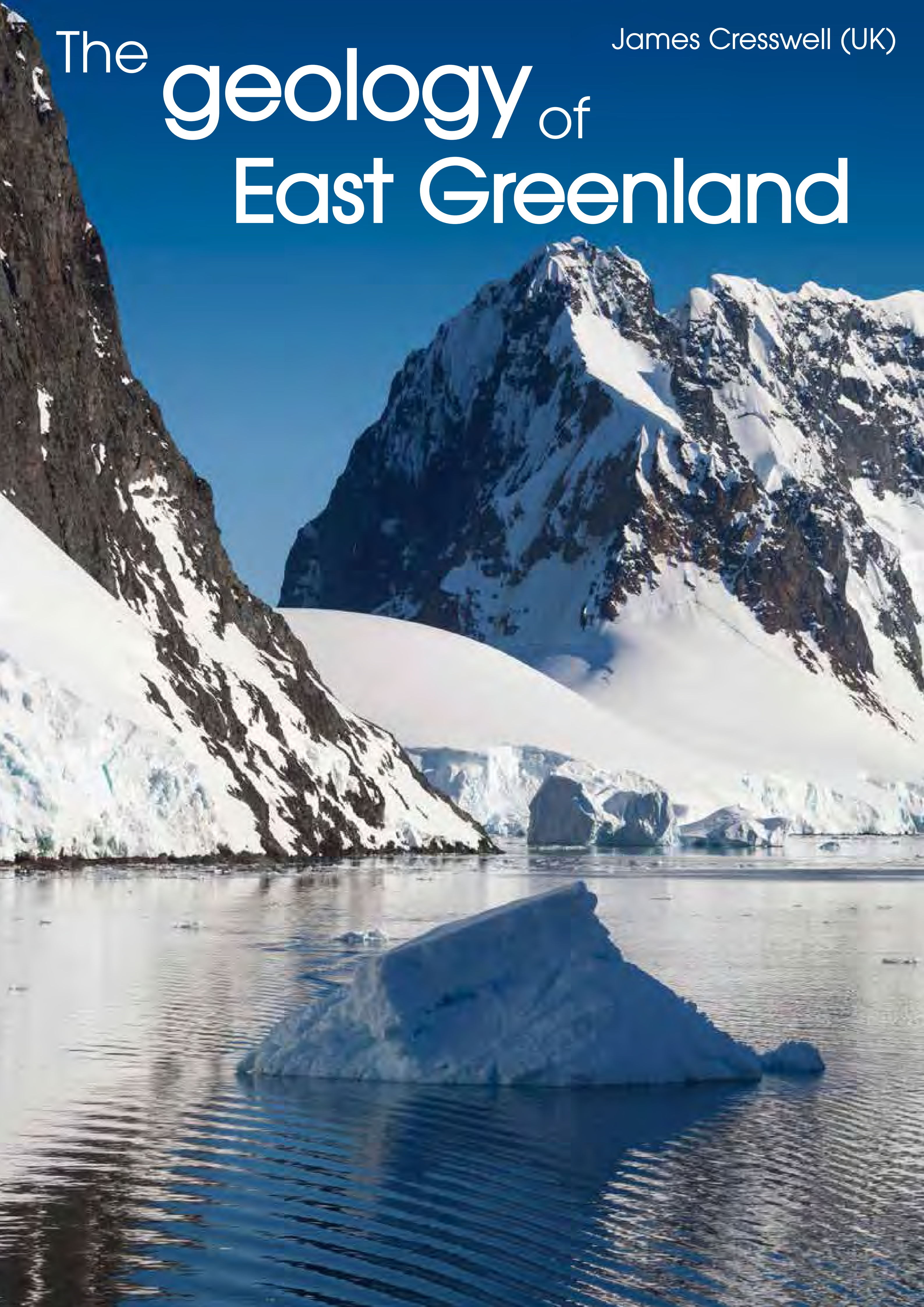
James Cresswell (UK)

The geology of East Greenland



Eighty percent of Greenland is covered by ice and, in places, this is up to 3.4km thick. So, Greenland might not immediately spring to mind as a place to go to observe rocks. However, it is a huge country and the ice-free area, at 410,000km^2, is nearly twice the size of the UK. This is generally sparsely vegetated, leaving the rocks beautifully exposed and the geology incredibly easy to see. The area of East Greenland around Scoresby Sund, Kong Oscar and Kejser Franz Joseph Fjords is the largest ice-free area in Greenland. It also has incredible geodiversity, with basement rocks as old as three billion years, an almost complete sedimentary record of the last 1.6byrs and huge volumes of flood basalts from the splitting of the Atlantic. If you were an alien and wanted to try to piece together the geological story of Planet Earth - but could only visit one area - East Greenland would be the place to go.

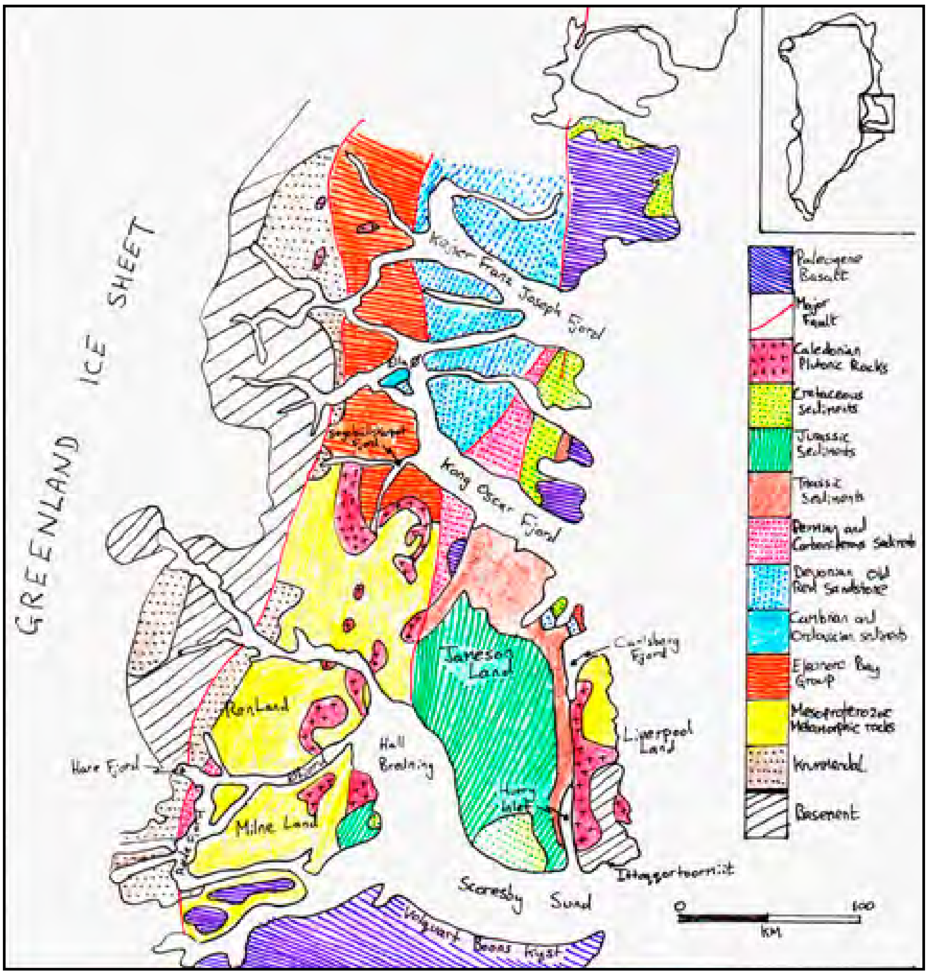


Fig 1. A simplified geological map of East Greenland.

The geological history of Greenland is vastly long and spans 3.8byrs. Its oldest rocks are the 3.8byr-old Isua Complex, situated in West Greenland, near the capital Nuuk. These rocks are the Earth's oldest, most well-preserved sedimentary and volcanic rocks, and they contain carbon particles that most likely originate from the oldest known life on the planet. To put into perspective just how old these rocks are, try to imagine that the planet is only one year old. It would have formed on 1 January, with the earliest known life and these Greenlandic rocks forming in March. Multicellular life did not evolve until October, the dinosaurs a few days before Christmas (going extinct on Boxing Day) and humans only appeared 15 minutes ago, with all of civilisation being in the last 10 seconds.

At the time these rocks formed, our planet was a very different place and the continents were still forming, and there was less continental crust than there is now. However, plate tectonics were taking place. Broadly, when one oceanic plate collides with another, one is forced to slide under the other in a process called 'subduction'. Minerals in the subducting slab dehydrate, causing the overlying mantle to melt and new rock types, like granites, to be produced. The early granites of East Greenland (and all subsequent granites) are continental crust and in all continental collisions, they are not subducted due to their relative buoyancy. Over time, the amount of continental crust increased and when pieces of continental crust collided, they welded together to form one block, and the immense forces involved thrust up chains of mountains. During this process, the rocks buckle and fold, with the intense heat and pressure causing them to transform into metamorphic rocks such as gneisses.

A large proportion of the rock exposed in Greenland, particularly in the west and south, is made of these strongly folded gneissic rocks, which are the eroded roots of different mountain belts, now welded together to form a stable, coherent block. This block is commonly known as 'the basement'. The coming together of the basement occurred over a huge period of time, spanning 3.8 to 1.75byrs. It was also not a simple process. For example, by 2.7bya, most of West, East and South Greenland had formed and were probably part of a theorised ancient continent referred to as Kenorland. Two billion years ago, this split up and parts of West Greenland rifted apart again, only to come back together 200myrs later. The final stages of basement building occurred from 1.8 to 1.725bya, when Greenland was part of another super continent referred to as Columbia. These youngest basement rocks are seen in South Greenland.

In East Greenland, basement rocks are exposed, but, in most places, are covered by younger rocks. The oldest exposed rocks in East Greenland are about 3byrs old and occur in the inner most regions of the Scorsby Sund, which is the largest fjord complex in the world. Fig. 2 shows gneiss of this age from Hare Fjord, which is particularly rich in garnets (the large visible red minerals). There is then a time gap to the next oldest rocks in East Greenland. These rocks are also basement gneisses and are 2byrs old. They outcrop in Liverpool Land and the innermost reaches of Kong Oscar Fjord (Fig. 3). Liverpool Land was named by the British whaler, William Scoresby, who also lends his name to the Scoresby Sund fjord complex and Scoresbysund, the alternative name for the settlement of Ittoqqortoormiit. This town is one of the remotest settlements in Greenland and, in

Fig 2. 3byr-old basement gneiss, rich in garnets.

Fig 3. 2byr-old basement gneiss in Ittoqqortoormiit.

Fig 4. Metamorphosed Krummedal rock; a schist that contains the minerals garnet, kyanite and mica.

2010, had a population of just 469. It was founded in 1925 by the Danish Government, which was keen to assert sovereignty over northeast Greenland. However, the area had been the site of Inuit habitation in the past, as archaeological remains show.

Overlying the ancient basement rocks of East Greenland are younger sedimentary rocks. However many of these rocks are themselves still incredibly old. The oldest are named the Krummedal supra crustal sequence, after a site in Scorbesby Sund, where it was first recognised that they are a separate unit. These rocks were lain down over a relatively short period of time, just 50myrs, and are 1byrs old. They were deposited and transported a considerable distance in a deep ocean environment after the breakup of Columbia. Radiometric studies show that the sediments derive from two separate sources, with one probably being in what is now North America, with the other being Europe (Henriksen, 2008). Today these rocks are only found outcropping in the inner most sections of the fjord complex, except for one small outcrop on the northern tip of Liverpool Land. The sequence, which is up to 8.5 km thick in places, forms a great thrust sheet that has travelled westwards over the basement rocks. In places, the sediments are only lightly deformed, but in other places they have been changed into schists which are types of metamorphic rock. Figure 4 shows an erratic made up of Krummedal rock. This rock is a schist that contains the minerals garnet, kynaite and mica. Fig. 5 (a photograph taken in Hare Fjord) shows Krummedal sediments in the distant cliff, which are beneath basement rocks that have been trust over them.

Øfjord Fjord (Figs. 6 to 10) is spectacular in its dimensions. It is 4 to 6km wide, but doesn't feel that big due to the enormous height of the valley walls. Grundtvigskirche (Fig. 6), at 1,977m, towers above the giant iceberg below. The rocks of the fjord are so sheer because they are incredibly hard and have been resistant to the glacial erosion that calved out the main valley of the fjord. They are also very complex. The red and white rocks shown in Figs. 9 and 10 are heavily metamorphosed rocks that were originally Krummedal sedimentary rocks. The red bands are very rich in garnets and are what geologists call a paragneiss. The white bands occur where the metamorphism has gone one stage further, and the rock completely melted to form a granite. In this case the granite is an uncommon type called Augen granite, which is characterized by having very course crystals. Dating of these granites show they formed 900mya (Leslie and Nutman, 2000). This would have been due to yet further continental collisions that gave rise to yet another super continent named Rodinia, which existed from 1.1bya to 750mya. The complexity of Øfjord does not end here. There are also younger, igneous rocks aged from 430 to 400myrs, which were intruded into older rocks during the Caledonian mountain building phase. Fig. 8 shows a red dotted line that has been drawn on to the photograph. This line highlights one of these younger intrusions, which is made up of darker rock than the surrounding rock. This intrusion and has been identified by Leslie and Nutman (2000) as a type of rock called a hypersthene monzonite. Fig. 7 shows a line of darker rock rising from the bottom left hand corner of the photograph. This is the same hypersthene monzonite, which cuts through the older metamorphic rock, and the top peak of the mountain is also made up of younger Caledonian rock, which is a pink granite.

With the super continent of Rodinia established, sedimentation began on Greenland's eastern margin. The scale of this sedimentation was vast. A staggering 18.5km thick succession of sediments was continuously laid down from 900 to 450mya. The oldest 14km of this sequence - the Eleonore Bay group - are the most photogenic rocks in East Greenland and could well be in contention to be the most photogenic rocks anywhere in the world. The Eleonore Bay sediments were lain down in shallow water, shelf conditions from 900 to 600mya. Figs. 11 and 12 show these sediments forming a spectacular stripy cliff in Segelsällskarpet Fjord, which is 1,900m high. The multicoloured sediments include fine grained quartzites, mud rocks, and different limestones and dolomites. Figs. 11 to 18 show various views of the Eleonore Bay sediments in Segelsällskarpet Fjord, while Figs. 19

Fig 5. Basement metamorphic rocks thrust over Krummedal Rocks in Hare Fjord.

Fig 6. Geotourists enjoy the scenery of Øfjord.

Fig 7. The 1,977m-high peak of Grundvigskirche in Øfjord. Most of the rock in the photograph is 1byr-old gneiss that was originally Krummedal sediments. The peak of the mountain is a pink granite and the dark stripe of rock rising from the bottom left corner is hypersthene monzonite, both of which were intruded during the Caledonian Orogeny.

Fig 8. A Caledonian intrusion of hypersthene monzonite is bounded by the red line. The surrounding rock is the remains of Krummedal Rocks that were metamorphosed 900mya in the building of Rodinia. The red layers are paragneiss, which are extremely rich in garnets; while the whiter layers are due to the complete melting of the original rock and are now augen granite. The photograph was taken in Øfjord. Figs. 9 and 10 show these bands more clearly.

Figs 9 and 10. A closer view of the red and white banded rock in Øfjord.

Figs 11 and 12. 1,900m-high, stripy cliffs in Segelsällskarpet Fjord. The colourful layers are part of the Eleonore Bay group and are made up of alternating layers of limestones, dolomites, mud rocks and quartzites.

Fig. 13. People standing on alternating layers of limestone and dolomite in Segelsällskarpet Fjord.

Fig. 14. Zodiacs shuttle passengers from the ship to Segelsällskarpet Fjord.

Fig. 15. Geotourists investigate the limestone and dolomite in Segelsällskarpet Fjord.

Fig. 16. Rocks that have been polished by a glacier in Segelsällskarpet Fjord.

Figs. 17 and 18. Stripy layers of limestone and dolomite in Segelsällskarpet Fjord.

Fig. 26. Folding in the Eleonore Bay sediments caused by the Caledonian Orogeny.

Fig. 27. Stromatolites from the Vendian tillites in the uppermost Eleonore Bay group.

Figs. 19 to 25. Eleonore Bay sediments in Antarctic Sound, viewed from the ship.

to 26 show the sediments as they are exposed in the fjord wall of Antarctic Sound. The uppermost layers of the Eleonore Bay sediments also contain stromatolites (Fig. 27). Lying immediately on top of the Eleonore Bay sediments are Ice Age deposits called tillites from the Vendian, about 600 to 542myrs old. At this time, Greenland was near to the South Pole, so there is nothing unusual about having tillites deposited at this time. However, these tillites are from a period when it is thought there may have been a global glaciation, which is referred to as 'Snowball Earth'. At this time, it is thought that all the world's continents may have been covered by glacial ice and the entire ocean by sea ice. It is also thought this global glaciation was caused by the breakup of the super continent Rodinia.

The Vendian tillites are well exposed on Ella Ø, as are the Cambrian and Ordovician sediments that overlie them. As Rodinia split apart, an ocean formed between East Greenland and Europe. This ocean is referred to as the Iapetus and is the same ocean that plays an important part in the story of British geology. England and Wales were on one side of the ocean, and Scotland with Northern Ireland on the other and joined to Greenland. In this ocean, the sedimentation continued through the Cambrian and Ordovician, depositing the rocks of Ella Ø and, because multicellular life diversified in the Cambrian, these rocks contain lots of fossils.

The next stage in the story of East Greenland is the final closing of the Iapetus Ocean, about 420mya. This thrust up a chain of mountains probably as high as the modern Himalayas. This mountain chain ran from Svalbard in the north, along the coasts of Norway and Greenland, through the UK and into Canada and the USA (which were all joined at this time). The mountain building phase is called the Caledonian Orogeny, which takes its name from the Scottish mountains that it formed. The force of this collision caused older sediments of East Greenland to be folded and thrust up in great sheets over the basement, and the intrusions seen in Øford were emplaced. Fig. 26 shows the folding in the Eleonore Bay sediments due to this collision.

When a mountain chain is thrust up, it will eventually start to erode causing sediments to be deposited. A 10km thickness of sandstone was deposited throughout the Devonian, Carboniferous and lower Permian in East Greenland, due to this erosion of the Caledonian Mountains. These sediments were deposited in continental conditions, with rivers flowing over an otherwise arid landscape. The sediments are red in colour, due to the presence of the iron mineral haematite. The red rocks of the Devonian are known as the 'Old Red Sandstone' and also outcrop in the Brecon Beacons of Wales, the Orkney Islands, as well as Svalbard and parts of the USA. The Devonian sandstone of East Greenland is very fossiliferous and over 10,000 fish fossils have been recovered from it. The most important and famous of these fossils were found in Kejser Franz Joseph Fjord. Evolutionary scientists believe that amphibians evolved from fish. To prove this, it is necessary to find fossils that show this process in action, and this is exactly what has been found in this part of East Greenland. Fossils have been found that show just this, having both fish and amphibian characteristics.

By the time of the Carboniferous and Permian, the most recent super continent, Pangaea, had come into existence and rivers continued to deposit red sediments. Fig. 28 shows red Carboniferous sediments in Kong Oscar Fjord, while Fig. 29 shows red Permian sediments in RØdefjord (meaning 'red fjord'). Figs. 30 to 32 also show these Permian sediments and how they have been cut by dolerite dykes that intruded during the later splitting of the Atlantic. At this time, rifting occurred and Jameson Land dropped down as a faulted graben, forming a basin, which later filled with sediments.

In the late Permian, East Greenland was covered by a shallow sea that eventually retreated, leaving the Triassic continents with desert-like conditions. Triassic sediments can been found along the eastern coast of Hurry Inlet and Carlsberg Fjord in Jameson Land. The eastern coast of Hurry Inlet is one of the richest locations for Triassic plant fossils in the world and, in addition to many important plant fossils, the remains of the dinosaur *Plateosaurus* and early mammals have been found. Also in Carlsberg Fjord, footprints made by a small carnivorous dinosaur have been found. Fig. 33 shows these Triassic sediments in Hurry Inlet, with the dark bands being igneous sills that later intruded into the sediments.

During the Jurassic, Pangaea began to split and a shallow sea flooded East Greenland, resulting in 55myrs of marine sediments being continually deposited. Today these sediments are found outcropping in Jameson Land and are full of ammonites. Because the sedimentation was continuous, the whole of the Jurassic is preserved, and 60 distinct ammonite zones have been indentified, making Jameson Land one of the most important locations in the world for studying ammonite evolution. In addition, many other types of fossils have been found in these Jurassic sediments, including marine reptiles, such as plesiosaurs and ichthyosaurs. The west coast of Milne Land also has outcrops of Jurassic sediments and a complete plesiosaur skeleton was found here in 1935. Marine sediments continued to be deposited into the Cretaceous and sediments of this age can be seen near the entrances of both Kejser Franz Joseph and Kong Oscar Fjords.

The splitting of Pangaea continued throughout the Cretaceous and, by about 50mya, Europe began rifting away from Greenland to form what is the present day Atlantic Ocean. As the continents began to split apart, huge volumes of lava erupted in East Greenland, and also in Scotland and Northern Ireland, which were still joined to Greenland at that time. The entire southern coast of Scoresby Sund (the Volquart Boons Kyst) is made up of these lavas, which stretch for many thousands of square kilometres south and offshore. The layers of lava are up to 10km thick in places. Fig. 34 shows the layers of lava on the Volquart Boons Kyst and Figs. 35 to 37 show amazing columnar basalt in a bay on this coast (Viking Bukta). Columnar basalt forms due to the contractions of lava as it cools. The exact reason why the lava does this is not fully understood, but it is theorised that it could occur when lava flows into shallow water.

If you are interested in seeing the geological wonders of East

News snippets

'Pauline': a new species of ostracod from Herefordshire

A new species of ostracod (a fossil shrimp-like creature) has been discovered at a site near the Welsh border in Herefordshire, excavated by the team from the University of Leicester. The 1cm-long fossil was preserved by volcanic ash, which fell during the Silurian period, 425mya. The species is new to science and rare because this is one of only a handful of ostracods found with the fossilised soft issue preserved.

Prof David Siveter, who worked on the species, named the specimen "Pauline avibella" in honour of his late wife Pauline. The word "avibella" means 'beautiful bird', because the shells of these creatures look a bit like a bird's wing.

Is this the oldest known dinosaur in the world?

Nyasasaurus parringtoni, a possible new species of dinosaur from Lake Malawi in southern Africa, has been dated 10 to 15myrs before the previous earliest known dinosaur specimen. The remains were found many years ago, but have been recently re-examined. The animal walked on two legs and measured 2 to 3m in length. It weighed between 20 and 60kg.

The age of this latest discovery means that many millions of years must have passed before dinosaurs became dominant on land. The reason the specimen has not been officially called the oldest known dinosaur is that the specimen is incomplete, missing one upper arm bone and six vertebrae. Although the team feel confident this is a dinosaur, reptiles were also present at around this time, with some evolving similar characteristics as dinosaurs.

2.7 billlion-year-old raindrops studied

Raindrops, preserved as imprints in rock from Ventersdorp in North West Province of South Africa, have been dated as being 2.7byrs old. They were originally discovered during the 1980s and are being re-studied to find out what the atmosphere was like on early earth. The raindrops originally fell onto ash leaving imprints. The depressions left by the drops can tell a story about how fast they were descending when they impacted the ground. From this, the density of air can be calculated. 2.7bya, the earth span faster, the moon was closer and the sun was weaker. With no animals or plants, the air was not breathable, being mostly nitrogen, CO_2 and methane, but with no oxygen.

Fig. 28. Carboniferous red sediments in Kong Oscar Fjord.

Fig. 29. Permian red sediments in RØde Fjord.

Figs. 30 to 32. Permian red sediments in RØde Fjord cut by dykes that intruded during the Paleogene, when the North Atlantic started to split.

Fig. 33. Layers of Triassic and Jurassic sediments in Hurry Inlet. The two darker layers are sills, intruded during a period of Paleogene volcanism.

Fig. 34. Layers of flood basalt on the Volquart Boons Kyst. These basalts erupted in the Paleogene when the Atlantic began to split and are up to 8km thick in places.

Figs. 35 to 37. Columnar basalt in Viking Bukta, on the Volquart Boons Kyst.

Greenland for yourself, GeoWorld Travel can take you there on a ship-based trip from 23 August to 4 September 2013 and/or again in 2014. Please contact GeoWorld Travel for more information (web: www.geoworldtravel.com; email: james@geoworldtravel.com; telephone: +44 (0)771 2249057 or post: GeoWorld Travel Ltd, Tara, Velindre, Brecon, LD3 0TB, UK.)

References

Henriksen, N. 2008: Geological history of Greenland four billion years of Earth evolution, Geological Survey of Denmark and Greenland (GEUS).

Leslie, A. & Nutman, A. 2000: Episodic tectono-thermal activity in the southern part of the East Greenland Caledonides, Geology of Greenland Survey Bulletin 186, 42–49.

Fig. 38. During September, the Northern Lights are often seen in Scoresby Sund.

Fig. 39. Scoresby Sund is full of large ice bergs that calve from the Greenland ice sheet.

A closer look at a Jurassic dinosaur bone from the Morrison Formation: a dinosaur bone primer

Kurt Lahmers (USA)

A closer look at a dinosaur bone found in the Garden Park area of Cañon City, Colorado (USA) shows some interesting details on the end of the bone. The holes in the dinosaur bone shown in Fig. 1 used to be tube-like structures called Haversian canals. These are branching channels, where the blood vessels and nerve fibres are carried through the bone.

Surrounding these canals are bone tissues called osteons. These are part of the cortical or compact bone, which is the strong part of a bone that holds up the body, while the spongy bone marrow (cancellous bone) produces red blood cells. Therefore, the cortical bone is that part of the outside structure of the bone that surrounds the cancellous spongy bone.

The dinosaur bone in this study is in siltstone matrix. Siltstone is composed of very fine-grained sandstone that has been deposited as silt. Through heat and pressure, this silt compacted and hardened into siltstone. This material is found depositional areas such as ponds and lakes, where standing or slow moving water permits fine-grained sandstone to fall to the lakebed forming silt. The dinosaur could have died either while in or near a body of water. Silt then covered its bones and the water allowed silica to replace the cells, one-at-a-time, over a huge length of time.

Our large dinosaur bone (Fig. 2) petrified in what became known as the Morrison Formation and quietly waited to be discovered and studied by the Colorado Springs Mineralogical Society (CSMS) 'Pebble Pups and Junior members', who decided to:

Investigate some of the structures of a dinosaur bone; and

Learn how to take pictures of paleontological specimens.

We accomplished this during a 45-minute monthly class. More exciting studies and papers are now planned.

Author's biography:

Kurt is a member of the CSMS Junior study group and is a 9^{th} grade student at Doherty High School in Colorado Springs, Colorado. He is a respected mentor to the younger Pebble Pups.

Further reading

Unk., . "Bone." Bone. Internet BioEd Project, Unk.. Web. 20 Jul 2011. <http://www.bcb.uwc.ac.za/Sci_Ed/grade10/mammal/bone.htm>.

Unk., . "Siltstone." Siltstone. LSF, 18/07/00. Web. 17 Jul 2011. <http://csmres.jmu.edu/geollab/fichter/SedRx/Rocks/Silt1.html>.

Unk., . "Siltstone." Siltstone. B2bchinastone.com, 2008. Web. 21 Jul 2011. <http://www.b2bchinastone.com/products-112/siltstone.html>.

Unk. "Haversian Canal." Wikipedia. March 2011. 1. USA: Wikipedia Foundation, 2005. Web. <http://en.wikipedia.org/wiki/Haversian_canal>.

Figure 1. As shown in this photo, the Haversian canals have dried out, leaving hollow holes throughout the bone. Photo by K Lahmers. SW Veatch specimen.

Figure 2. This Jurassic dinosaur bone was once a rather large, live, and active dinosaur that was part of a prehistoric ecosystem that included streams and ponds. Photo by K Lahmers. SW Veatch specimen.