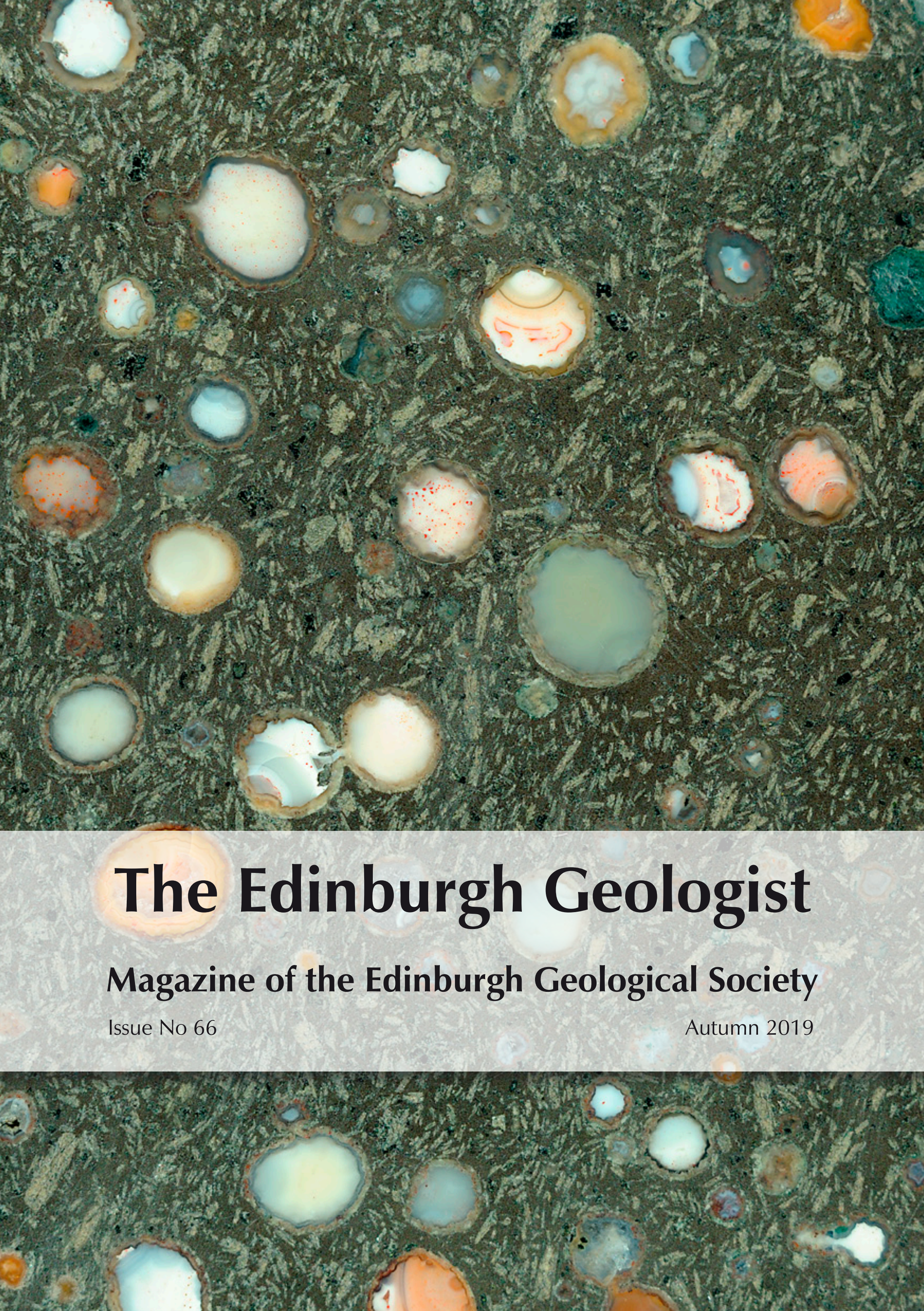

The Edinburgh Geologist

Magazine of the Edinburgh Geological Society

Issue No 66 Autumn 2019

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Cover Illustration

Small agate-filled vesicles in Devonian lava from Scroggie, near Balmerino in Fife: x 0.9 approximately. Image courtesy of National Museums Scotland, NMS G.210.871 A. There are more than 5500 agates in the National Museums' collection, and this specimen is from the Heddle agate suite, donated after Matthew Heddle died by Alexander Thoms, to whom it had been bequeathed.

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The Edinburgh Geological Society was founded in 1834 with the twin aims of stimulating public interest in geology and advancing geological knowledge. We organise a programme of lectures and excursions and also publish leaflets and excursion guides. For more information about the Society and membership, please visit www.edinburghgeolsoc.org.

Ladies' Day

An editorial ramble by Phil Stone

As usual, this issue of Edinburgh Geologist ranges across disparate geological themes, but our articles have one unifying feature. All the principal contributors are women. In this, the year that the Geological Society of London has celebrated the centenary of its first admission of female Fellows (at a momentous meeting on 21 May 1919), I rather wish the coincidence had been pre-planned. Such foresight cannot be claimed I'm afraid, but perhaps it is more telling for that combination of authors to have emerged unbidden.[1]

Rachel Walcott leads off with a beautifully illustrated account of Matthew Heddle's agate collection — and provides our striking front cover. Paige DePolo tracks dinosaurs on Skye and takes to the sky, kind of, in the process. Carol Cotterill heads out into the North Sea, to the Dogger Bank, and explains the foundations of what may become Britain's largest offshore windfarm — and graciously includes a male co-author. Keira Greene gives graptolites a poetic appreciation, imaginatively celebrating these biostratigraphic wonders of the Scottish Southern Uplands. The graptolite palaeontologists Gertrude Elles and Ethel Wood were two of the first eight women admitted to the Geological Society of London and would have appreciated Keira's very different response to their mutual inspiration. Finally, our book review, *Introducing Geology*, is provided by Alison Tymon.

Passing over the temptation to link Paige DePolo's dinosaurs with London's pre-1919 geological élite, let's move rapidly on to another gender revolution that took place more locally seventy years ago. Then, in 1949, five women were admitted as the first female Fellows of the Royal Society of Edinburgh, and amongst them were two

[1] And not to be outdone, the British Geological Survey will soon have its first female Director; Dr Karen Hanghøj will take up the role on 14 October.

[2] Keira's contribution to *EG* is taken from her film *Eustatic Drift*, which premiered in May this year at the Alchemy Film Festival in Hawick – what an appropriate location.

geologists: Doris Reynolds and Ethel Currie. Reynolds developed the controversial theory of 'granitization' which, although later disproved, focussed attention on the hard questions surrounding the origin of granite. She was based at Edinburgh University, perhaps overshadowed somewhat by her famous partner—I wonder if Arthur Holmes was ever introduced as Doris Reynolds' husband. Currie, a palaeontologist and Carboniferous stratigrapher, was Assistant Curator at the Hunterian Museum in Glasgow and in 1952 became the first female president of the Geological Society of Glasgow. Here in Edinburgh, we didn't take that radical step until 2014 although ladies were first admitted to our Society in 1865—"in accordance with the general progressive tendency of Edinburgh". They even enjoyed half-price membership!

Of course, today's challenges and opportunities, for everyone with geological inclinations are very different to those that arose in the past—and the moraine complex of the Dogger Bank provides plenty of food for thought. Around ten to twelve thousand years ago it was the rolling hill country at the northern margin of Doggerland, the low-lying expanse of tundra that occupied much of what is now the southern North Sea. It was home to mammoths, deer and many of our human predecessors—but then the ice melted, and sea level rose. By about 5000 BC only a few low-lying islands remained, although the *coup de grâce* for Doggerland's inhabitants may have been a tsunami generated by the Storegga Slides (three huge submarine landslides off the Norwegian coast) at about 6 200 BC. We'll soon face our own battles with a rising sea level, and geology will have an increasingly vital role. Just think about coastal defences and relocation of infrastructure (and people) with the construction materials and site investigations that will demand, not to mention the associated major changes in hydrogeological regimes. Then there are the essential geological contributions to renewable energy developments and CO_2 storage—I'm sure you can add to the list. Welcome to the Anthropocene!

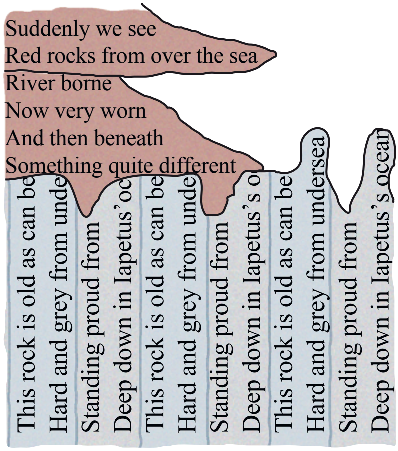
More cheerfully, let's not forget our subject's pleasures and their communication to new audiences. Geologically inspired poetry has the potential 'to reach those parts that others cannot' and will enjoy a showcase next year at Edinburgh's Geopoetry Festival, scheduled for 1 October 2020. This gathering, to be held on National Poetry Day, is to be hosted by EGS, the Geological Society of London, and the Scottish

Poetry Library, and aims to bring together poets and geoscientists "to further encourage the rocks to speak". We hope to have more on that in the next issue of *EG* but, in the meantime, one of the Festival conveners, Professor Patrick Corbett of Heriot-Watt University, provides us with his own take on Siccar Point in our concluding editorial column.

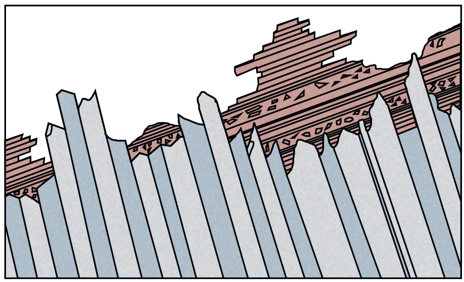
Geology? Don't bet on it!

Finally, here's something for all those readers who were disappointed to discover that the editorial headline—Ladies' Day—didn't refer to the Musselburgh Races. It is a well-known phenomenon that sometimes the eventual examination of long-neglected rock specimens can prove less entertaining than the content of the old newspapers in which they were wrapped. This was my recent experience when the packing material turned out to be the horse racing pages from the *Scottish Daily Express* of Monday 5 August 1968. A creased, yellowing photograph of galloping horses was accompanied by the results of the Kingsbury Handicap at Windsor on the previous Saturday, and carried the following caption: ***Foxroy beats off 10 rivals to win from Phantom Jet and Chuffed. Fourth was Geology.*** Can any punters out there tell us more about a racehorse called Geology?

Siccar Point



Patrick's Unconformity



Hutton's Unconformity

An appropriately unconformable view of Siccar Point by Professor Patrick Corbett, kindly drafted by Grant Ross.

Edinburgh's Geopoetry Festival
1 October 2020
Deadline for contributions 1 March
More information:
https://www.geolsoc.org.uk/GSL-Geopoetry-2020

Heddle's Agates

By Rachel Walcott

Professor Matthew Forster Heddle (1829-1897) FRSE was, indeed remains, Scotland's most prolific and thorough mineral collector and renowned mineralogist (Johnston 2015). By the end of his life he had amassed a collection that included one third of all known minerals at the time. Heddle seems to have had a particular fondness for silica, as varieties of quartz make up one third of his 7000-strong collection. Many of these, 1600 in all, are agates. While Heddle viewed the agate collection as separate from the main mineral collection, this was not a collection assembled for its beauty. As with the minerals, he was primarily driven by the desire to discover, describe and identify new features and, where possible, to understand how they formed. This motivation is reflected in the specimens and nature of his collection, now housed in National Museums Scotland (NMS).

Scottish agates

Agates are semi-precious gems largely made from cryptocrystalline quartz. They are colourful, banded nodules that typically form in the cavities of vesicular lava flows. The cavities, which act like molds, form through the coalescence of volatiles that emerge during decompression as the lava erupts and flows. As such, they have a number of interesting features; for example, the cavities are often elongate in the direction that the lava flowed before finally crystallising. Unlike most minerals, agates crystallise from the outside in, that is from the cavity wall inwards, tending to become less hydrous in composition as they do so. Layers of chalcedony and/or opal may completely fill the vesicle (Figure 1) or a small pocket may remain in the centre, which is often filled with crystalline quartz or amethyst. Whereas the outside of the agate is usually a dull green, the layering and contaminants provide an array of colours and textures inside, rendering each agate unique. All of these features were of keen interest to Heddle.

While some notable agate sites are in the Palaeogene lavas of the western Scottish islands such as Mull, Rum and Arran, most agates are found in the Permian and Devonian lavas

Figure 1 Agate from the Blue Hole near Usan, Angus, showing horizonal onyx banding and other features Heddle described in his final paper: 'fortification' banding (top left), and 'tubes of escape' (bottom left and middle right), x 1. NMS G.210.1271.

of the Midland Valley, particularly towards the north east (Figure 2). Agates are most commonly found *in situ* in vesicular andesite but are occasionally found in basaltic rock or lining fractures as in the example from Burn Anne in Figure 3a. Harder wearing than the encompassing lava, agates are often all that is left once the host rock has weathered away. Loose agates, or 'Scottish Pebbles' as they are locally known, are often found in ploughed fields and on beaches.

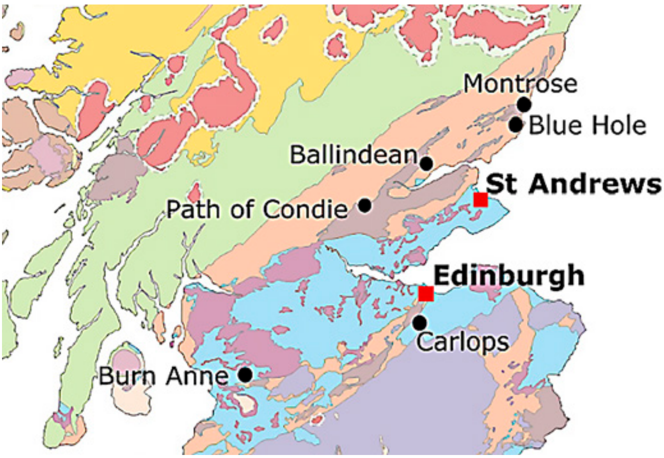


Figure 2 Map of central Scotland showing many of the locations where Heddle collected agates. For geological explanation see BGS 1:625 000 scale Bedrock Geology UK North.

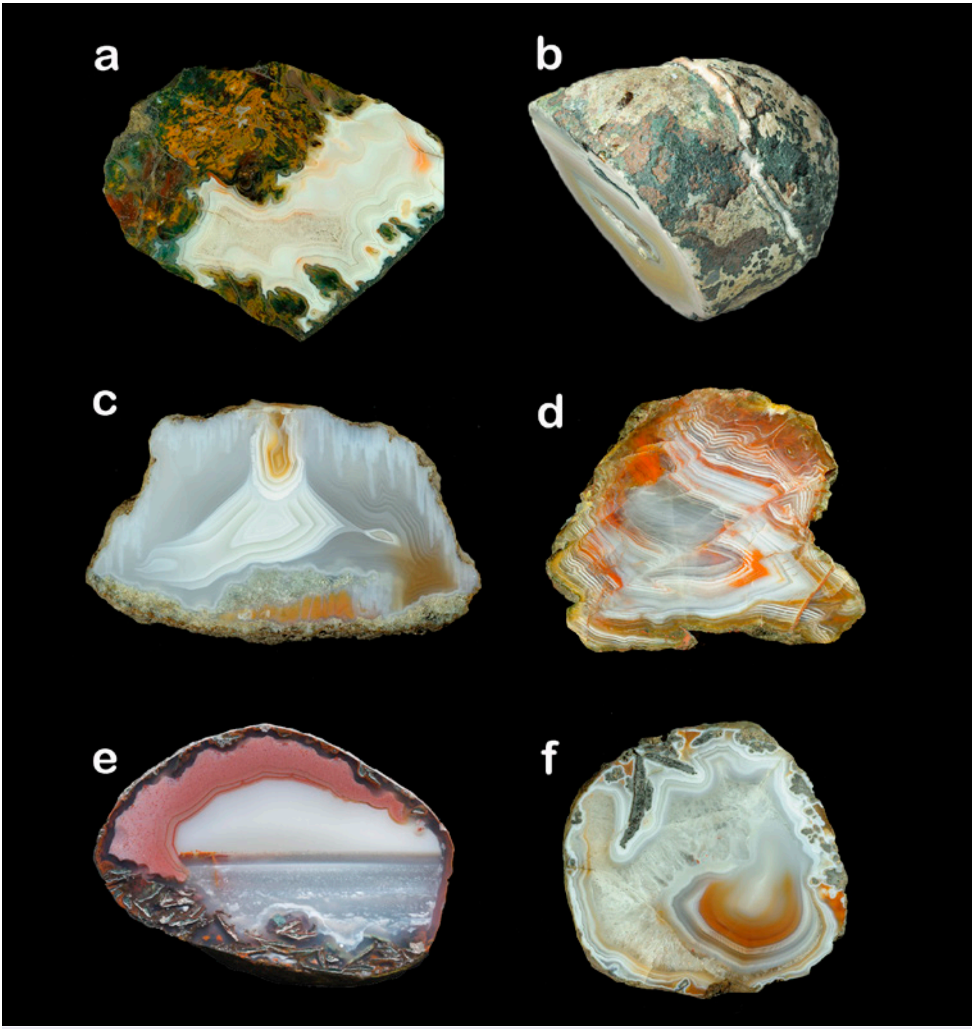


Figure 3 (a) Vein Agate with moss texture from Burn Anne, Ayrshire, x 0.6 (NMS G.210.486), (b) Agate exhibiting the green colouration of its skin and with a sealed fracture or 'rent', location unknown, x 0.8 (NMS G.210.1658), (c) Stalactitic Agate from the Blue Hole, x 0.7 (NMS G.210.1542), (d) Sheared 'fortification' agate, location unknown, x 0.6 (NMS G.210.1120), (e) Heddle's famous Seascape agate from the Blue Hole, one of two halves, x 0.8 (NMS G.210.453), (f) Agate exhibiting pendulous celadonite skin coated in chalcedony, location unknown, x 0.5 (NMS G.210.1639). The location of many Heddle agates was not recorded.

Heddle the collector

Collecting agates was a sociable activity for Heddle. We can't be sure when he started to assemble his agate collection, but he was certainly active by the 1850s when he met his life-long friend Patrick Dudgeon (1817–1895). Together they collected vein agates from Burn Anne located close to Dudgeon's house in Cargen, Dumfriesshire, but they mostly focussed on areas closer to St Andrews where Heddle taught Chemistry, areas such as Fife, Perthshire and Angus. Other companions were Robert Miln (1824–1905) who lived in Broughty Ferry, Angus, and Alexander Thoms (1837–1925) of St Andrews. Not only did these friends provide companionship but they shared good finds (Figure 4).

The most important agate locality was the Blue Hole in Angus. One third of Heddle's collection comes from this locality alone, not to mention substantial parts of Miln's and Thoms' collections. Agates from this locality were noted for their delicate beauty and bright green mineralised skin or 'paint' as it was locally known. These days, the precise location of the Blue Hole is uncertain, although we know it is on the shore near Usan, no more than 3

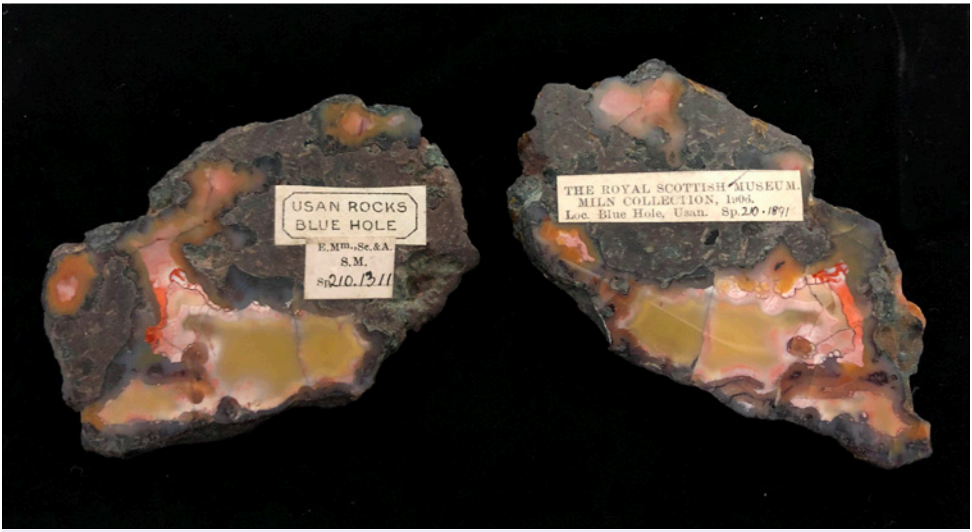


Figure 4 Heddle shared a lot of agates with friends. The Blue Hole agate on the left is from the Heddle collection (NMS G.210.1311), the counterpart (right) is from the Miln collection (NMS 210.1891), x 0.8.

miles south of Scurdie Ness in Angus (Heddle and Thomson, 1894).

Agates were not collected just for their aesthetic value, however. Unlike the collections of his companions, which were primarily a representation of geographical diversity, Heddle paid relatively little attention to the source of the specimens judging from the extant labels found with them (Figure 5a). Rather, he was fascinated by how they formed. For example, he collected broken agates as they revealed a lot about their 3-dimensional structure and sequence of formation (Figures 3b). If they revealed interesting textures he cut and polished them irrespective of how small they were; he had some specimens only 1 cm in diameter. He also collected anything unusual, for example uncut agates that reveal the flow direction of the lava or agates in vesicles that crystallised just as they started to coalesce. He spent weeks digging the Blue Hole, partly because the skin on agates there was particularly thick and soft and good for analysing. Thin sections and thick sections were used to analyse composition of non-silica minerals and he conducted a range of experiments to identify the 'skin' minerals coating the agates and those minerals within the agates. He found that some layers stuck to the tongue when licked and that chalcedony becomes stained when boiled in honey (Heddle 1899)!

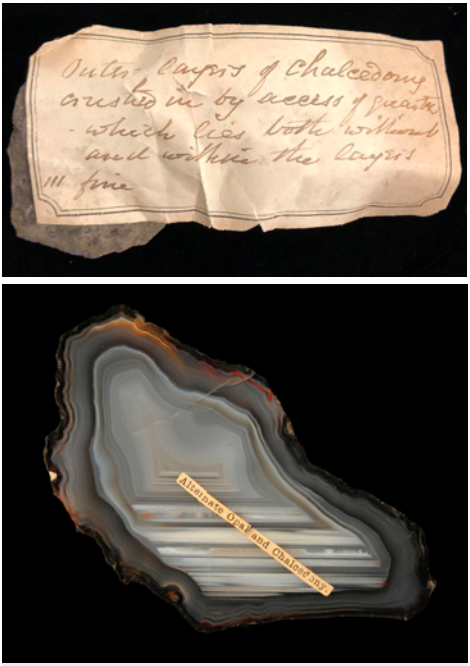


***Figure 5** (a) Label of Heddle's with one edge glued to an agate from Montrose, (NMS G.210.1120). Heddle's main motivation for collecting agates was to understand their formation through careful observation. (b) Labels put on fortification and onyx agate from Montrose which was displayed in the Scottish Mineral Gallery after Heddle's death (late 1890s–1940s) (NMS G.210.929), x 0.5.*

Heddle published dozens of papers but two of his last were on agate composition and formation. One paper written with a colleague, J. Stuart Thompson, concerned the chemical composition of the green micaceous mineral celadonite $K(Mg,Fe^{2+})(Fe^{3+},Al)[Si_4O_{10}](OH)_2$ which together with delessite (a type of chlorite $(Mg,Fe,Fe,Al)(Si,Al)_4O_{10}(O,OH)_8$)) commonly coats agates (Heddle & Thomson 1894). A second more substantial paper was on the sequence of crystallisation of agate and the resulting patterns (Heddle 1899). He was liberal with inventing new terms for his observations, for example, discachtæ, oonachatæ and hæmachatæ for the small disk-like, white and red spotted textures observed in some agates respectively. Not all of these terms are still used although some have survived, for example 'fortification agate' (Figure 5b) and 'tube of escape' (Figure 1).

In his 1899 paper, Heddle suggested that the minerals lining vesicle walls were formed from the alteration and mixing of host rock minerals, particularly augite. Sometimes these initial layers of chlorites, micas or even zeolites were so thick or loose that they would flake off or dangle into the cavity space, producing Moss Agate (Figure 3a), within the next layer of clear chalcedony; the chalcedony sometime casts loose lining material forming 'stalactites' (Figure 3c and e). Next come the bands of either onyx (horizontal bands in Figure 1), or more chalcedony. If the agates are partly unfilled, then they may have a core of quartz, amethyst or more rarely calcite, or even an empty space (Figure 3e). Finally, one of the unique features of agates with a name coined by Heddle that is still in common usage: the so-called 'tube of escape'. These are routes through which excess silica was expelled from the core of the agate back into the host rock (Figures 1 and 3b).

Heddle made many thin sections which are now housed in the Hunterian Museum in Glasgow. Using these, he noted that chalcedony has a fibrous texture with fibres orientated at right angles to the growth or banding directions. Heddle suggested that these might be the very high temperature form of silica—tridymite. We now know that these are actually formed by spirals of chalcedony and moganite, the latter being a hexagonal form, low-temperature polymorph of quartz that was discovered quite recently (Heany & Post 1992). Another important suggestion by Fallick *et al*. (1984) is that the silica gel from which agates formed originated in water at only about 50°C rather than at high temperature. These corrections aside Heddle's paper

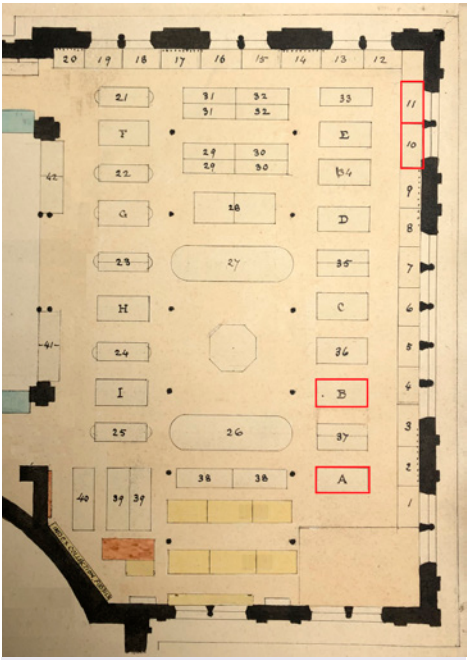


Figure 6 Plan of the Scottish Mineral Gallery as it was in 1896, two years after Heddle set it up in what is now the National Museum of Scotland. Cases containing agates are outlined in red. John Goodchild later added the agates which Thoms donated, putting them into the hexagonal case in the centre and four additional upright cases.

remains a very useful resource to understand agate formation and a great tribute to his observational skills.

In 1894, when Heddle was 65 years old, he was employed by the Industrial Museum in Edinburgh (now part of National Museums Scotland) for several months to develop a new gallery of Scottish Minerals. He used almost all the 7000 minerals that he donated and partly sold to the museum. They were located on the top, northwestern-most gallery of what is now the National Museum of Scotland (Figure 6). In this display he exhibited 300 agates, half of which were his own. When Heddle died, he bequeathed 1000 of his best specimens to Thoms, who donated them to the museum the following year. John Goodchild, the curator at the time, added most of them to the gallery where they were arranged to show the origin, variety, 'unmaking' (fracture and alteration) of agates, all explained in an accompanying museum guide (Goodchild 1899). Many of these agates remained on display for several decades until they were hastily packed away at the advent of the Second World War. Today there are a few Heddle agates on display in the Restless Earth Gallery with most now housed in the National Museums Collection Centre. They are accessible to interested parties by prior arrangement. There was nothing nostalgic or egotistical about Heddle and his collection, he simply loved collecting minerals and understanding the stories that they told. Agates were no exception.

You might be able to view this broken agate (NMS G.210.1671) in 3-dimensions by looking at the two images and slightly crossing your eyes until both images become superimposed. [Good luck, I can't manage this trick – Ed.]

Acknowledgements
Thanks to Phil Stone for his encouragement and patience and to Bill Crighton for the images of agates.

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Tracking down Scotland's dinosaurs

By Paige dePolo

When one imagines the places where fossils are found, the locations evoked are remote, challenging to work in… and dry. Classic localities like the Gobi Desert, the Badlands of South Dakota, and the deserts of Utah are characterized by blinding sunlight, little shelter, and an abundance of dust. Where would a dinosaur hunter be in these types of environments without a trusty broad-brimmed hat *a la* Indiana Jones? Folks with this mental image of fossil hunters may have a difficult time imagining palaeontologists working in the wet, coastal environment of the Isle of Skye, Scotland. Yet the coastlines and tidal platforms of the Trotternish Peninsula (the northernmost peninsula on Skye) preserve sedimentary rocks with footprints, teeth and bones from a wide variety of animals, including dinosaurs. Even more excitingly, these rocks are from the Middle Jurassic (174–164 million years ago), a time where dinosaur fossils are rare globally. The fossils from this part of the world are, therefore, quite special. In particular, several recently discovered, laterally extensive, *in-situ* dinosaur track sites possess the potential to provide insights into dinosaur behaviour and paleoecology from this poorly recorded time period.

Working on the Isle of Skye presents a series of unique challenges that are driven by uncontrollable factors like the weather and the tides. The dinosaur track sites were located on intertidal platforms, which meant that there was a narrow window of opportunity for examining the footprints each day. Additionally, the platforms were covered with seaweed, limpets, and other marine life which served to obscure fine details of the footprints. The final challenge from nature at the sites was the weather—sunny, clear days, while not unheard of on Skye, are decidedly less common than in the average desert.

When first encountering one of these track sites, the magnitude of the task is a bit overwhelming. How is a person supposed to understand the information contained in the footprints if the area is large, flat, and covered in slippery things? How is the careful, painstaking, slow work of a good paleontological description going to be accomplished if one is persistently being chased by the incoming tide or being rained on and blown about by high winds? How can one confidently and consistently recognize footprints in this heavily eroded environment?

Large problems can often be solved by breaking them down into smaller pieces and fieldwork on these track sites started in the simplest way possible—with clearing the platforms of seaweed. This job was certainly nothing to sneeze at—one of the platforms spanned approximately 3000 square meters and the work of partially clearing it took four people a full tidal cycle (about five and a half hours).

Once the tracks were better exposed, the challenge arose of how to precisely figure out their spatial relationships. It seemed like the best way to overcome the logistical challenges of mapping the footprints and documenting the sites was to fly a drone over them and collect a series of photographs that could later be used to make three-dimensional models of the outcrops. Indeed, the drone was flown with great success at two of the four sites being studied. However, drone flight is extremely dependent on ideal weather conditions (low wind, no rain) that occur infrequently on Skye. Although most of the winter and spring were spent trying to find the perfect time to fly the drone on Skye, only two

A panoramic photograph of one of the tracksites investigated along the Duntulm foreshore on a rare, sunny day. The outcrop is flat, large, and some parts of it still have extensive weed coverage even after much was cleared away. Photo credit; Paige dePolo.

The drone taking flight over one of the platforms. All flights were coordinated and executed by the inestimable Tom Wade (Airborne Geosciences Facility, University of Edinburgh). Photo credits; Rob Parry.

days between the end of November in 2016 and the end of May in 2017 manifested with the right combination of all factors. Since only one site could be documented in a day, thanks to the narrow tidal time window, that meant that photographs still needed to be collected for two sites.

As PalAlba's (a research consortium of Scotland-based palaeontologists) annual fieldwork approached in May 2017, the pressure of figuring out a way to get the data necessary to make good maps of these track sites became more intense. How could the team ensure that a good dataset was collected during this last major window of opportunity? After all, the weather was emphatically out of our control. We had to figure out a way to take photographs of a similar quality and with a similar amount of overlap to a drone without relying on said drone. It turns out that a quite simple solution was at hand using the resources available at the University of Edinburgh—a couple of point-and-shoot cameras and a few pieces of scrap metal were used to construct an intervalometer (or more wryly, 'camera on a stick'). The cameras were programmed to trigger every couple of seconds and spaced to have enough overlap to generate a three-dimensional model. Then, mounted on a pole, they were carried at shoulder height by two 'dancing partners' and sweeps were made across the outcrop following a gridded pattern. The intervalometer was waterproofed so that it could be used under the extreme weather conditions on Skye. The major limitation on its operation became consideration of the safety and resilience of its operators.

When May rolled around, the intervalometer was successfully used on the sites that did not yet have a photo dataset for creating three-dimensional models. From them, the raw descriptive work of understanding how many tracks there were at each site, what each track looked like, and how the tracks were spatially related to one another could finally be completed!

Armed with these hard-won descriptions and models, some interesting conclusions can be made about Skye's dinosaurs. About 170 million years ago, this part of the world was a coastal margin connected to the larger Scottish landmass. The footprints found on Skye's intertidal platform come in many different shapes and sizes and indicate that long-necked sauropods, plate-backed stegosaurs, theropods, and ornithopods all were making tracks on Skye during the Middle Jurassic.

The footprints found on Skye extend and nuance the story told by the island's dinosaur body fossils. Bipedal ornithopod dinosaurs, which were herbivorous grazers, are only known on Skye from the footprints

My 'dancing partner', Amelia, and I manoeuvring the intervalometer over some tricky terrain at one of the track sites. High-tech science facilitated by cameras on a stick. Photo credit; Shasta Marrero.

These images illustrate variations in size and shape of the footprints preserved on Skye. From left to right and top to bottom, we see footprints from stegosaurs, theropods, sauropods, and ornithopods. The red/white gradations on the scale card are 1 cm, the diameter of the lens cap is 5 cm, and the black scale bar and grey pencil are both 15 cm. Photo credits; Davide Foffa and Paige dePolo.

they left behind in ancient mudflats. Stegosaurs and theropods also left their tracks on these transient surfaces which later dried out, developed mudcracks, and then were flooded by the nearby ocean to form lagoons. Sauropods trampled through the sediments deposited in these lagoons. This pattern seems consistent across multiple track sites on the Isle of Skye and possibly indicates that different clades of dinosaurs preferred different living environments. Sauropods dominated the lagoons while other smaller types of dinosaurs preferred to walk on the drier, subaerial mudflats.

This diverse dinosaur fauna is only one part of the story told by Skye's fossils. Tantalizing hints of salamanders, frogs, turtles, lizards, crocodylomorphs, early mammals, ichthyosaurs, and plesiosaurs also are found in rocks of the same geological age on the island. These animals occupied a variety of ecological niches within the same geographical areas and indicate that the coastal ecosystems of Scotland were thriving

My field helpers Moji, Davide, and Rachel posing with 'Seaweed Mountain' in mid-November 2016. Photo credit; Paige dePolo.

during the Middle Jurassic. Thus, the Isle of Skye is a globally important location for studying this enigmatic time period.

Acknowledgements

This piece is adapted from the outreach portion of the author's MScR. in Palaeontology and Geobiology at the University of Edinburgh. I gratefully acknowledge the advice and guidance of my supervisors, Steve Brusatte and Tom Challands. This research could not have happened without a veritable horde of cheerful field assistants: Davide Foffa, Moji Ogunkanmi, Rachel Bartlett, Amelia Penny, Michela Johnson, Shasta Marrero, and Paulo Pereira. Funding for PalAlba's fieldwork comes from National Geographic, the Association of Women Geoscientists, Derek and Maureen Moss, the Edinburgh Zoo, and Edinburgh Geological Society.

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How the past can influence the future: why buried landscapes matter!

By Carol Cotterill, Emrys Phillips and Kirstin Johnson

Dogger Bank—named after medieval Dutch fishing boats called *Doggers*; famous for the numerous Battles of Dogger Bank in 1696, 1781,1904, 1915 and 1916, and now maybe best known for the Dogger shipping forecast—as I write this the wind is northwest 5 or 6, moderate to rough sea states with showers but good visibility. Now we are not naval historians or keen ocean-going seafarers, so why, may you ask, have we spent the last nine years of our careers researching this isolated topographic high in the central North Sea?

In June 2008 The Crown Estate announced the opening of nine development zones within UK waters for offshore windfarm leasing, the largest of which was the Dogger Bank zone. Forewind, a consortium of Equinor (previously Statoil), Statkraft, Innogy SE (previously RWE nPower) and SSE committed to a detailed site survey and Environmental Impact Assessment towards securing the necessary Zone Appraisal and Planning consents for construction and development. Prior to this, the most recent updates to the 1992 Regional Report by Cameron *et al*., were undertaken in 2008/2009 as part of a Joint Nature Conservation Committee project on Special Areas of Conservation. However, as this report was predominantly associated with seabed features and habitats, no updates to the deeper Quaternary geology were carried out. So, the scene was set for a new detailed look at Dogger Bank!

The Dogger Bank is approximately 100 km wide by 250 km long and lies in an area of shallow water. The majority of the bank lies within the UK sector of the North Sea (Figure 1) but it also extends into Dutch and German territorial waters. The proposed windfarm zone is situated 125 to 290 km northeast of Yorkshire coast and is the largest of the Round 3 zones, covering an area of 8660 km^2, with water depths ranging from 18 to 63 m Lowest Astronomical Tide (LAT), and is located entirely within the UK sector. The lack of understanding regarding the sedimentary and structural architecture of the

Quaternary sediments on Dogger Bank presented a major issue for the development of a windfarm in this area. The stratigraphy and structure of the Dogger Bank was believed to be a relatively simple ‘layer-cake’ with much of the upper 60 m (the foundation depth for the windfarm) of this unconsolidated sedimentary sequence being assigned to the Dogger Bank Formation (Balson & Cameron, 1985; Cameron *et al*., 1992). However, the acquisition of new high-resolution survey data during the site investigation of the DBZ has proven that this is far from the case.

The earliest reference to the Dogger Bank being glacial in origin was made by Thomas Belt (1874) who stated that *“The ice north was now gradually receding, and leaving great banks of moraine rubbish in the old ocean bed, to be ultimately levelled by the sea when it long afterwards returned, and which now form the Dogger and other great submarine banks”*. But the modern seabed gives no indication of this kind of geomorphology at all…….so what was hidden beneath the modern marine sands?

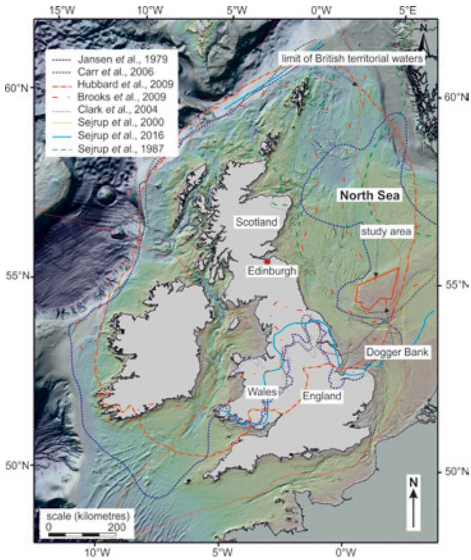

Figure 1 ***Map showing the location of the Dogger Bank in the southern North Sea Basin, and the Round 3 windfarm zone indicated by the red polygon. The limit of the UK territorial waters is also marked in red. EMODNET DigBath bathymetry (UK waters) and GEBCO bathymetry (Non-UK waters). Coloured lines indicate a compilation of published Last Glacial Maximum ice sheet extents, highlighting the degree of uncertainty: further details and references available in Phillips et al. (2017).***

The first piece of the puzzle came from the geotechnical results. Downhole measurements acquired using a Cone Penetrometer (CPT) (a method for testing the strength of unconsolidated sediments or ‘soils’) indicated that the Dogger Bank Formation was lithologically very similar throughout, and yet the geotechnical results varied wildly with both depth and geographical location. Spot core samples, taken roughly every 3 m downhole for the length of the CPT showed that the dominant sediment type in the Dogger Bank Formation was stiff to very stiff clays with multiple sand layers/lenses. These deposits range in thickness from 30–50 m. Below the Dogger Bank Formation deposits are a sequence of dense to very dense poorly sorted, silty to fine-grained sands containing interbeds of hard clay and silty fine sand. The presence of shell fragments and organic matter within the sands has been used to suggest that they were deposited in a marine (possibly nearshore) environment, consistent with their belonging to either the Eem and/or Egmond Ground formations. Above the Dogger Bank Formation are an overlying sequence of fine- to medium-grained Holocene sands that are being reworked by contemporary marine processes. The sands range in thickness from a thin veneer (<1 m thick) to localised channel infill deposits of up to 35 m.

The second puzzle piece came in the form of a seismic horizon. Sub-seafloor information, acquired using sound, revealed a number of strong reflections. These reflections correspond to changes in acoustic impedance, or the speed that the sound wave travels through the sediments. This is a good indicator of a change in lithology, a change in water content, or a change in the density due to compression or desiccation. One of these seismic horizons, chosen due to its laterally continuity across most of the study area and the fact that the geotechnical data suggested a major change in something occurring at this level, revealed a buried glacial landscape which has been hidden from view since the end of the last ice age. The resultant sub-bottom horizon map is shown in Figure 2a. The red and yellow colours represent highs (minimum depth below the seabed c. 2.5 m). In contrast, the green and blue colours indicate areas where this surface occurs at a much deeper level (maximum depth c. 60 m). The resultant pattern reveals elongate, arcuate features (Figure 2a), which are interpreted as a series of moraines (purple colours on Figure 2b)—glacially formed accumulations of glacial debris.

The final piece of the puzzle came to light through a detailed analysis of some of the seismic survey lines. Three areas across this buried glacial landscape were selected running perpendicular to the main moraine complex (MC1, Figure 2a) as well as one area of longer lines crossing multiple moraines as well as low-lying basins and troughs (Area D, Figure 2a). An example interpretation

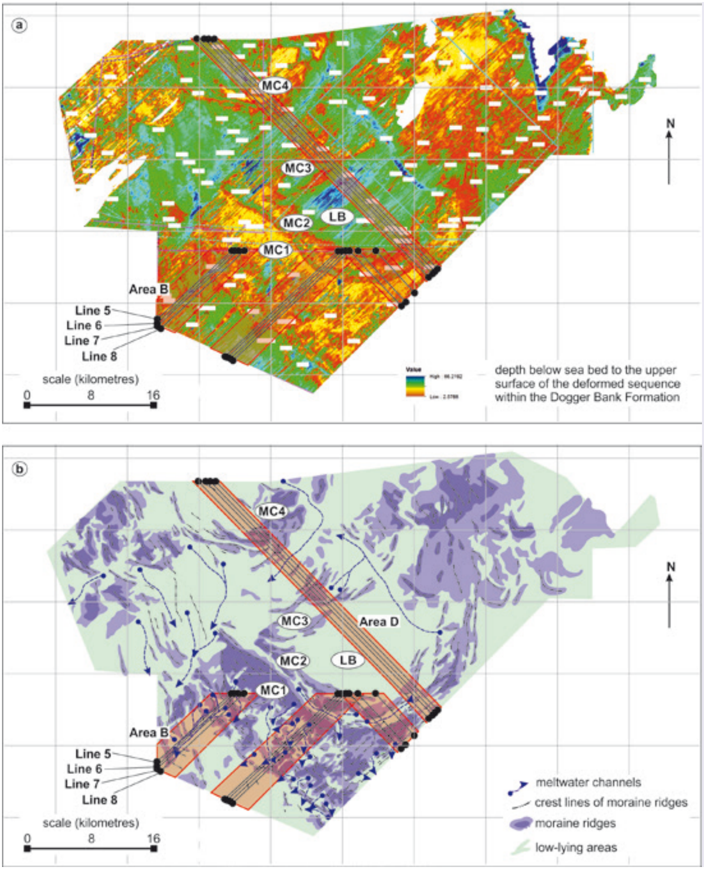

***Figure 2** (a) Horizon map constructed for the top of the Older Dogger Bank within Tranche A; (b) Landform map of the buried glacial landscape concealed within the Dogger Bank Formation comprising a suite of topographically higher arcuate moraine ridges separated by lower lying basinal areas and meltwater channels (after Cotterill et al., 2017b).*

is included as a supplement in the online version of *Edinburgh Geologist* 66. It reveals an unprecedented level of detail across a now buried thrust moraine complex which formed due to the bulldozing effect (glacitectonic deformation) at the margin of a major ice sheet.

The interpretations showed that a number of key geomorphological and sedimentological features dominate this buried landscape (supplementary figure; Cotterill *et al.*, 2017a; Cotterill *et al.*, 2017b; Phillips *et al.*, 2018):

- Although predominantly clay, the Dogger Bank Formation is actually formed of three distinct sub-units, identified by their geotechnical responses and seismic character—a basal, highly consolidated unit that appears to form primitive, early moraines; a lower unit that is highly deformed and ranging in thickness from a few metres to >35 m in thickness; and finally an upper unit that is less deformed with more draping of the sediments, infilling the topography created by the deformed lower unit.

- The large moraine complexes are composed of highly deformed lower clays that have been folded, thrusted, over-ridden and over-consolidated. The largest of these moraines is up to 15–20 km across. The geometry of the deformation structures within these moraines indicates that they were formed by ice moving across the area from north to south. This suggests the main influence building the Dogger Bank was probably Fenno-Scandian ice which is thought to have covered a large part of the North Sea during the last ice age (Weichselian glaciation).

- Large low-lying basinal areas between the moraines which are dominated by the upper less deformed clays. The style of sedimentary deposition is indicative of ice-marginal or pro-glacial outwash laid down as the ice retreated northwards towards the end of the last ice age.

- Meltwater channels with multiple stages of infill, often from different directions/(?)sources, incised into the underlying sediments. The channels often start and end abruptly, suggesting that they represent sub-glacial 'tunnel valleys' which were eroded by highly pressurised meltwater flowing beneath the ice sheet. However, the site also includes a network of much later wide, laterally extensive pro-glacial channels that formed in front of the retreating ice sheet. These complex channels are infilled with fan sediments and debris flow deposits which flowed off the nearby moraine highs.

The detailed analysis of high-resolution seismic data from the Dogger Bank has shown that the multiple units comprising the Dogger Bank Formation record a complex history of sedimentation and large-scale, ice-marginal to proglacial glacitectonism associated with the active retreat of the Weichselian ice sheet. This complex glacial landscape was later buried beneath a thin sequence of Holocene sediments.

All of this new geological information is being used to help guide the siting of turbine foundations as well as reducing the risk of jack-up platforms de-stabilising during turbine installation due to sudden and unexpected penetration from increased loading. By integrating geophysics, geotechnics and geology, the team have developed a methodology to interpret buried landscapes, the lateral variability of these environments and the impact of these unseen features on renewable energy developments in the offshore realm.

Acknowledgments
This research is an ongoing collaboration between BGS and the energy companies developing the Dogger Bank project areas. Thanks to the Forewind Consortium for access to the survey datasets, and to Equinor and SSE for their continuing support.

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Dr Carol Cotterill (cjcott@bgs.ac.uk) and colleagues
British Geological Survey,

Eustatic Drift

By Keira Greene

everything about us now is rock
everything about us then was wet
how did it all begin?
sleep-wake
wake-sleep
all that solidifies eventually speaks

under the dandled sun
we were found
ancestral calendars
skeletal signifiers

and later we were named
most things are named
bearing resemblance to hieroglyphs
they arrived at graptolite
graptos after written and lithos after rock

once we were plankton slouched in the ocean
but now we are code
surfaced and held in the laminae of rock like open scores

in a torrid spike we were stilled
there and not there
an endless vacation where one face looks to the future
and the other to the past
to when we raked the ocean like cream

billions of architects
we built micro-utopias
to live together in common corridors
in horny sheaths

irresistible time passed
perhaps we were swimming?
and sticky temporal sequences
time jelly strong and knotted together
stretched out like a ribbed mirror

without tongues
we wrote everything down
in tunics of dark grey and pelagic mudstone
over soft cherty ribs
thick bands of volcanic ash
fragmented crystal clasps
this and much more we remember
in the heat of the day we toll

sleep turning to wake
turns to wake again and sleep again
all that solidifies eventually speaks
in the mud of a new dawn we listlessly quiver
as bodies climb into our beds
their front pressed to our front
feet rubbing gradient folds

we've been collecting in a deep communion
a fever
a complex juice of aeons

we've shifted across vast territories of encounters
subversions
and on our way we learned the path is lost
flowing
forming laterally in the middle distance
no longer a path but a gap
and the pass you go will write you
trust us

listen to our voices float on the underside
we can see the exposed shoulders
they are rising
they rise and fall
and over their tips we hear
the locking and unlocking
the locking unlocking of doors

*"once we were plankton slouched in the ocean
but now we are code,
surfaced and held in the laminae of rock like open scores"*

This narrative voice comes to us from the fossils of Graptolites, our long extinct plankton ancestry. Their speculative voice speaks to us from within deep time as they coil past and future, blending evidence of our interspecies story. In *Eustatic Drift* we experience the real and imaginary potential of the Graptolites, as a tangible index of a once dominant species, and as a latent oracle. It investigates graptolites through film, dance, images and words.

The film opens with wide images of the remote landscape of Dob's Linn, Scotland, significant for its graptolite-bearing strata. The landscape is richly complex in these singled-out moments, held at a distance. History is sunk into the fabric of the rock and at the same time in constant change; change is its constant truth. The landscape is cut with images of the fossils; they remind us of the certainty that everything is vulnerable, of trauma that has lost all meaning, but the Graptolites present a post-literative world, in which language and hybridity must evolve.

In a studio environment dancer Katye Coe performs the Graptolite as an open score. She unfolds the rock and imagines how the species may've moved. In one instance we read in their script:

"perhaps we were swimming?"

Coe's performance bears resemblance to the development of a seedling in the dark. She draws upon the depth of our interspecies memory in the absence of scientific knowledge as to how the Graptolite species moved or how deep in the Ocean they lived.

In *Eustatic Drift* the camera meditates on the surface of images, preoccupied with that which runs beneath *"there and not there"*. Immanence is rooted in the dialectic of embodied experience that is critical to all humans. And to embody an awareness of our interaction with other species is critical for human survival.


in a torrid spike we were stilled


we've been collecting in a deep communion

Graptolites were small marine colonial organisms, the fossilised remains of which are commonly found in black shale rocks that once were muddy sea floors; they look like impressions of tiny hacksaw blades on the rock surfaces. Graptolites first appear in the fossil record about 520 million years ago, part of the explosion of diverse life in the Cambrian Period, and disappeared in the early Carboniferous, 350 million years ago. For about 100 million years, mainly through the Ordovician and Silurian periods, they evolved quickly and were widely distributed throughout the world's oceans. Their rapid evolutionary change make these fossils particularly valuable for dating and correlation of marine sedimentary rock successions worldwide.

Dob's Linn in southern Scotland exposes mudstone spanning about 25 million years through the late Ordovician and early Silurian periods. The original sediment was deposited in a wide ocean — Iapetus — separating 'Scotland' from 'England', both parts of larger land masses at the time. It is the defining locality for the Ordovician–Silurian boundary worldwide, with particular species of graptolites being key to identifying this fundamental point in time.

Keira Greene is an artist who works across moving image and performance. Her practice is critically engaged with the filmed image of dance and the moving body on screen. Often she works with language, exploring how text, speech and images can be turned into scores for movement, music and script. Her work is often collaborative and she works closely with dance artists and musicians to develop this research.

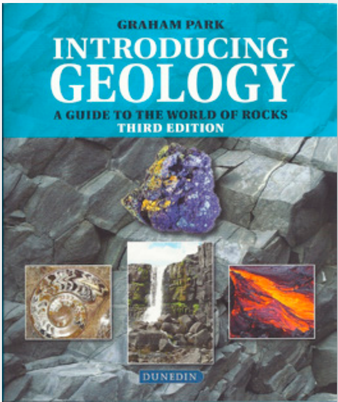
She has exhibited and screened her work widely with recent exhibitions and screenings including Cubitt, London, Jerwood Space, London, Whitechapel Gallery, London, Tate, London, The Commons Bolinas, San Francisco, CA. She is performance curator for Whitstable Biennale 2018 and a founding trustee of the Stuart Croft Foundation. She is currently undertaking a practice-based PhD at Kingston University, supported by Technē.

Credits for Eustatic Drift:
Dance — Katye Coe
Cello — Ute Kanngiesser
Sound — Paul Abbott
Special thanks to Jan Zalasiewicz, Rob Barnes and Siobhan Davies Studio
With the support of a Jerwood Visual Arts Artists Bursary and The Elephant Trust

Keira Greene
For more information on *Eustatic Drift* see http://keiragreene.com/

Book review

Introducing Geology by Graham Park. Dunedin Academic Press, Edinburgh. Third edition 2019. Paperback, 134 pp. Price £9.99. ISBN 978-1-78046-075-8.



This book provides an approachable introduction for interested adults who are studying the subject. I have been recommending it to U3A geology groups for a few years and it is good to see a new edition. The revision has allowed the author to improve the line drawings, in particular exchanging symbols for colour, which makes many of the diagrams easier to understand. The text is clear and easy to follow, though, inevitably very densely written in order to compress a huge amount of information into a book of a little more than a hundred pages. Clear cross-referencing between the text and the tables, diagrams and photos, makes the facts easy to read, learn and remember. Technical words are highlighted in bold in the text and each appears, with a clear definition and a page reference, in the twenty-page glossary which serves as a basic geological dictionary.

The book is structured so that the more immediately attractive topics—minerals, volcanoes—are found in the first few chapters. Those on sedimentary and igneous rocks go into enough detail to satisfy most people, though there is limited information on how to identify rocks and those who live in or visit Scotland may be disappointed by the very short section on metamorphic rocks. It was sad to read the old chestnut about rivers in mountainous areas flowing faster than rivers in lowlands, years after experiments have shown that velocity due to kinetic energy in rivers with high discharge is greater than the velocity of rivers in mountains, where potential energy has to overcome friction. However, there is an excellent section on glacial processes and landforms, with helpful photos. The two consecutive chapters on geological time and fossils are nicely linked by discussion of absolute and relative dating respectively, with well-chosen photos of examples of most of the fossil groups and a particularly beautiful image of insects preserved in amber.

The chapter on plate tectonics contains exemplary explanations linking continental drift, ocean-floor spreading, distribution of climatic zones, palaeomagnetism, plate movements, subduction, mountain-building and continental rifting. From experience, it is not easy to teach global plate tectonics to an adult audience, but this chapter will provide excellent further reading to reinforce complex ideas. The section is well illustrated with maps and diagrams and it is helpful that arrows have been added to the world map of plate boundaries. A long chapter on the history of the Earth, well-illustrated with palaeogeographic maps, will challenge the beginner but will be helpful for those who are interested in the global picture, particularly how Scottish geology fits into world plate tectonics.

A brief look at economic geology concludes the book, though no doubt the author would have liked to have added examples and diagrams to explain mineral extraction, the processes of ore formation and how roads and tunnels are built, had there been space.

A few errors have survived the revision for this third edition, such as a caption to a photo of a calcite cleavage rhomb, unfortunately labelled as a crystal. Dolerite is described as fine-grained in a photo caption, but (correctly) as medium-grained in the igneous rocks table on the following page. The common misunderstanding of the difference between exposure (rocks visible at the surface) and outcrop (the area where a rock is found, though it may be obscured by soil and vegetation) has not been eliminated. Weathering and erosion are not clearly distinguished and this has led to an error in the caption for Fig. 3.1, which describes a granite tor as an example of erosion, instead of weathering. I was sorry to see the use of the words 'acid' and 'basic' to describe magma composition. These terms were superseded some years ago by the words 'silicic' and 'mafic', so it is unfortunate that they have re-emerged here.

For the audience for which it is intended, Graham Park's book is straightforward and well-illustrated and provides the basis for a good understanding of geological features and processes.

Alison Tymon

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