

A megaflood in the English Channel

In the 2016 Harold Jeffreys Lecture, **Jenny Collier** describes the discovery of plunge pools and streamlined islands in the English Channel, the geological consequences of a Pleistocene Brexit.

Island Britain is deeply embedded in our psyche. Indeed, the white cliffs of Dover are a modern icon of our national identity, with the perception that the English Channel (La Manche) repeatedly protected us from “unwanted continental influences” throughout history. But when did this concept of Britishness evolve? It is well known that, less than 500 000 years ago, when our hominid ancestors battled with the glacial world, southern Britain was physically connected to northern France via a rock ridge at the Dover Strait. This allowed them, and other land animals, to migrate back-and-forth as the climate cooled and warmed. This land bridge disappeared to form the isolated Britain we know today, but how it did so has been the subject of much debate. Did it just slowly erode away in a series of cliff falls as it was weakened by tides and storms, as we see around the coastline today, or did something more dramatic happen? Once posed, this question remained unanswered for more than 50 years, until in 2003 we took to the water with the latest geophysical equipment and discovered an astonishing landscape below the waves. Over the following years we have slowly pieced together evidence for an array of features carved into the floor of the English Channel that we believe show that the rock ridge was removed by a catastrophic event. This event literally changed the course of our history, with the implications resounding right up to the political climate of today.

Catastrophic flooding

The large continental ice sheets that dominated the northern hemisphere in the Pleistocene left their mark in the UK landscape. Hanging valleys and drumlins, for example, landscape features formed under



1 The Channeled Scablands, in Washington State, USA, is thought to have been created by a series of megafloods from repeated breaching of an ice dam around 10–20 000 years ago. Too little water flows over the Palouse Falls to have carved the deep canyon in which it flows. (Scott Elliott Smithson/Flicker)

the ice sheet, are familiar from geography lessons at school and holidays in the Lake District. In a similar way, the ice fronts themselves leave an array of characteristic landforms such as moraines, tunnel valleys and misfit valleys. During the 20th century, scientists slowly collected evidence for these features on land and, from their spatial and temporal relationships, built up a history of the ice ages. As part of this endeavour, curious landscapes near the ice fronts were also identified that are now recognized as resulting from catastrophic flooding (Bretz 1923). Their formation needs a rapid release of stored water to inundate an otherwise dry expanse of land, carving and depositing a characteristic set of landforms. A retreating glacier produces a lot of meltwater so it is easy to imagine how some of it might become temporarily dammed behind a lobe of ice or some sort of geological barrier before being released

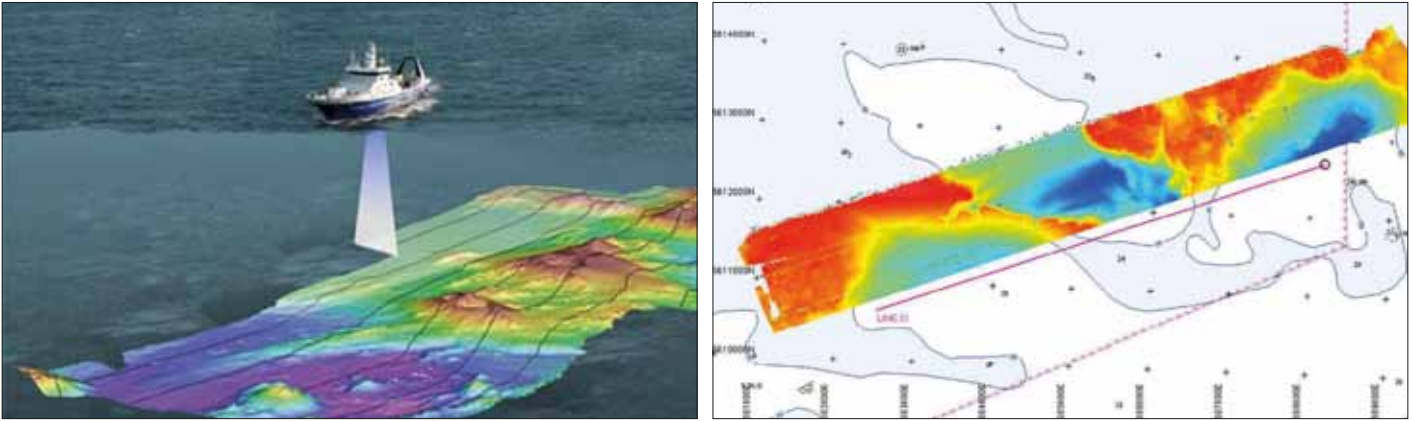
and returning to the ocean. Indeed we have examples of this today, albeit on a smaller scale, when Icelandic volcanoes under the ice cap erupt and trap water in their craters which may be released later in a *jökulhlaup*.

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“Curious landscapes are now recognized as resulting from catastrophic flooding”

While their initial recognition was controversial, periods of catastrophic flooding are now accepted as characteristic of melting ice sheets.

The best-studied example is in the Channeled Scablands region in the state of Washington, USA (figure 1). Here there are spectacular plunge pools, potholes and chaotic blocks – features left as the lake water breached and over-spilled the dam, cascading onto the landscape below (Baker 1978). Downstream, a network of teardrop-shaped bedrock islands and anastomosing channels are found, quite unlike any landscape carved by steady-state river systems, even Pleistocene ones!

So what of our own British–Irish and Scandinavian ice sheets? Prior to our work



2 (Left) Cartoon of a boat at sea collecting the data. (Right) A computer screenshot taken onboard during the early bathymetric surveys of the River Arun. The coloured multibeam bathymetry swaths are superposed on the best previous map.

there was little evidence for this behaviour, although a set of enigmatic deeps (the Fosse Dangeard) had been discovered at the Dover Strait (Pas de Calais) during routine survey work for the siting of the Channel Tunnel in the 1970s. This first led Smith to propose a catastrophic model – after all, there was known to be a rock ridge that would be a perfect barrier dam for a large lake when meltwater was prevented from draining northwards by a huge wall of ice across the northern North Sea (Smith 1985). However, this idea was not taken up by the scientific community because of the lack of supporting data. But had we really looked for the other evidence? Could it be carved into the floor of the Channel – one of the busiest shipping routes in the world – and not yet discovered?

Tools of the trade

Measuring the depth of water is one of the most basic marine geophysical measurements. However, until recent decades this was an extremely time-intensive process, requiring a boat with an echo sounder, sailing back and forth in parallel tracks across the seafloor. An echo sounder releases a short acoustic pulse, typically in the kHz band, and records the travel time of the return. This technology was developed during the second world war as part of submarine warfare. However, undertaking these measurements from a moving vessel which, even on a relatively calm day, are unstable is no easy matter; motion compensation methods at the time were poor and the resolution was therefore low. On the continental shelves, attention was mainly focused on tracking mobile sandbanks for maritime safety and finding routes for underwater cables. For these applications a lateral accuracy of around 20m and vertical accuracy of a few tens of centimetres was deemed acceptable. The soundings appeared on charts, often as spot points together with hand contours of water depth.

In the post-war era when the plate

tectonic revolution took place, scientists thought that the shelves in general were flat and, frankly, a bit boring. Few resources were committed to study these areas. By the late 1980s, new swath bathymetry systems were developed to study the deep-water elements of plate tectonics such as mid-ocean ridges. Rather than recording the water depth point directly below the boat, now a fan of acoustic energy was emitted that allow measurements to be made in a band up to three times the water depth across the vessel (figure 2). Not only did this make the process much, much quicker, it also improved the resolution significantly, with the introduction of beam-forming giving a much narrower footprint on the seabed than the old systems. This was like going from cutting your lawn with a pair of scissors to having a rotary lawn mower – quicker and a better finish!

For the first time, continuous bathymetry data could be collected without needing a boat to sail up and down multiple times, and three-component motion sensors were interfaced to solve the moving platform issue. Initially developed for deep water (typically operating at 12kHz for water depths >1000m), shallow water systems operating in the 240kHz range eventually came onto the market in the early 2000s. This breakthrough came about because of the declassification of the Global Positioning System and the ability to combine these data with modern gyroscopes to correct for a boat's pitch, roll and yaw to an accuracy of less than a centimetre. Now the lateral resolution was reduced to a metre or so and vertical resolution to a few centimetres. Instead of spot points and contours, continuous grids of bathymetric data with a 5m cell size could be produced.

In 2002, my group at Imperial College London was part of a university consortium that acquired one of these new shallow-water systems. No mention of catastrophic-flood hunting was made in the

proposal – we thought it was too speculative. We planned to use it at a set of distant locations to study volcanic and tectonic processes, yet what we discovered in our own back yard was truly astonishing.

First steps

Once we had bought our sonar and completed the sea trials, we were ready to go. But not only was the new sonar quite expensive, it was also complicated to set up. The system was portable which, while giving ultimate flexibility, also required it to be installed before the start of each survey; the clock was ticking and research money was being spent while the boat remained tied up in the dock. Therefore as a first project we looked for a target close to home, and decided to work on a palaeo-river system in the English Channel as part of a larger national project to understand Palaeolithic seascapes.

During the Pleistocene glaciations, sea level fell by up to 120m, so the English Channel as we know it today had become exposed dry land. As the coastline advanced, the major rivers of southern England and northern France extended out onto this ever-growing expanse of land (Gibbard 1988). We started our work on one of these systems – the Palaeo-Arun or offshore extension of the River Arun that enters the English Channel seaway today at Littlehampton. As we left the port of Brighton we had two pressing concerns: would the interface between the GPS antenna, the motion sensor and the outboard sonar all synchronize correctly, and what would be the state of preservation of the Pleistocene landscape, now below 20–30m of water? The sea level had risen across this region since the last glaciation – would there be anything left? Would the rising tide have rubbed everything out, leaving a featureless, sediment-covered surface?

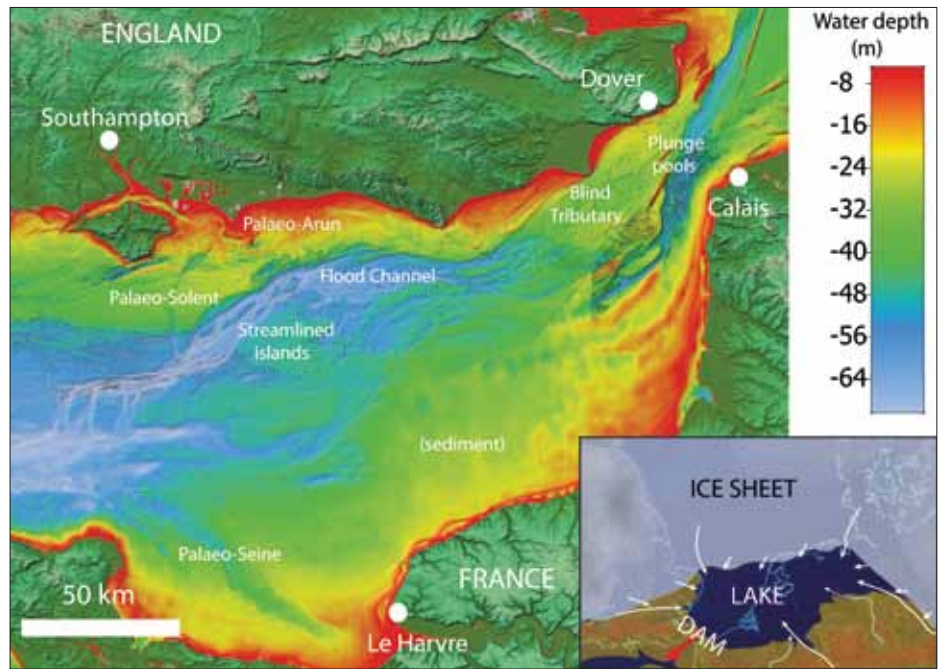
From the first time we put our new sonar in the water, things were looking

promising. Barring a few early glitches, the Reson SeaBat sonar system worked like a dream. Just as importantly, rather than a flat, featureless, sediment-covered surface, the seafloor was clearly exposing bedrock and carved features (figure 2). This was satisfaction enough – and the mood on the boat was buoyant and self-congratulatory. Then one day, as we surveyed further and further out from the coastline, the trace of the river just stopped. Instead of forming a steadily graded tributary, it was simply cut off and left hanging with a 10 m drop to the floor of a larger river. It was easy to imagine it forming a small waterfall – but this was southern England where gradients are shallow and such features generally lacking. It was jaw-dropping; we made a half-page spread in one of the Sunday newspapers and we knew we were really on to something.

Over the following years, we have pieced together many sections of bathymetric data. This has come from many sources and several of us were involved in stitching them together. Despite having modern multibeam systems, the English Channel is a vast area and so we needed to dig deep into the archives to slowly fill it in. We became expert in dealing with Datum issues, correcting for mobile seabed and gridding data of variable density. While bathymetry was our main dataset, we have also collected sub-bottom seismic and core data in order to determine what the seabed was made of. As each area was completed – first the downstream portion and later the critical Dover Strait region – it became more and more clear that the assemblage of landforms generated by a catastrophic flood were indeed present.

A Pleistocene landscape

Our new bathymetric map of the eastern English Channel is shown in figure 3. The main flood channel is visible along most of the Channel floor. This was unexpected; a vast quantity of loose sediment is generated from ice sheet erosion and periglacial weathering during glacial periods and we expected to see it blanketing the bedrock. Today, however, these deposits seem to have been almost totally swept away. We believe this is because of the high seabed shear stress developed under today's tidal regime. The funnel shape of the English Channel makes for strong tides and these seem to have revealed the bedrock valley. When we plotted the predicted seabed stress from tidal models against the landscape, we could see an almost perfect correlation. The flood channel system is cleanest where the seabed shear stress is high, and it becomes increasingly choked with sediments where the seabed shear stress reduces. The modern tides therefore



3 Our new bathymetric map of the English Channel and surrounding land, showing the megaflood landscape. The inset shows a recreation of the situation before the megaflood.

provide an explanation for the visibility of the seascape – they have swept the region free of significant sediment in all but the central part of the study area.

The new map shows a major flood channel system extending from south of the Isle of Wight to beyond the Dover Strait. In plan view, the channel traces a broad “S” shape across the area. Just like the River Arun that we saw during our first survey, other rivers such as the Solent were also truncated by the flood waters as they rushed towards the Atlantic Ocean. We don’t see the confluences of the Adur, but this is likely to arise from the complete sediment infilling of these sea-level low-stand valley extensions. We reflected that if we had chosen this rather than its neighbouring River Arun back in 2003, we might not have been guided to the megaflood landscape.

Perhaps what is most impressive about the flood channel is its size. It dwarfs the other rivers, such as the River Seine and the Solent, measuring up to 15 km bank-to-bank. Indeed this would have been by far the largest European river in recent history! From the size and shape of the channel cross-section, coupled with its gradient, we estimated that at its peak this conduit would have transported around $1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ of water, making it one of the largest known megafloods on Earth. For comparison, the maximum rates along modern rivers in flood such as the Amazon reach just 25% of this value.

In the centre of the main flood channel there is a whole series of islands, 36 in all. The islands, which are up to 10 km long, have characteristically flat tops and stand

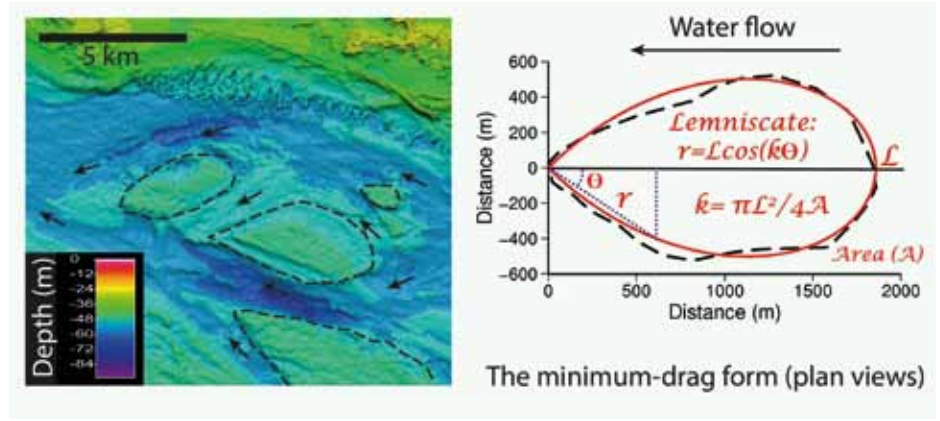
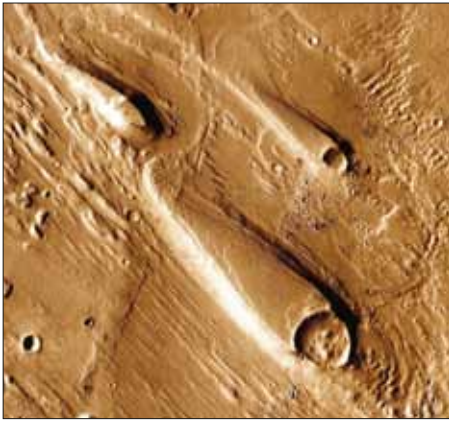
10 m proud of the channel in which they sit. But were these streamlined islands, those most characteristic features of the downstream portion of catastrophic flood terrains? The high speed of the flood waters are thought to result in the tear-drop or lemniscate shape as it minimizes hydraulic drag (Komar 1983). Interestingly, some of the earliest recognized stream-

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lined islands were found on Mars by Mariner 9 and were taken as one of the first pieces of evidence for water on the surface of that planet (Burr *et al.* 2009). Of course

islands also form in normal rivers where they are made by depositing gravels and do not necessarily form lemniscates. So we needed to demonstrate that those on the floor of the English Channel had the right shape and the right composition.

In the case of the English Channel examples, we could show that the islands had near perfect lemniscate outlines and were surrounded by anastomosing scours ~1–2 m deep, 200–500 m wide and 8–15 km long (figure 4). Just like in the Channeled Scablands, the islands form in family groups, with cross-over channels isolating new islands from the tips of others (Collier *et al.* 2015). There was also a relationship between the shape and surrounding bedrock geology – those carved into chalk were slimmer (higher length:width ratios) than those carved into Tertiary sandstones. This was an important observation; gravel islands would not show any correlation. Later we were able to use seismic reflection data to show bedrock ridges rising up from below and into the islands themselves. There was no doubt: these islands were not



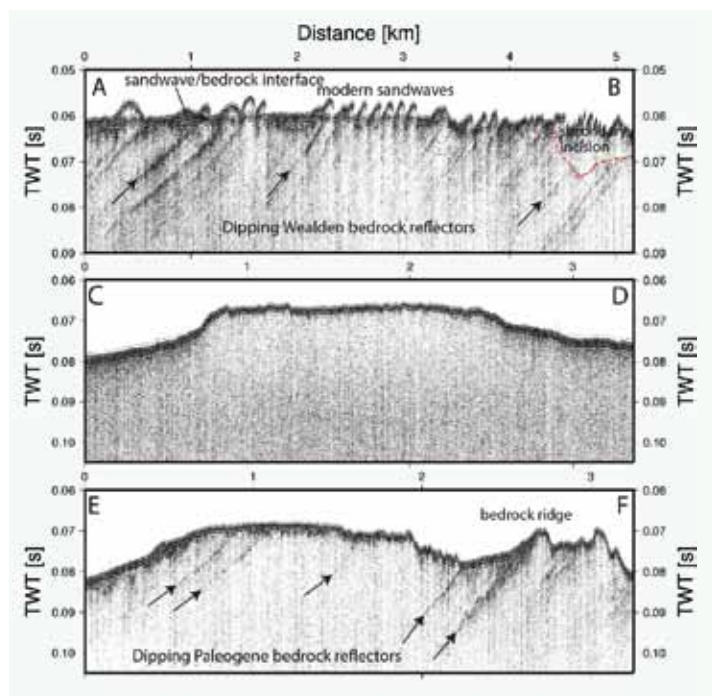
made of gravel, but bedrock.

As we collected the seabed imagery from various parts of the English Channel, we repeatedly saw the same result: Pleistocene extensions of modern rivers truncated by a main flood channel that was full of bedrock-cored streamlined islands. However, as we worked our way towards the Dover Strait, there was another, particularly well-developed and distinct large tributary system offshore of the Weald area of England (labelled “blind tributary” in figure 3). This system is cut into a prominent 20 km wide bedrock platform that lies at water depths of ~25–30 m. It consists of a network of elongate valleys, up to ~600 m wide that extend ~40 km upstream from their confluence with the main channel. Importantly, the valley network starts on the platform and shows no connection to onshore drainage, indicating that it was initiated on the platform itself. In modern-day *jökulhlaups* (a type of glacial outburst flood), the escaping waters first flow as sheet floods before starting to carve out channels. Based on this observation, we believe the bedrock platform represents an initial flood erosion surface that formed a broad spillway in the Strait, prior to subsequent incision of the main flood channel network.

A bad day to be in Dover

Moving eastwards towards the critical breach point, the main flood channel continues to weave its way and passes, almost without noticing, between the jaws of the chalk cliffs on either side. So where was the evidence for the dam failure? After all, this was the place where the system was most confined and during the rock ridge failure the waters would have carried large chunks of chalk bedrock. In the Channeled Scablands this zone is characterized by deep potholes, erratic boulders and giant plunge pools. Of course, one needs to be realistic – we are not looking at a dry landscape, the sea has risen across the whole area, removing large boulders and smoothing potholes. But what about those enigmatic deeps found in the works for the Channel Tunnel, the Fosse Dangeard.

4 Streamlined islands on Mars (above left) and on the floor of the English Channel (above), characteristic of formation under high speed flow in a river larger than any now in Europe (top right). The latter are shown to be made of bedrock (right) from sub-bottom profiling.



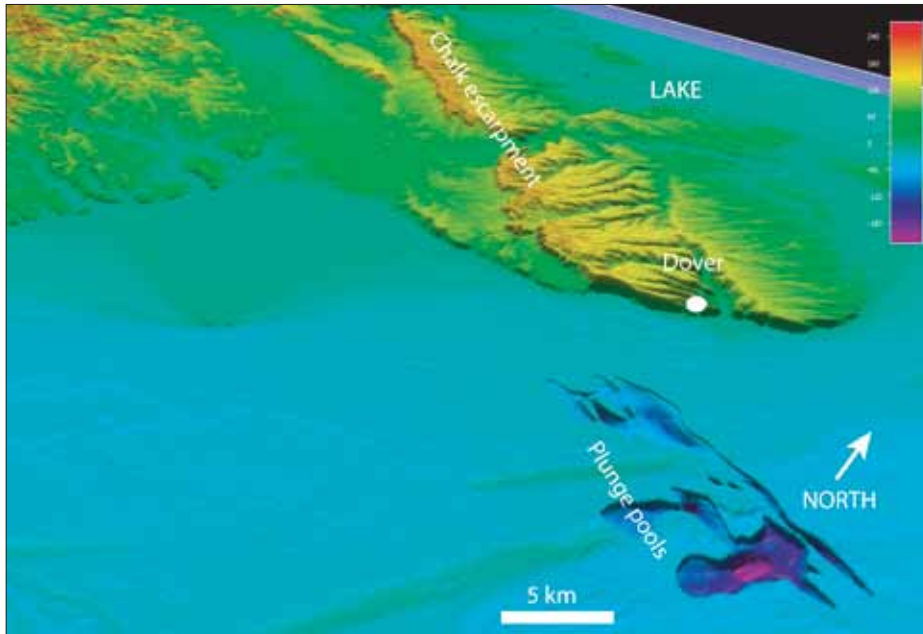
Could these deeply incised basins be the filled-in remnants of the plunge pools?

We set about collecting seismic data across the Dover Strait. We put together data from the original Channel Tunnel campaigns with previously collected academic data and our Belgium colleagues collected new data across the critical region. The data showed a set of six bowl-shaped depressions 5–10 km long, 4–6 km wide and up to 120 m deep. Importantly, the holes were in exactly the right place – at the foot of the chalk outcrop where the escarpment would have been (figure 5). Carving such a set of holes into solid bedrock requires the force of water that would result from overspill from a 200–300 m high precipice. Initially this would have been the most spectacular waterfall in modern Britain, until eventually removal of the lip of the dam gave way to a full-scale collapse of the barrier and the contents of the lake thundered down onto the dry, tranquil English Channel valley below.

A key question is when did this happen? Given the submerged nature of our landscape it is much harder to date than

examples on land such as the Channeled Scablands. One possibility would be to drill the Fosse Dangeard and recover sediments trapped at its bottom that might contain dateable material. Such an endeavour is challenging, given its location in the middle of the world’s busiest shipping lane, and is yet to be attempted.

An alternative is to look at the place where all the sediment eventually ends up – in giant alluvial fans at the Atlantic shelf edge. These systems collected the products of the ice sheets throughout the glaciations, and scientists working on them have demonstrated that something dramatic happened to the pattern of sedimentation around 450 000 years ago (Toucanne *et al.* 2009). Most tellingly, “ice-rafted debris” appeared – showing that as the ice sheets broke up and sea level rose for the first time, large icebergs floated down the English Channel. This would have been quite a sight for the early Europeans – the Straits were truly open. However, the analysis of the shelf sediments also showed another change at around 250 000 years ago; we now believe this second event carved the



5 Topography of today's Dover Strait with the sediment within the Fosse Dangeard plunge pools removed. Note how the deep, bowl-shaped holes lie at the foot of where the chalk escarpment would have stood. Water plunging over the 300m high escarpment chiselled the holes before the dam collapsed.

deep channel system seen through the Dover Strait today. So in fact there seems to have been a two-stage process to the opening of the Dover Strait and traces of this are also seen in the downstream morphology (Gupta *et al.* 2007).

Speculations and implications

So what happened on that day back around 450 000 years ago when the rock ridge failed? This is a difficult question to answer. Unlike an investigation of the failure of a man-made dam where the building materials are well-characterized and the construction uniform, the properties of the rock dam would have been variable. Any walk along the North or South Downs today shows seams of irregular flint nodules within the chalk, and areas where past rivers have cut nicks into the chalk escarpment. Was a catastrophic failure inevitable or, like many “accidents”, did it require a combination of factors? In truth, of course, we will never know. However, from time to time the Dover Strait region is known to experience medium-sized earthquakes. Perhaps the most famous one happened in 1580, when the ground motion was felt as far away as London (García-Moreno *et al.*

2015). Possibly an earthquake happened when the lake waters were at their peak, triggering a rock fall at the escapement crest through which the flood started. Alternatively, perhaps there was a major fall of ice from the back of the lake that sent a pulse through the lake and overspilled the chalk barrier. We can speculate that if

events had not transpired to break this barrier, we would still be physically connected to continental Europe.

When we first released our results, one of the most unexpected reactions came from scientists at the Natural History Museum working on the Ancient Human Occupation of Britain (AHOB) project. They were tracing the pattern of early occupation of Britain and had found evidence for what they described as a “population crash” around 250 000 years ago. This was a particularly warm period of NW European history, with abundant evidence of large mammals such as rhinoceros and lions in southern England – but strangely no sign of early hominids. Usually, as hunter-gatherers, the humans were expected to follow the large herds of animals that were so important to

their diet. The removal of the land bridge provides a perfect explanation. The lack of a navigable pathway prevented their re-colonization of this outpost of Europe after the glaciation, whereas the other large mammals with their greater numbers and herd mentality managed to get across and into southern England. Perhaps this was the first example of the consequences of a geological Brexit?

Future directions

It is no exaggeration to say that the knowledge of the surface of our own planet lags behind those of our near neighbours. The fact that we discovered the English Channel megaflood within the current decade is a prime illustration of this. The water that blankets 70% of the surface of the Earth shields it from satellite imagery. While much has been learnt by indirect methods in the deep oceans (satellite altimetry – measuring the height of the sea surface or geoid and exploiting the fact that this surface is a gravitational equipotential) the shallow-water continental shelves that surround us cannot be studied with this technique and so remain largely unexplored. Several marine nations have undertaken full mapping programmes of their territorial waters, including our neighbour Ireland. Yet in the UK, despite our island status and long history of marine research,

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we have covered very little. However, a new initiative to map the shelves around our islands – MAREMAP – is underway, which will help to co-ordinate our efforts as more survey data become available. There is also a growing trend of making seabed data publicly available, as the value of our surrounding shelves is recognized. When we started our work this was not the case and we had to knock on many doors to gain access to the data archives. I am proud to have played a small part in showing the potential of such datasets. Much of the new work is likely to be driven by the growing need for informed management of our marine resources, but fundamental science also waits to be discovered. ●

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HAROLD JEFFREYS LECTURE

Jenny Collier delivered “Making Britain: evidence for catastrophic flooding in the English Channel” at the RAS Ordinary Meeting on 11 November 2016. The annual RAS lecture commemorates Sir Harold Jeffreys’ long career in mathematics and the physics of the Earth. The lecture covers a topic from geophysics or planetary sciences. See <http://bit.ly/2ld72DC>.

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