REPORT

A Scottish meteorite impact deposit

Britain's geology is perhaps more diverse than any equivalent area in the world and spans almost 3 billion years yet, for too long, it seemed that there was no evidence here for one of the most spectacular events on Earth – a giant meteorite impact. Our geology has been studied for more than two centuries so perhaps the only evidence we might have would be localised and easily overlooked, like the thin layer of mm-scale microtektites, once molten beads of rock blasted out by an impact, that were found near Bristol in 2001 (although they actually proved to originate from the 100 km Manicougan Crater in eastern Canada). But, just a few years later a spectacular discovery revealed that a world-class impact deposit, metres thick and extending for tens of km, had been hiding in plain sight at a location visited by countless geology students and their teachers. For decades the Assynt region in north-west Scotland has been a training ground for geologists, drawn by the immensely old Lewisian Gneiss, the spectacular hills of Torridon sandstone that overlie it, and the structural complexity of the Moine Thrust Zone. But surely there could be nothing startlingly new to discover here?

The oldest sedimentary rocks here are known as the Stoer Group, after the tiny village where they are best seen. They comprise hundreds of metres of red sandstones and mudstones that, despite their 1.2 billion-year age, have been barely metamorphosed and look little different from Old Red Sandstone barely a third as old. The sandstones were deposited on wide braided river plains, the mudstones in lakes, but it was a landscape entirely devoid of vegetation as the first land plants were still more than 700 million years in the future!

The Stoer Group outcrops at various points along some 50 km of the west coast from Pollewe in the south to the Stoer peninsula in the north, but they are seen particularly well in the Bay of Stoer, some 35 km north of Ullapool (Fig. 1). It might seem rather a long way to travel for some seemingly unremarkable (other than their age) sandstones and mudstones, but sandwiched within them is an extraordinary layer, up to 12 metres thick, that can be traced throughout the 50 km length of the Stoer Group, and for this it is worth making the journey.

Called the Stac Fada Member (SFM), this distinctive layer has long been recognised as something odd. In a matrix of red sand and mud, with a few Lewisian gneiss pebbles, is an abundance of dark grey or green angular fragments a few cm across (Fig. 2). Even decades ago these were recognised as having been molten and, understandably, it was assumed that the SFM was some kind of volcanic deposit, perhaps a lahar (volcanic mudflow). But the apparent absence of any other evidence of volcanism in the Stoer Group seemed rather odd. Then, in 2008 an extraordinary claim was made – the SFM was actually an ejecta

***Figure 1**. Looking south-east across Stoer Bay, with the headland formed by the SFM in the foreground and the Lewisian and Torridon hills in the distance.*

***Figure 2**. Detail of typical SFM at Stoer, with green-grey melt fragments in a sandy red matrix.*

deposit from a giant meteorite impact, and the green/grey fragments were once glass formed by the rapid chilling of impact-melted rock blasted from the crater! Not everyone was immediately convinced, but the key evidence for this was unequivocal. The SFM contained grains of 'shocked quartz, their crystal lattice deformed by immense pressures caused by the impact of a giant meteorite travelling at perhaps 15 km/s. These are the most extreme events on Earth. The energy involved is mind-blowing, generating momentary temperatures (>10,000°C) and pressures (>30GPa, equivalent to the pressure at the bottom of an ocean 3,000 km deep!) that are unmatched by any normal process on Earth. We may not be able to see the shocked quartz grains without a microscope, but there are plenty of other clues to the scale of this catastrophe for the observant geologist to look out for.

This is a remote area of Scotland but fortunately some of the key sites are within easy walking distance of the road, and if just one location is to be visited then it has to be Stoer. From near Lochinver the road to Stoer meanders through a spectacular undulating landscape eroded into the almost 3 billion year old Lewisian Gneiss that lies beneath the Stoer Group and, indeed, beneath much of northern Scotland. The stunning scenery owes much to repeated glaciations over the past 2 million years but elements of it are far older, with the Stoer Group and younger Torridon Group (1 billion years) themselves lying on a highly irregular surface eroded into the Lewisian Gneiss more than a billion years ago. This ancient land surface can be seen up-close on the south side of Clachtoll Bay and it is worth spending a little time in this beautiful sandy cove to examine the intensely deformed Lewisian Gneiss, the sandstones and mudstones near the base of the Stoer Group, and the layer of gneiss fragments – a fossil debris fan – that separates the two. If time and tide allow, it is then a pleasant walk north around the headland, past more Stoer Group sandstones and mudstone, to the Bay of Stoer. Alternatively you can drive to Stoer and park next to the cemetery, from where the shore is easily reached across a field.

The SFM itself is conspicuous in the distance, forming a dark narrow headland with a distinctive 'shark-fin' stack just offshore, beyond which the cliffs rise considerably in height. From the cemetery it takes only 20 minutes or so to reach the SFM via the cliff-top path, but it is worth spending time exploring the older part of the Stoer Group spread out in dipping layers on the shore. They reveal a wealth of sedimentary features that tell us much about the environment in which they were deposited and across which, a little later, the impact deposit was to spread out with such devastating consequences. Cross-bedding in the thicker sandstones tell us the direction in which the rivers were flowing, while wave-rippled and mud-cracked surfaces show that shallow lakes and rivers dried out periodically. Much of the fine layering within the sandstone beds is contorted, and this 'soft-sediment deformation' is evidence for rapid deposition of waterlogged sediment and, perhaps, the effect of earthquake tremors.

With care it is possible to walk along the shore at low tide, although some of the thicker sandstone beds can prove something of an obstacle, but whether approaching from the shore or the cliff-top path there is no mistaking when the SFM itself is reached. It projects further out into the bay than any of the other rock layers and a series of thin layers of mudstone and sandstone, one of them beautifully rippled, are overlain abruptly by a seemingly structureless mass of rock rising several metres above the beach. This dark red rock is speckled with grey fragments of impact-melted rock and for anyone seeking a souvenir there are countless pebbles and boulders of this strange rock scattered across the beach nearby, so there is no need to hammer the outcrop itself. This first encounter with the SFM is actually a down-faulted block and the main outcrop lies just a little further on where the same thin sandstone and mudstone layers are succeeded by what seems to be a chaotic jumble of bent and distorted orange-brown sandstone 'rafts' within the dark red groundmass of the SFM itself. But stand back a little or, better still, view from the clifftop nearby, and a pattern emerges. These huge sandstone rafts are found only in the lower half of the SFM and absent from the higher part forming the dark crag beyond, and the junction between the SFM and the sandstone layers beneath is not as simple as it first appears. In several places the impact ejecta has been forced between some of these layers to form

Figure 3. *Looking north-west across the SFM at Stoer.*

conspicuous wedges. The most obvious of these appears to thin northwards to a layer just a few cm thick, but viewed from immediately south it can be seen as just the edge of a lobe that thins westwards. Others can be seen beneath an undulating sandstone layer towards the south end of the promontory (Fig. 3) and, indeed, the downfaulted block and the offshore 'shark-fin' stack are more of these westward-thinning wedges that have lost their sandstone 'caps' through erosion. These crumpled sandstone 'rafts' and westward-thinning 'wedges' demonstrate the immense force with which the expanding cloud of debris ripped up huge slabs of semi-consolidated sand from what, until moments before, had been tranquil river beds. They are also key to locating the impact site itself, which must lie somewhere to the east. I suggested that a negative gravity anomaly more

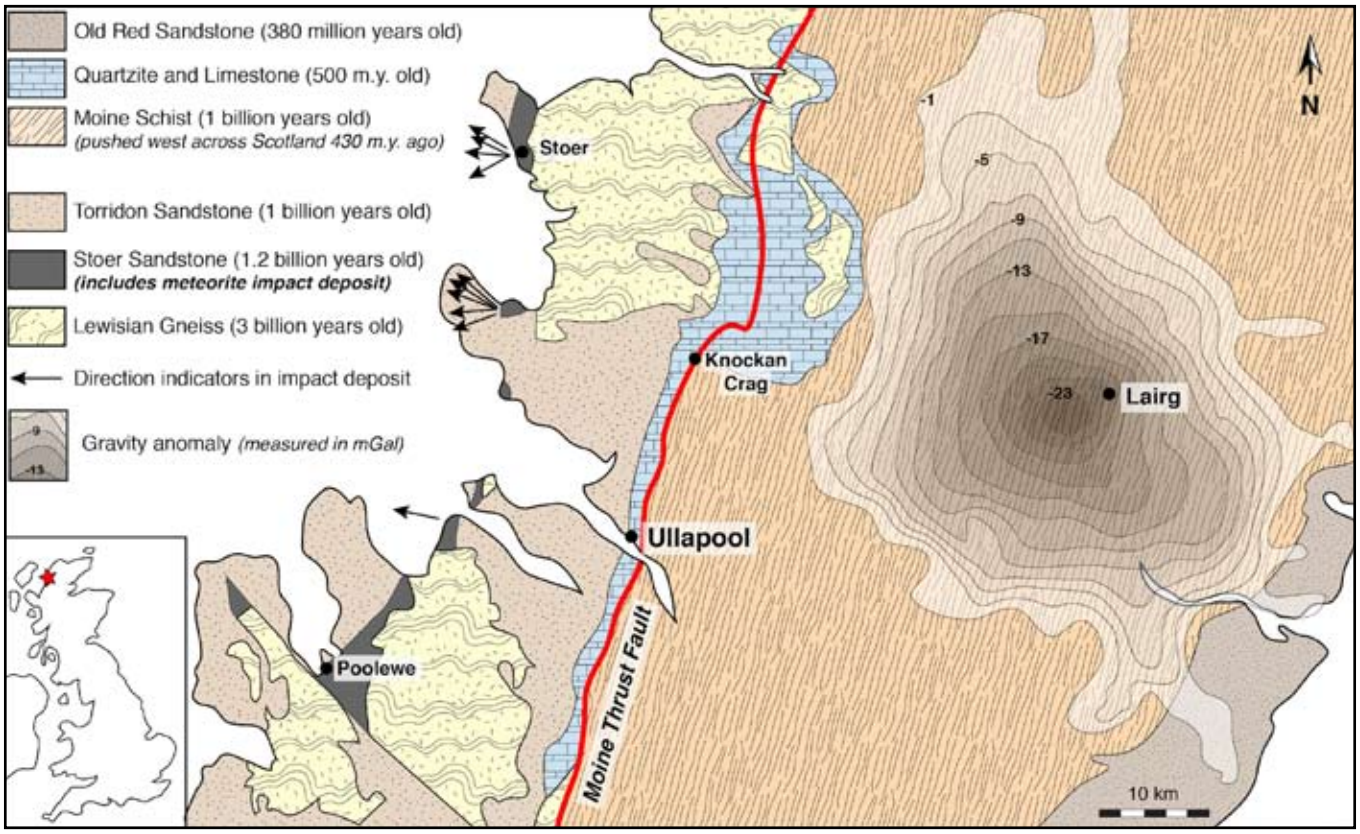

Figure 4. *Geology map of the region showing the relationship between the SFM and the Lairg gravity anomaly.*

***Figure 5**. Feldspar-lined steam escape pipes seen in plan on the top of the SFM at Stoer.*

than 50 km to the east, beneath the town of Lairg, might represent a buried impact crater (Fig. 4) but, if so, it now lies deep beneath a thick blanket of Moine Schist thrust westwards across the region around 430 million years ago. Lairg is a pleasant place to visit and worth stopping for a light lunch (less gravity) but, alas, there is nothing of this crater to see at the surface although the surrounding hills do superficially resemble an impact crater. Intriguingly, the first authors to describe the SFM as an impact deposit maintain – based on the same field evidence – that the crater is to the west, beneath the Minch Channel. From what you can see at Stoer, which view do you think is correct?

The sandstone rafts at Stoer demonstrate the destructive forces involved, but they also show evidence for considerable heat. Their texture is more like quartzite than the sandstone beds below, and clearly they were thermally metamorphosed by the impact deposit that enveloped them. More evidence of this heat can be seen in the upper part of the SFM where irregular cavities and pipes, lined with pale orange feldspar, are exposed in section on the dark crag behind and in plan on the surface above (Fig. 5). These tubes represent escape routes for superheated steam, with analysis of the feldspar indicating a temperature of more than 200°C when it was deposited.

The grey-green melt fragments become smaller in the upper metre or so of the SFM and, with careful searching, it is possible to find small accretionary lapilli among them on its weathered top surface. These pea-sized pellets formed as layers of dust accreted around mineral grains as the finer material settled out of the impact cloud, and they are much like the accretionary lapilli that form in some volcanic ash clouds. Most are less than a cm across here and rather sparse, but at Enard Bay, about 15 km further south, they are abundant in the top three metres of the SFM and often twice as large (Fig. 6).

The top of the SFM is almost as abrupt as its base, although the actual junction with the strata above is hidden in a rather inaccessible gully. Beyond, the cliffs increase in height above a series of thinly-bedded sands and muds, around 100 metres thick in all. These were deposited in a lake, a setting very different from the predominantly riverine environment that had dominated the landscape until just moments before (geologically speaking). This profound and abrupt change has been interpreted as the result of damming of eastward-flowing rivers by debris thrown out by the impact and it suggests that somewhere to the east, closer to the impact site, the ejecta layer was more than 100 metres thick. The lake eventually filled with sediment, and new river systems, represented by sandstones that succeed the lake deposits, developed across what must have been a landscape profoundly altered by the impact

***Figure 6**. Accretionary lapilli weathering out from the upper part of the SFM at Enard Bay.*

and its aftermath. These lake and river sediments above the SFM are very difficult to access at Stoer, but they can be studied up close at Enard Bay en route to the SFM outcrop there. Nonetheless, it is worth ascending the hill to avail of the spectacular view looking back across the SFM impact layer and sandstone ledges of Stoer Bay, to the undulating ancient landscape on the Lewisian Gneiss and the extraordinary hills of Torridon Sandstone beyond (Fig. 1).

For those with more time to spare it is worth visiting Enard Bay, or more specifically the small bay immediately west of the headland of Rubh' a' Choin (Grid Ref NC 031147), accessed by a 4 km walk along a rough coastal path from the south end of the idyllic Achnahaird Bay. The SFM there is rather different, most noticeably in the abundance of large accretionary lapilli towards the top. The lake sediments above are beautifully exposed, as are the succeeding river sandstones passed along the coastal path.

Another site worth visiting, and much closer to the road, is at Second Coast where the SFM is exposed on either side of a small cove (Grid Ref NB 925912). It is only about 4 metres thick here, with neither lapilli nor sandstone 'rafts', but the striking feature of this site are the numerous angular blocks of Lewisian Gneiss embedded in the river sandstone that lies immediately beneath the SFM (Fig. 7). The best explanation for these blocks, which range from small chips to veritable boulders, is that they were catapulted out at high speed (4–5 km/s) during the very first moments of the impact, raining down onto the river plains before the main mass of the SFM ejecta deposit reached here.

For many readers Assynt may seem a long way to travel yet even before the discovery of this meteorite impact deposit it was host to some of the most spectacular geology in the UK. Recognising the SFM for what it is – evidence for one of the most catastrophic events in Earth history – is surely the icing on the cake for the geology of this remarkable region.

Further reading

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Goodenough, K. M. & Krabbendam, M. 2011. *A geological excursion guide to the North-West Highlands of Scotland*. NMSE Publishing Ltd., 224 pp. (Stoer and Enard Bay are covered by Excursions 3 and 4, which can be downloaded from the BGS Earthwise website at http://earthwise.bgs.ac.uk/index.php/Geological_excursion_guide_to_the_North-west_Highlands_of_Scotland)

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Michael J. Simms

National Museums Northern Ireland,
Cultra, Holywood BT18 0EU

michael.simms@nmni.com

***Figure** 7. Angular blocks of Lewisian Gneiss embedded in the sandstone immediately beneath the SFM at Second Coast. The slab on the right is embedded vertically, an orientation difficult to explain other than by it falling out of the sky!*