders of magnitude.

Photomosaic of one of the pinnacles that are formed mainly of carbonates. A cluster of these pinnacles have become known as the 'Lost City', located on the Atlantis Massif of the Mid-Atlantic Ridge. The most actively venting areas are paler in colour. This particular pinnacle is about 25 m tall (from Kelley et al., 2005).

Both acetate and formate are among the complex organic substances that have been produced, and it has been suggested that these were key ingredients to the emergence of life on Earth. They could even be the types of compound waiting to be found on other planets in our solar system. Such a unique environment clearly needs to be preserved for further research, but there is one concern: the 'Lost City' lies within a 10,000 km^2 area of the Mid-Atlantic Ridge allocated by the International Seabed Authority (ISA) to Poland to explore for deep-ocean mineralisation. The secretary-general to the ISA told Sky News in March 2018 that there was no suggestion that damage would be caused, as this is a site of scientific interest, although the Authority is still in the process of formulating rules that will govern mining activities in areas of scientific or ecological interest.

Fracking and earthquakes

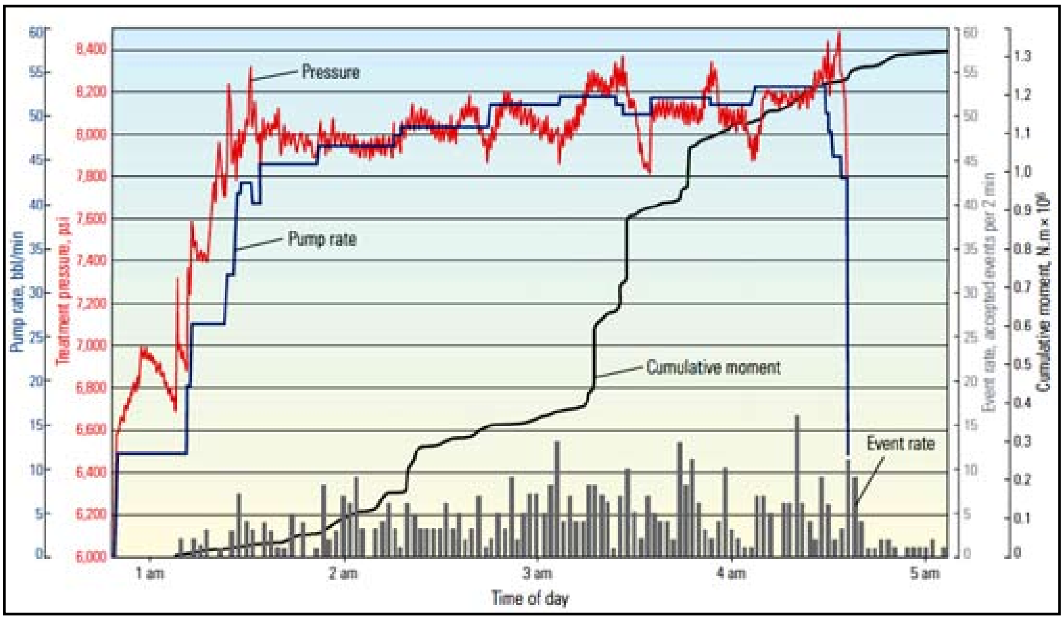
In October 2018, alarm bells rang when a series of microseismic events was reported by Cuadrilla Resources during fracking for shale gas at its Preston New Road site. The largest of these, measuring 0.76 on the local magnitude scale, compelled the company to pause its operations for 18 hours. A few days before, there had been a 0.4 magnitude event, which according to the Company was *".....an extremely low level of seismicity, far below what could possibly be felt at the surface but classed as an amber event as part of the traffic light system in place for monitoring operational activity."* In that instance they not only reduced the rate at which the fracturing fluid was being pumped, but went also suspended operations for that particular day.

It is easy to find online postings expressing concern over the very mention of seismic activity. This is probably because of the 'populist' belief that earthquakes invariably cause vibrations and damage to buildings etc. But the quakes generated as part of the hydraulic fracturing (fracking) process (as opposed to those triggered by deep-seated wastewater injection, see *Geobrowser* for 2017) are too small to be felt at surface. In fact these microseismic tremors provide essential confirmatory evidence for the changes in stress and rock volume that must occur in order for shale gas to be released. Furthermore, as the graph below shows, when monitored through surface sensor networks and integrated with other parameters they provide a greater understanding of the strain and stress variations within a particular hydraulic fracturing operation. This can help to predict and so prevent undesired fracture growth or fault reactivation that may otherwise cause a company to pause or modify its operations (*Le Calvez et al., Oilfield Review 28, 2, 2016*).

During 2018 the largest microseismic event at Cuadrilla's site was only just above the 0.5 magnitude limit for fracking currently allowed by the UK authorities. It was lower than the vibrations transmitted from quarry blasts or a rollercoaster and, as noted by Cuadrilla, '…*similar industries in Lancashire and elsewhere in the UK…are able to work safely but more effectively with significantly higher thresholds for seismicity and ground vibration*.' That limit was possibly intended to placate the increasingly influential anti-fracking lobby and has been criticised as being too rigorous by the companies concerned, many of which would prefer the slightly higher threshold of around 0.75 magnitude. The controversy was presaged by an article in the Quarterly Journal of Engineering Geology by Westaway and Younger (*QJEGH, 47, 2014*), which noted rather caustically that the then-current proposals '…*fail to take account of the mainstream literature on engineering seismology and earthquake hazards'*.

Ironically, some encouragement for the fracking companies has been provided by the very inconsistency of the UK government's position over this issue. Thus the Department of Energy and Climate Change recommendations of May 2012 stated that their 0.5 magnitude seismic threshold should be periodically reviewed, but in a November 2018 letter, the Energy and Clean Growth minister informed Cuadrilla that '*The government believes the current system is fit for purpose and has no intention of altering it*.' Protestations followed in February 2019, when Cuadrilla and Ineos Shale noted that the current 'absurd' threshold severely constrains the volume of sand that could be injected into the shale rock, and puts at risk the viability of any shale gas extraction. However the new government formed in July this year is emphasising potential economic benefits, an attitude which, coupled with Cuadrilla's modified plan for fracking (*www.drillordrop.com, July 30th 2019*), could see operations at Preston Road commencing by the end of August.

The UK debate over limits to seismicity for fracking is mirrored in other parts of the world. For example in Oklahoma, which has recently seen very strong fracking-related earthquakes (*see Geobrowser for 2017)*, the authorities lowered the threshold from magnitude 2.5 to 2.0, the latter also being the limit adopted for fracking operations in Alberta. These rather high limits reflect the underpopulated nature of those areas, in marked contrast to our own overcrowded island. Even so, Ben Edwards, Reader in Seismology at the University of Liverpool, suggests that by using a risk-based approach to seismicity, where events are allowed that that do not pose any risk to humans or structures, even a 1.5 magnitude threshold would 'arguably be conservative' (*BBC News website, February 2019*).



Cumulative seismic moment (i.e. aggregated micro-earthquake sizes) and recorded microseismic event magnitudes plotted against various fluid injection parameters during a planned pumping schedule. The abrupt increase in cumulative moment halfway through indicates a significant increase in deformation (from Le Calvez et al., 2016).