Stac Fada, April 2021, Ken Amor, Oxford Univ.

The Stac Fada (SF) lies within the Stoer Group in NW Scotland which extends down the coast for about 50 km.

From Osinski et al, J Geol Soc, 2020

This Group is formally part of the Torridonian Supergroup but can be considered as an individual unit on its own. The Stoer Peninsula exposure has interesting features and easy access but it is complex and many interpretations are possible. The Stoer Group sits unconformably on Lewisian Gneiss also has an unconformity above with about a 200 Ma gap with the overlying Diabase Formation. It was first identified by Sandy Stewart at Reading, who did a lot of work on the Stoer Gp and regarded it as forming in a graben or half-graben (which seems to be accepted generally) with a broadly westward palaeocurrent direction, with occasional reversals from west to east, in a typically red-bed sedimentary environment and at least 70% of it made up of locally weathered Lewisian gneiss. There are ripple marks, desiccation cracks, and possible microbial mats as well.

The overlying SF Member was first identified as somewhat unusual by Peach and Horne in 1907 and they regarded it as a possible volcanic deposit. At Stattic Point it is slightly more resistant than the overlying rock, yet has a very similar sandy looking matrix, but what distinguishes the SF are the greenish clasts, identified as vitrified glass, peppered throughout the Stoer Gp. These melt clasts vary in size from mm to a few cm across, generally ubiquitous across the unit, with some clasts as big as 17cm on the long axis. On fresh surfaces in the interior, the clasts are dark green, and geochemically, two distinct populations have been identified, possibly reflecting the lithology from which they melted from.

It seems clear that the deposit was produced from the impact of a large asteroid, since shocked quartz has been found, which as far as is known can only be formed from large impact phenomena (or nuclear test sites), which generates pressures of between 7 to 35 GPa. More recently shocked zircon has also been identified (known as reidite) and trace element geochemistry shows that the SF has a very high Ni content, and enhanced Pt group elements, and when normalised to chondrite values, the more horizontal the trend for these trace elements, the more strongly it relates to the impactor (i.e. the asteroid).

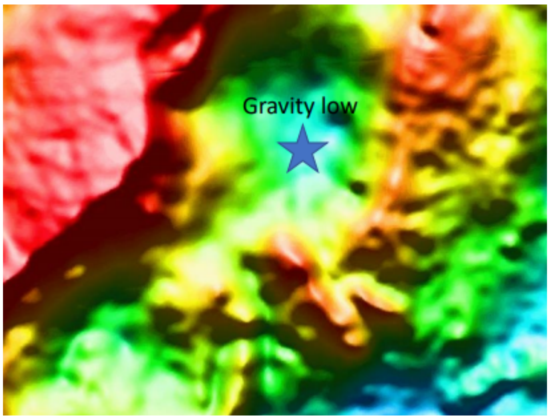
There is no evidence at the outcrop of any form of crater so it is assumed that the SF represents an ejecta blanket distributed around where the crater was unless the impactor was coming in at a very low angle. There seem to be stacks of shear planes within the SF as material has moved from L to R as the ejected material slowed down, overlapped each other and came to rest and this appears to be the case at Stattic Point. At Enard Bay, there are very clear upper and lower surfaces for the SF, with a 10cm layer with an undulating surface interpreted as an airfall bed, representing the final stage as dust dropped out of the atmosphere from a plume cloud, similar to a Plinian type eruption, after which normal graben sedimentation began again with more planar beds on top. The lower surface of the SF is sharp, suggesting that pre-existing detrital material had been moved, possibly at hundreds of km/hr by the impact blast, over a barren surface, and subsequently incorporated into the SF.

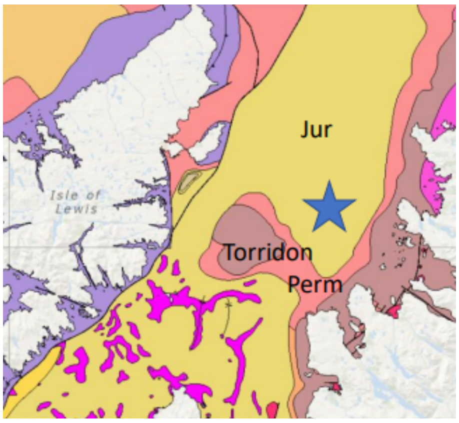
Fluid inclusion studies by John Parnell in the underlying sandstone which exhibits dewatering pipes with feldspar crystals, suggest that they were heated to around 200-300 deg C sometime after it was deposited. The accretionary lapilli look very much like volcanic lapilli and presumably formed in a similar was from a Plinian type cloud or as immediately above a density current that swept over the countryside, with a fine-grained outer core with a coarser grained interior, with occasional pieces of shocked quartz. These typically occur in the upper parts of the SF. Curiously, none of the Lewisian fragments examined does not contain any shocked quartz and no indications of being highly fractured or had gone through any shocked process. Therefore, it is assumed these quite angular Lewisian blocks had simply been loose material that had simply been incorporated into the density current and swept along, rather than having been blasted out from the crater.

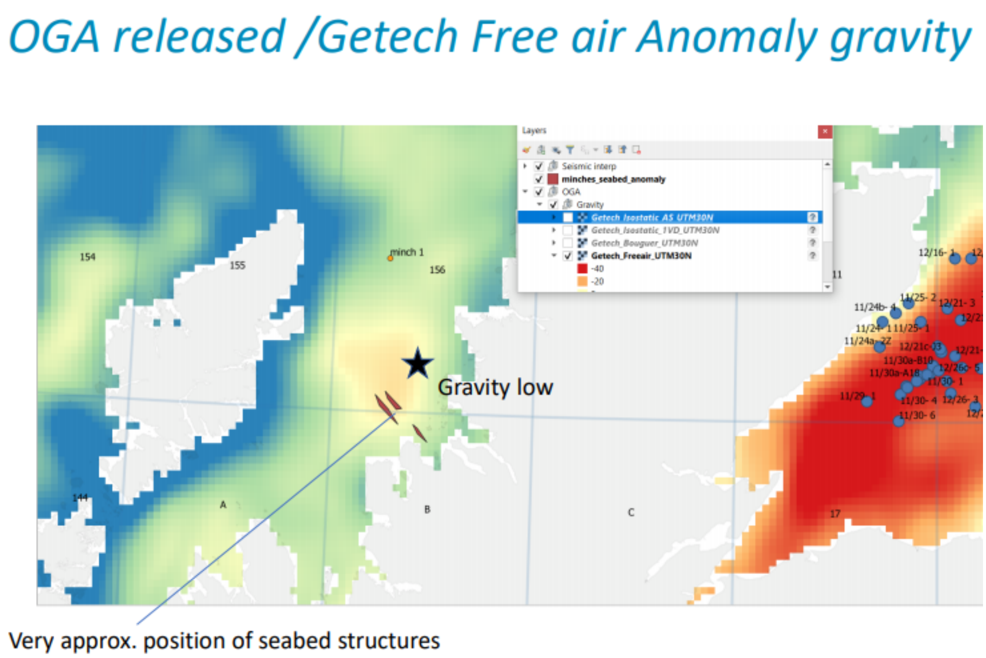
Craters on other planets, for example Copernicus on the Moon shows the ejected material is deposited in a parabolic type of trajectory and falls quite close to the rim (but outside of it) while there are terraced slopes inside the crater and a central uplift. Similar morphology on the flatter surfaces on the northern part of Mars however, show either large basalt outpourings the size of oceans, while on the south of Mars the impacts like Tooting crater have a more 'mud splat' morphology with a lobed appearance with a long run-out distance outside the crater, about six times the diameter of the crater radius. This is thought to be related to a high volatile content quite close to the surface of parts of Mars, which gets super-heated from the energy of the impact and helps to fluidise the material into some sort of density current like a pyroclastic flow or ignimbrite which can flow for quite long distances. So, what we see in the SF, the ejecta blanket looks more like the Tooting crater on Mars than that on the Moon. Sadly, for this study, the Martian rovers have tended to land on the inside of craters rather than on the outside zone with the impact debris!

Considering the likely crater formation process, with zones of melting, vapourisation, shock metamorphism and fracturing, with excavation paths for the ejecta material, these zones can vary with the water saturation of the target rock, and hence the zone of melting can increase and the level of shock metamorphism decrease, with a water saturated target. When the shock wave meets the surfact, it can induce spallation of quite large blocks and ejected a significant distance. So this leads on to features seen at Stoer, where there are very large ingress of deformed sandstone, which are interpreted as quite large spalled blocks of material from the underlying pink sandstone, now completely embedded within the impact ejecta. These blocks may have been launched ballistically and then fallen into a density current, or simply picked up and transported a more modest distance by the density current itself. It also looks as if some of the ejecta material has been injected between the bedding planes of the Stoer group sandstone. All these features seem to be atypical of most other ejecta sites and so the exact process is not clear.

So where could the impact crater be? It has been tentatively placed west, in the Minch.







There are a lot of impact sites around the globe where the size of the impactor was probably less than 50km in diameter and these can be regarded as part of normal geological processes. And there will presumably have been Chelyabinsk type air-burst shock waves (as occurred in 2013) occurring as well. A 10km diameter crater may not have been significant event in the geological record, but in terms of modern society, such an impact would have a devastating consequence. The impact rate on the moon can be approximated but there is no clearly definable rate of impact on Earth, especially as asteroids up to 1km diameter will probably not have left any trace if they had impacted in the deep ocean, and impact ejector are actually very rare on Earth.

Discussion

The nature of the gravity anomalies was raised. There are gravity low anomalies in both the Minch and near Lairg and there are some unpublished gravity data which is of higher resolution, but there are several unknowns including the thickness of sediments in the Minch basin and if the Stoer Gp is preserved in the Minch.

With the geochemical data including the REE, is it possible to constrain the end-member composition of what type of asteroid it might have been? Yes, people have tried this for other sites around the world, and the indications for SF is that it is likely to have been a chondritic rather than an iron meteorite.

Asteroid or bolide or comet? There is no firm definition of these in the literature, but unpublished research has shown that there are two melt glass compositions in the SF: the grey ones have a terrestrial composition, while the green ones have a very clear extra-terrestrial signature. In addition, the sandstones above the SF are themselves enriched in the Pt group metals, possibly from surface ejecta being reworked into later sediments. Another interesting feature is the fact that evidence for cross bedding in the sandstone beneath the SF decreases as the contact is approached, suggesting that there may have been ground shaking in the shallower sediments, followed by the big spallation blocks falling into soft sand post impact. It is also clear that, over the 50 km of outcrop, there is a great deal of heterogeneity in number of large blocks and melt inclusions, so it could not have been a single homogeneous ejecta cloud. And it was pointed out that in a graben environment, there would have been a range of topography locally, and cliff falls. Enard Bay in particular, was a very complex exposure.

A question arose from the map of impact craters worldwide, which appeared to cluster. There will be a sampling bias; for example, satellite photography in regions like Australia can readily pick up impact sites, compared to forested areas in the northern hemisphere say, plus an age bias – old cratons versus young sediments, recent glaciation etc.

The discussion moved on to other known meteorite impact. In the village of Kaali, on the Estonian island of SaaremaaIn, a group of nine meteorite craters are visible as a pitted area, certainly within the time of human occupation, and reported to be about 1,500 BC in age. These may well represent a large meteorite which broke up in the atmosphere, producing a range of small impacts over a small area.

When was the last km scale impact event? There is the Indo-China to Antarctica tektite field from about 780,000 yrs ago, yet no crater had yet been discovered, which could have been an airburst, but one at very high temperature to result in so many melted objects.

The Libyan desert clasts which have been identified as having some extra-terrestrial material, and yet there has been no crater found, so the presumption is that it also could have resulted from an airburst which melted the desert sand. One member had been to the Oasis crater in the Kupfra basin, formed about 28 Ma, in which the local L Cretaceous Nubian Sandstone strata had been pushed near vertical, but no glass or fragments had been found.

This emphasises the fact that very few impact craters have been dated with any accuracy, either from radiometric or palaeontological/stratigraphic means.

Given that the SF is Mesoprotorozoic in age, the nearest sediments of this age would probably be in E Greenland, perhaps a target for future scientific exploration.