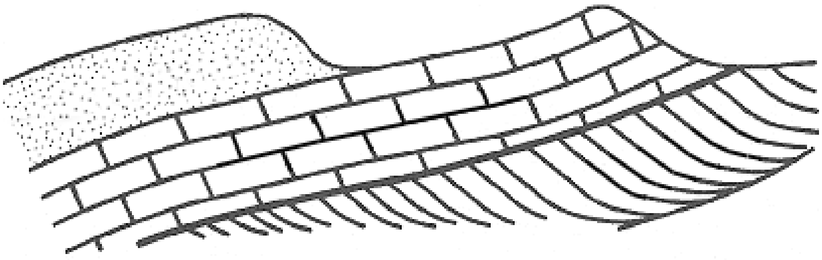
Farnham Geological Society

[**www.farnhamgeosoc.org.uk**]

Farnhamia farnhamensis



A local group within the GA

Vol. 18 No.2

Newsletter

Issue No: 90

June 2015

List of contents

Editorial

I don't have much to say this month except (1) please note the various changes to the meetings and dates as in the table below and (2) enjoy the interesting range of articles in this bumper issue, several written by FGS members.

Date	Speaker	Topic
10 July	Members Evening	*William smith / New Zealand*
8 August	No meeting	
11 September	Dr Mike Streule Imperial College, London	*History of tectonics in the Alps*
9 October	Dr Paul Taylor Natural History Museum	*A brief history of time in 10 fossils*
6 November ***Note: 1st Friday of the month***	Dr Matthew Pope University College, London	*English Channel Neanderthals*
Sunday 22 November	Society's Annual Lunch	*Frensham Pond Hotel*
11 December	Dr Gina Barnes SOAS, London	*Jade: its tectonic formation, geochemistry and archaeology in East Asia*
15 January 2016	AGM	
GA Annual Conference and Field Excursion will be at BGS Keyworth, 9-10 October, on Building Stones		

Liz Aston, Editor

FGS field trip to Pett Level and Fairlight Cove; addendum

During this interesting FGS visit last October we saw some old rooted tree stumps and remains of peat deposits below high tide level (Figure 1). These were part of an ancient wooded landscape, partly preserved in the peat, and drowned since Neolithic times by rising sea levels. Boulder Cliff, a submarine site off the coast of the Isle of Wight has similar tree and peat remains in a well preserved Mesolithic palaeosol now dated to 8,000 years BP.

Recently a core was obtained and analysed from sealed sediments at this site. A reconstruction using evidence of geomorphology and microfossils from the core has shown changes in the flora and fauna during occupation of this site before it was submerged.

The sequences suggest a mixed habitat of oak forest and herbaceous plants. However the recent discoveries show evidence of wheat (or a relative of wheat) – 2,000 years before the first documented farming in Britain. Quite a discovery!

Geologists and archaeologists have been working at Pett Level and Boulder Cliff; among them is Dr Richard Bates. His brother Martin led us on a field trip to the Medway Valley Palaeolithic Project a few years ago.

Reference : Science Magazine, Vol.347 (Feb. 2015,) pp.945, 998.

Joan Prosser, FGS Member

Field Trip to Box Rock Circus and Brown's Folly Nature Reserve - May 2015

Box Rock Circus

In the corner of the recreation ground of the picturesque Wiltshire village of Box, lies a mini Stonehenge edifice of geological education and information. The Rock Circus is the brainchild of Elizabeth Devon, who enthusiastically guided us around the exhibits of local rock as well as specimens from further afield. These are arranged in a circle with an obelisk of Box Ground limestone, a very high quality building stone excavated and donated by local quarry company Hanson Bath & Portland Stone, at the head. Moving clockwise the exhibits comprise:

Crystalline Climbing Block containing igneous and metamorphic samples including some donated by local quarry companies and sourced from Elizabeth's mother's coffee table top as well as other beautiful examples of gneiss and marble. This is followed by Silurian lava and Devonian Old Red Sandstone. Opposite the obelisk is the Fossil Rubbing Block, with various fossil casts. Unfortunately these casts are a victim of their success and are starting to wear and become weathered but are due to be replaced with casts in metal. Following the circle back around to the obelisk are the Tropical Limestone, New Red Sandstone and finally the Sedimentary Climbing Block made of sedimentary rocks, fossils and minerals.

These exhibit blocks are intended to appeal to children of ALL ages, and succeed admirably as demonstrated by the enthusiastic attention they received from our group and these future FGS members!

Across the middle of the circus are two sets of dinosaur "footprints", one large and the other smaller, scientifically arranged to indicate walking and running, to encourage children to interpret the story that the prints may tell. Finally there are a series of black lines marked around the granite sett perimeter to demonstrate the evolution of life on Earth condensed into one calendar year. The origin of the Earth, 4,600Mya, on the 1st January is shown by the first black line behind the obelisk, followed by the arrival of simple cells 3,600Mya, on 18th March and Algae demonstrating photosynthesis 3,400Mya on 3rd April and so on. This is an elegant way of showing the development of life and the more condensed explosions of variety from the emergence of animals with shells and skeletons, 542Mya or 19th November to Homo sapiens at 23minutes to midnight on the 31st December.

The Rock Circus imparts an immense quantity of information in an interesting, imaginative and readily accessible manner. There is much more on the website: http://www.boxrockcircus.org.uk

Box Rock Circus is testament to how Elizabeth channelled her enthusiasm, if not outright passion, for geology and the desire to impart the knowledge to others by engaging the local people, companies, groups and societies so much so that it is now a source of civic pride. The unerring support of a “long-suffering” but willing spouse was also vital!

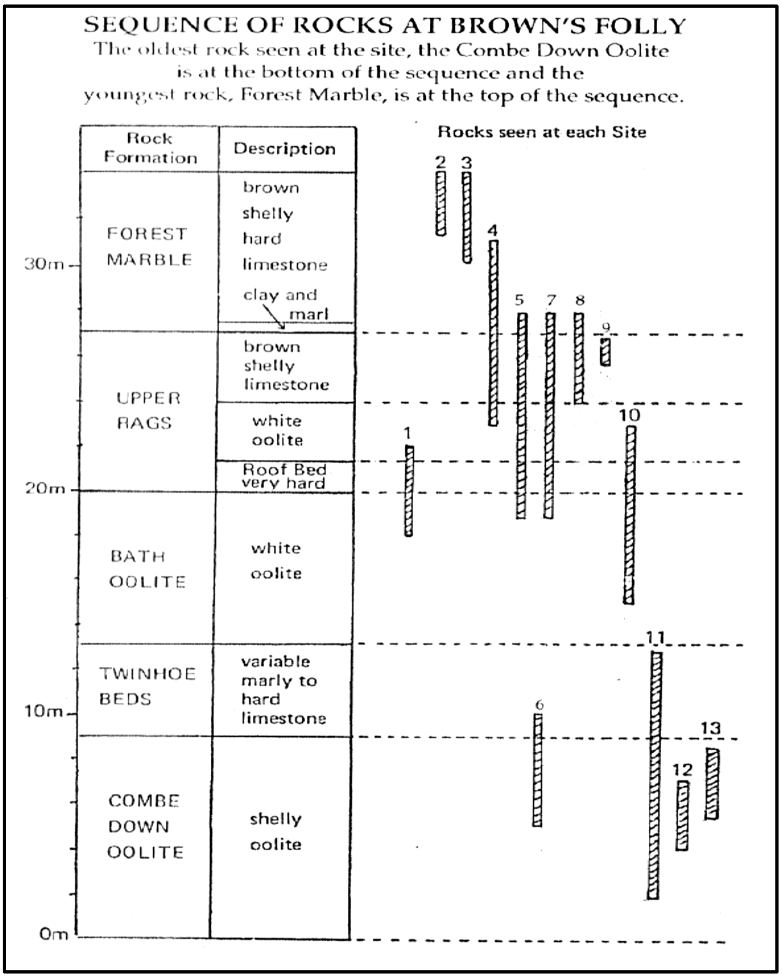
Before Elizabeth took us to Brown’s Folly Nature Reserve she outlined the geology of the valley in which the village of Box sits. The principal strata are Great Oolite overlying Fullers Earth and then Inferior Oolite. The Great Oolite layers comprise the good quality building stone that are such an important feature of the buildings in the locality and Bath as well as important buildings throughout the country. The Fullers Earth clay is mainly responsible for the serious landslip issues in the area. The Inferior Oolite layers are interesting due to the greater abundance of fossils but are far less useful for building purposes.

Intriguingly it is thought that the whole 32m plus sequence of rock was formed over only a 2Ma period, which incorporated several changes in sea level to bring about the appropriate conditions for each layer. The valley itself is far too large for the rather small By Brook which now flows through it. As such the hypothesis is that it is a post-glacial valley eroded by melt water.

The morning was interrupted by, what appeared to be, light rain. However Graham explained that it was just the morning dew being blown down from the nearby trees. Satisfied with this explanation we can safely assume that Graham’s record of organising only dry weather for field trips remains intact!

Brown’s Folly Nature Reserve

The reserve is a designated SSSI site and consists of 91 acres on the hillside overlooking the valley of the River Avon near the village of Bathford. It is owned by the Avon Wildlife Trust. The extensive limestone extraction of the past, largely by mining, has left the rock exposed and accessible for study at many sites. This has made it possible to establish a detailed picture of how the strata were formed and what the area would have looked like at the time. This geology seems to be the “pride and joy” of the Bath Geological Society who have produced a geological guide and website http://www.brownsfolly.org.uk/. There is an excellent pamphlet produced by the society entitled “The Rocks of Brown’s Folly” by Ron Smith. It is not the intention of this report of our field trip to plagiarise this pamphlet entirely (although it may at times seem like it) as several copies were purchased and can be borrowed from the attendees, if necessary, for more detailed reading. However the diagram showing the sequence of rocks is just too useful to leave out as it shows very simply and clearly the whole sequence and what strata are visible at each of the 13 sites that can be visited.



First stop – Site 1:

It is likely that this site was originally an adit mine, the two side walls of which remain; however the roof has collapsed and was cleared. The very hard Roof Bed is clearly visible on both sides sitting atop the now fractured Bath Oolite, which was mined for building stone. This layer is also known as Farleigh Down Stone. We were fortunate to discover some freshly fractured pieces, which when examined under hand lens clearly showed the tiny spherical ooids. Encouraged by Elizabeth we reflected on the conditions under which the layer formed. It would have been a warm sea, highly agitated, somewhat turbid and sludgy at the bottom. The highly agitated water would have restricted the formation of other fossils as creatures could not have lived in such a zone and skeletons of other animals would have been broken down along with the shells. The area would have been located at about 30°N with conditions similar to those of Indonesia and the Bahama Banks today, but with pterosaurs flying overhead!

The Roof Bed would have been retained as a roof as these adit mines were constructed and worked. Being much stronger and harder suggests that the water would have been calmer, thus this layer contains more fossils, with bivalves evident on the underside.

Second stop – Site 2:

This hollow seems to be the result of rocks collapsing into a mine, similar to several other such collapses that can be seen on the reserve. These rocks are some of the youngest present on the reserve, but still 170Ma. They form the Forest Marble layer. Although not strictly a marble, as it is not metamorphosed, it retains the name as the stone takes a polish very well and as such is used for ornamental purposes. Its other main use is for walling as it splits easily along the lines of shell bands. The rock contains more whole shells in layers than the lower limestone layers and exhibits cross-bedding. The conditions for the formation of this layer would have been shallow, warm, near-shore marine shell banks, in other words a rather pleasant desert island location. Unfortunately our visit was quite a few Ma too late.

Third Stop – Valley Panorama

We stopped on the path along the E edge of the reserve to appreciate the views across the Bristol Avon valley to Bathhampton village and Bath itself in the distance. The Great Oolite stratum continues on the opposite side of the valley but without the Forest Marble layer on top. The By Brook joins the River Avon on its meandering way to Bath. The diverse route of the Avon is somewhat intriguing and is thought to have been created by the effects of glaciation; however there appears to be little evidence to confirm this theory.

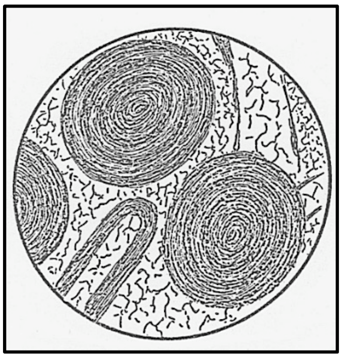
The dry stone wall parallel to the path is constructed of Forest Marble. A small, fresh sample of broken rock was carefully examined under hand lens to reveal a beautiful star-shaped crinoid ossicle, looking very like a minute starfish. Try 'googling' 'star-shaped crinoid images' to see what we found.

Fourth Stop – Brown’s Folly

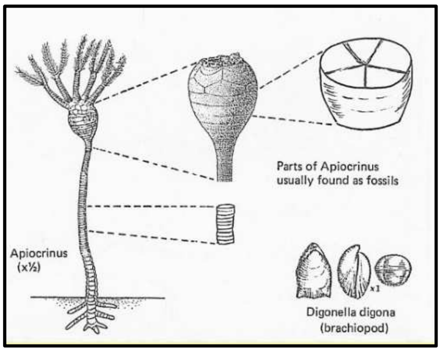
Why this tall tower is so named is unknown. What is known, however, is its construction of Farleigh Stone with finely sawn stone (Ashlar) corners. These limestone corner pieces were sawn underground when freshly mined and therefore still saturated and soft. Each piece is marked to ensure it is installed in the same orientation so that it is resistant to weathering and takes about a year for the surface to harden. A quaint story associated with the tower is that the ladies of the manor liked to take tea at the top – pity the poor serving maids!

Fifth Stop – Site 5

We skipped Sites 3 and 4 and took the steep path down to Site 5. The exposed face is made up of Brown Shelly Limestone, White Oolite and the Roof Bed layers of the Upper Rags over the White Oolite of the Bath Oolite strata. The Roof Bed is the marker layer which shows quite clearly where you are in the sequence. The Roof Bed also exhibits some minor faulting. The cave in the White Oolite below the Roof Bed has been sealed with an opening secured with a grille as it is now home for a colony of Greater Horseshoe Bats.



Ooliths under microscope



Fossils, site 4

Adit Mine, Site 10, Browns Folly

Stop 6 – Site 7

We skipped Site 6 as the same rock strata can be seen at Site 11, later on. Site 7 exhibits similar views of the strata as Site 5, although somewhat more jumbled as the Roof Bed had largely collapsed, however the Clay and Marl layer above the Brown Shelly Limestone was more clearly visible.

The adjacent area of grassland is being carefully managed to reinstate it as calcareous grassland. Trees and shrubs have been removed and over winter a small number of Wiltshire Horn sheep were introduced to the reserve to graze this area. This will help rare plants and insects to thrive in the reserve, which in turn will support the very important bat and bird populations at Brown's Folly.

Stop 7 – Site 8

Expectation levels were somewhat raised in anticipation of visiting this site. Initially enthusiasm was muted as upon first sight there did not seem to be anything of great interest. However it soon became apparent that there was a very different rock outcrop at the same level as the Brown Shelly Limestone which transpired to be a Patch Coral Reef. Elizabeth showed us a wonderful sample of the net-like coral as well as another intriguing sample of coral with a small Brachiopod trapped inside a burrow tube.

Stop 8 – Site 9

The discrete outcrop of Brown Shelly Limestone has distinct lines of cross-bedding. This may be the only matter of interest at this site, but it is a very good example of cross-bedding from which it is possible to determine the ancient current direction.

Stop 9 – Site 10

We passed through a kissing gate and descended a little further along a path through the lower wooded area to reach Site 10. This was originally an adit mine, but was only excavated a short way into the hill, and then was used as a munitions store. The White Oolite above the Roof Bed is very weathered, beneath the Roof Bed lies the Bath Oolite which was the material mined here. To the left of the mine entrance the Roof Bed tilts in in a downhill direction to display a good example of cambering. To the right the Roof Bed is faulted in three locations, leaving isolated blocks at different levels. It may well be the case that this faulting limited the mining activities at this site.

Stop 10 – Site 11

We continued down and along the path to the lower track on the way to Site 11, passing large blocks of rock that had broken away from the main rock mass. At Site 11 there are two high exposed rock faces separated by scree and other large blocks of rocks that had tumbled down. Although some of this may have been caused by mining activity it is likely that it is mainly the result of a slip down the hill on the underlying Fuller’s Earth Clay. Much of the exposed face consists of Combe Down Oolite, the oldest rock on the reserve, and contains a considerable amount of fossil debris and some small whole fossils. However this makes the stone here unsuitable as a building material and for working. Near the top of the Coombe Down Oolite there is a band of Brachiopod fossils filled with calcite. Above this lies the Twinhoe Beds which were a source of ironshot in localities south of Bath.

It was at this site that we lost Graham for a while. Despite the unsuccessful attempt of the one man search team to find him, celebrations were postponed as Graham emerged from examining the cave at the top of the rock scree.

Stop 11 – Site 13

The last site of our visit consisted of an outcrop of the topmost Combe Down Oolite and has very well preserved burrows and displays complex cross-bedding. This stratum was formed as calcite “sand” in a warm sea.

Final Thanks

Back at the car park we gathered for Janet Catchpole to formally and warmly thank Elizabeth for such a splendid and fascinating tour of Box Rock Circus and Brown’s Folly Nature Reserve, as well as Graham for organising the trip. It was a very full day but extremely satisfying and interesting.

John Greenwood, FGS Member

Geology From A Rail Seat – Durango to Silverton Railway

January 2015 lecture given by Dr. John Williams BGS

The Durango Silverton Narrow Gauge Railway was built in 1882 to provide access to the rich mining area of Silverton. In 1981 it became a thriving tourist attraction. The journey starts at 1,987m on Cretaceous Mancos Shales and ends up at 2,831m on Tertiary volcanics having traversed along the Animas River through Jurassic shales and sandstones, Cambrian and Precambrian granites and metamorphosed gneisses, schists and quartzites of the Ancestral Rockies. These have undergone uplift to form the San Juan Mountains. The area was glaciated during the Late Wisconsin glaciation with the largest glacier reaching Durango, leaving terminal moraines in the valley.

View N from Durango along the braided Animas River, E of railway and road. Animas City Mt (L), Hermosa Fm’n Permian/ Triassic red ssts to E & W, glacial outwash plain in centre.

The High Line, cutting through pink Cambrian granites. (Animas River in valley, bottom L)

The Needle Mountains, Pigeon Peak, Turret Peak, Aeolus Mountain - Precambrian granites

Silverton. Anvil Mountain in the background - Tertiary volcanics.

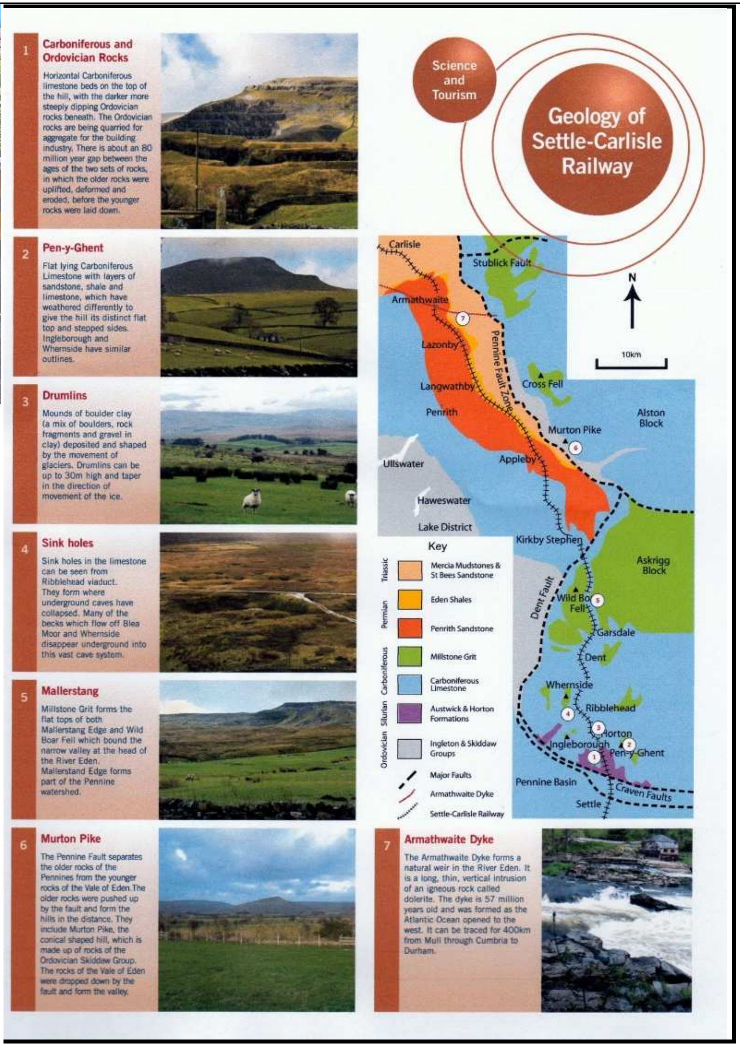
The other route was the Settle to Carlisle line starting in the Carboniferous Limestone area of the Pennines, running through Permian red beds and Triassic mudstones at Carlisle (see Figure 1, (L), the leaflet from University of Leeds Science and Tourism department for Friends of Settle and Carlisle Railway).

The talk was illustrated by more detailed scenic views of the area with views of the viaducts and tunnels that are a feature of this route.

Contamination by Pb, Cd, Cu, Mn, Zn & Fe that discharge from the countless mines and tailings (waste) piles - legacies of the Au and Ag mines.

Right: Leaflet about the Settle to Carlisle line.

http://www.see.leeds.ac.uk/misc/scienceandtourism/Final%20copy%20leaflets/SettleCarlisle%20Railway%20Leaflet%20%28Map%292.pdf



Science and Tourism

Geology of Settle-Carlisle Railway

1 **Carboniferous and Ordovician Rocks**

Horizontal Carboniferous limestone beds on the top of the hill, with the darker more steeply dipping Ordovician rocks beneath. The Ordovician rocks are being quarried for aggregate for the building industry. There is about an 80 million year gap between the ages of the two sets of rocks, in which the older rocks were uplifted, deformed and eroded, before the younger rocks were laid down.

2 **Pen-y-Ghent**

Flat lying Carboniferous Limestone with layers of sandstone, shale and limestone, which have weathered differently to give the hill its distinct flat top and stepped sides. Ingleborough and Whernside have similar outlines.

3 **Drumlins**

Mounds of boulder clay (a mix of boulders, rock fragments and gravel in clay) deposited and shaped by the movement of glaciers. Drumlins can be up to 30m high and taper in the direction of movement of the ice.

4 **Sink holes**

Sink holes in the limestone can be seen from Ribblehead viaduct. They form where underground caves have collapsed. Many of the becks which flow off Blea Moor and Whernside disappear underground into this vast cave system.

5 **Mallerstang**

Millstone Grit forms the flat tops of both Mallerstang Edge and Wild Boar Fell which bound the narrow valley at the head of the River Eden. Mallerstand Edge forms part of the Pennine watershed.

6 **Murton Pike**

The Pennine Fault separates the older rocks of the Pennines from the younger rocks of the Vale of Eden. The older rocks were pushed up by the fault and form the hills in the distance. They include Murton Pike, the conical shaped hill, which is made up of rocks of the Ordovician Skiddaw Group. The rocks of the Vale of Eden were dropped down by the fault and form the valley.

7 **Armathwaite Dyke**

The Armathwaite Dyke forms a natural weir in the River Eden. It is a long, thin, vertical intrusion of an igneous rock called dolerite. The dyke is 57 million years old and was formed as the Atlantic Ocean opened to the west. It can be traced for 400km from Mull through Cumbria to Durham.

Exploration in Greenland: an awkward target for remote sensing
March 2015 lecture given by Dr. Philippa J Mason, Imperial College

Greenland is a vast, remote and dangerous place with massive potential to host mineral deposits of economic value - a perfect target for remote sensing to assist in identifying the deposits. It is however, one of the most difficult targets for remote sensing - low sun angle, very steep terrain (which is either brightly illuminated or in deep shadow), short ice-free season, bad weather, presence of ice, snow and water (extremely bright, dark targets) all combine to make processing and interpretation of remote sensed images tricky and time consuming (Figure 1). Fieldwork is expensive and logistically extremely difficult so a flexible and holistic approach to all work here is necessary; you will need plans A, B, C, D and E to avoid disappointment and expense!

After much discussion and fieldwork, we decided upon the data and methodology needed to enable a multi-disciplinary assessment of prospectivity for a number of economic commodities, Ni, Cu and PGE (Platinum Group Elements), in previously unexplored terrains of SE Greenland. The results being intended to attract investors for further development of areas identified during the project. The SE coast of Greenland comprises vast and relatively unexplored Archaen and Proterozoic terrains which had shown potential for hosting mineral discoveries. It is ideal for a GIS-based assessment using remotely sensed and other regional geoscientific data.

Greenland is ranked very highly for mineral potential and favourable administration for exploration but extremely poorly in terms of infrastructure and accessibility; to say that it is logistically challenging is an understatement. Like many polar/near-polar regions, exploration here is difficult and usually undertaken by a small number of companies experienced in this kind of region.

Our project involved three separate phases: i) testing, compilation and assessment of rock and sediment samples; ii) systematic, multi-parameter spatial analysis of remotely sensed and all other available geoscientific data; and iii) exploration and ground validation of target areas pinpointed during the course of the project.

The study area consists of two parts: a) the Reference (SW Greenland) and b) the Survey (SE Greenland) areas, as illustrated in Figure 2. The ‘fingerprints’ of known mineral occurrences in the Reference area are used to help predict new occurrences in the Survey area. This approach is not new to exploration or geospatial analysis but in Greenland at the time was a novel tactic.

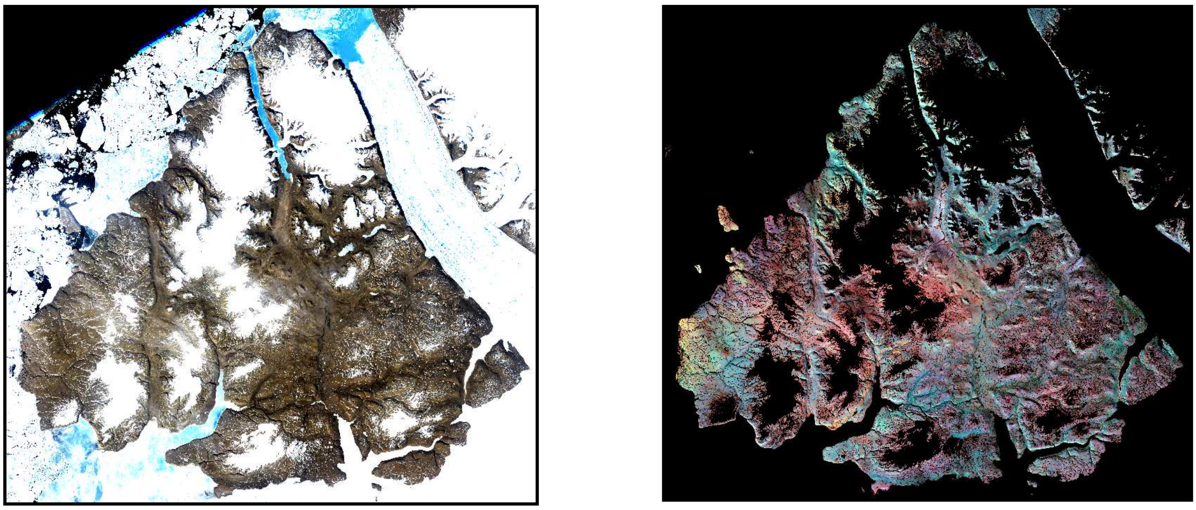


Fig. 1: Landsat 7 imagery: True-colour composite 321(red blue green (RGB)). Raw (left) and false colour composite 457(RGB) after removal of sea and ice (right), Washington Land, ca 85°N, NW Greenland.

The project area (24,500km^2 of highly exposed, poorly explored Archaean and early Proterozoic shield terrain) has significant potential for hosting mineral deposits, and stretches from Kap Farval in the S to the Ammassalik peninsula in the N (see Figure 2). The terrain is extremely remote and only a few expeditions have been to this part of Greenland. We built on that knowledge during our own field work in the summers of 2006 - 2009, and visited numerous additional locations collecting samples.

The government records the 44,000km coastline as narrow, mountainous with extreme elevations (>3,500m), in arctic/subarctic conditions, just 20% ice-free. With <100 hamlets/towns, no railways, minimal roads, few airports, transport by sea and helicopter is essential. Fieldwork is hampered by the persistent presence of icebergs along much of the coast, helicopter reconnaissance is hindered by the lack of re-fuelling stations (fuel must be carried on-board ship). Field work can be done by ship alone but that restricts access to near-shore localities, and far less distance can be covered. A mixture of the two is the optimum.

For any fieldwork in Greenland, experience, networking and local know-how are essential. Precise and detailed planning for season and location are vital. Equipment & consumables for the entire program must be ordered pre-season because resupply is almost impossible. The field season is short (May-September, or shorter), which necessitates innovative solutions (portable XRF's etc.). Greenland is also a dangerous place, requiring customised safety and emergency procedures in the arctic and remote camps (emergency beacons, VHF, satellite phone, customised medicine chest and first aid/trauma treatment). In the 'rain-shadow' of the Greenland ice sheet, the E coast terrain is generally dry and barren. Compared to the W coast, it is also high, steep, largely ice-covered and almost devoid of vegetation and wildlife.

The Reference area is well studied and a great wealth of data and experience has been gleaned from it. The Survey area, in contrast, has been mapped only at regional scales. The geological understanding of the W coast far exceeds that of the SE coast, which may explain why very little commercial exploration has been conducted here. The map of known mineral occurrences identifies many more on the W than on the E coast and almost none on the SE (Figure 3); the potential to find new occurrences is considered greater where occurrences have already been found. The discrepancy in understanding mineral potential between W and E coast terrains is being addressed.

The geology - The Precambrian shield of SE Greenland comprises three distinct basement provinces:

- Archaean terrain reworked during the early Proterozoic (Ammassalik Mobile Belt, of the Nagssugtoqidian Orogen, prospective for Ni, Cu & PGE),
- Archaean terrain almost unaffected by Proterozoic or later orogenic activity (the N Atlantic Archaean Craton, prospective for Ni, Cu & PGE), and
- Juvenile early Proterozoic terrain (the Ketilidian Mobile Belt or Orogen, recently recognised as a new Au province).

This project involved assessment of all three terrains. The terrains of the E coast are thought to extend beneath the ice cap to the W coast, with the same litho-tectonic suites and litho-geochemical characteristics, and to then continue into NE Canada (Figure 4) - they should therefore all have a similar potential to yield mineral deposits. Greenland is also considered to be closely related to similar terrains in Finland and Russia.

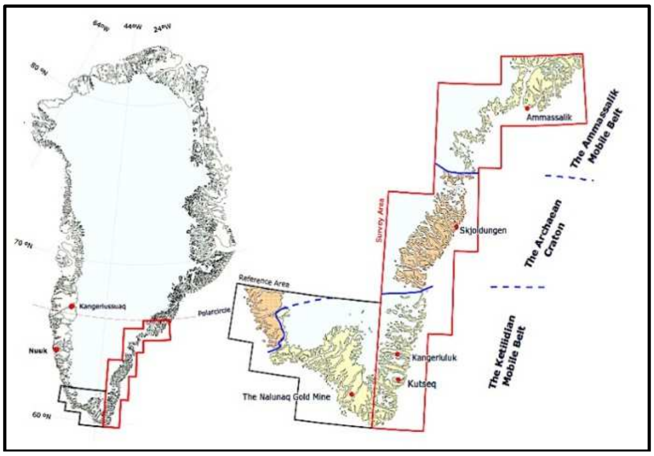


Fig. 2: a) (above) Map of Greenland showing the project area; and b) detail showing the project Reference and Survey areas in S and SE Greenland.

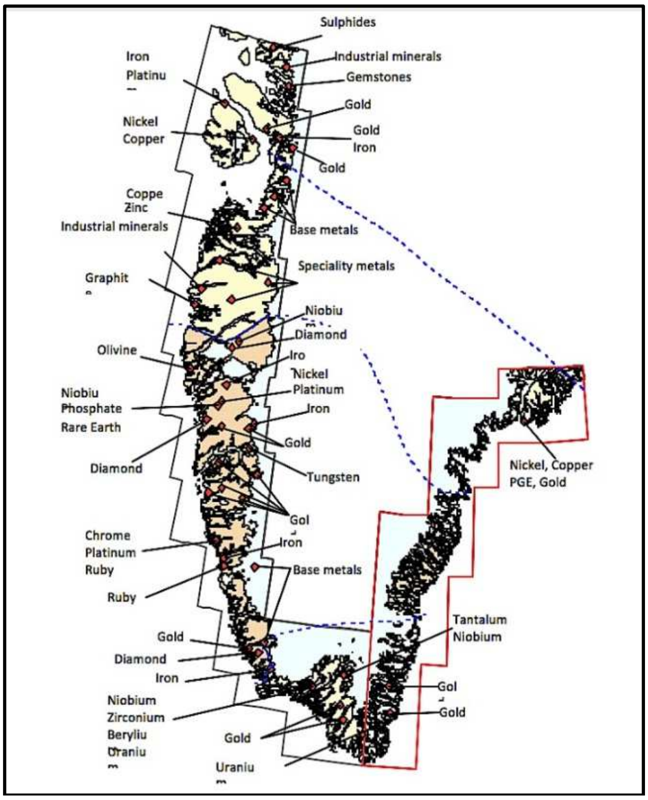


Fig. 3: (R) Mineral occurrence map of Greenland with the Project Survey area shown in red. Blue dashed lines = lithotectonic terrain boundaries.

NB for each terrain more discoveries have been made on W coast than on SE, despite the geological framework being the same.

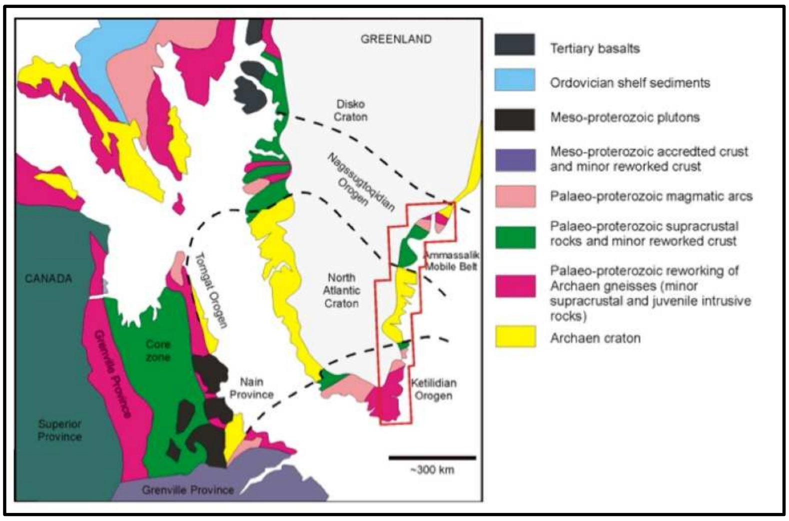


Fig. 4 (R): Proterozoic reconstruction of Greenland and Canada, showing the Atlantic-Arctic litho-tectonic trend (modified after van Gool et al., 2002). The approximate position of the Survey area is shown by the red polygon.

This sizeable Survey area comprises numerous litho-structural and geochemical settings; a number of well-known mineral deposit models are therefore being evaluated within these terrains; here we focus on komatiitic hosted Ni-Cu-PGE.

Remote sensing has been widely used in a great many application areas since Landsat-1 was launched in 1972. It has wide applicability in the geosciences and the resolutions available change continually and rapidly. It allows one to visualise and analyse beyond the visible part of the electromagnetic spectrum into the Infra-Red and microwave regions. Due to atmospheric effects, remote sensing instruments use discrete wavebands which allow us to compare the images with the known spectral reflectance behaviour of materials and in turn to produce results diagnostic of certain rocks, minerals, plants etc (see Figures 5, 6).

Data preparation begins with compiling various maps from the E coast (available at coarser scales than elsewhere in Greenland) and incorporating detailed work undertaken by students. Maps (1:500,000 scale) were used to extract background geology and to target the fieldwork (two sheets cover the Reference and Survey areas). These regional maps contain considerable internal geometric distortions, making accuracy very difficult; this emphasises the importance of the ASTER (Advanced Spaceborne Thermal Emission & Reflection Radiometer, Jet Propulsion 'Laboratory, NASA) imagery in providing an accurate basemap for interpretation and data capture.

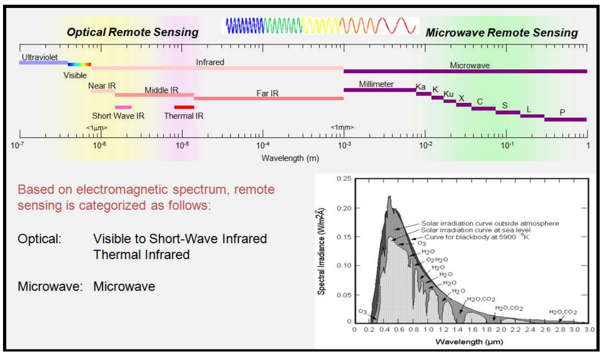


Fig. 5: Types of remote sensing, spectral regions in which they are operative, and solar irradiance curves

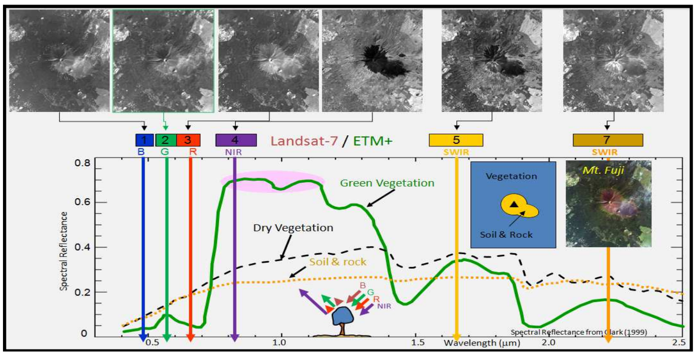


Fig. 6: Spectral signatures of materials allow interpretation of images in specific wavebands & targeting of specific rocks and minerals.

The mineralisations of interest occur in massive sulphide form and these are often small, dark and almost impossible to identify directly using remote sensing. We therefore concentrated on identifying any potential hosts, focusing on four key lithologies: ultramafic rocks (4), mafic meta-volcanic supra-crustal packages (3), gabbros and other mafic igneous intrusions (2) and other alkali igneous intrusive bodies (1). The vast majority of exposed rocks in this part of Greenland are un-mineralised felsic crystalline lithologies (gneisses, granites and granodiorites) so we are interested in identifying any other outcropping lithology.

Major structral features were extracted from regional geological maps; their positions are again often inaccurate and require correcting using ASTER imagery; in this case, working at a scale of about 1:50,000.

These interpreted (and mapped) structures represent zones of fracturing (potentially including faulting, shearing, jointing and other planes or zones of weakness and discontinuity). These are considered important as conduits and potential destinations for mineralised fluids, which are otherwise too small to be directly detected in the remotely sensed imagery and may not be obvious during fieldwork.

Mineral occurrences from several sources provided evidence for both the prospectivity predictions and for the later validation of those prediction maps. These data are simply point locations of known mineral occurrences. The occurrences were derived from the Geological Survey of Denmark and Greenland (GEUS) SW Greenland database, from Greenland's public geochemical database and from the laboratory results of our own fieldwork. For the komatiite-hosted Ni-Cu-PGE deposit model, a total of 78 known mineral occurrences were used in the spatial modelling.

Remotely sensed multi-spectral images (each covering an area of 60 x 60 km) formed the most reliable and accurate basemap framework for all other mapping and data capture; they were also used to generate a series of spectral indices. Ideal acquisition time is during the snow-free months and these were collected in July and August 2001 and 2006.

The global and free Shutle Radar Topographi Mission (SRTM) Digital Elevation Model (DEM) does not extend beyond 60° (N or S), and the ASTER Global DEM, which does cover Greenland, had not been released, so, the first step to correcting the data for terrain distortions was the generation of DEMs from the individual ASTER scenes. The DEMs were then used to ortho-rectify each ASTER scene, to remove terrain distortions.

The most important preparation, prior to any image processing, involves the removal of the very brightest targets (ice and snow), and darkest targets (water) from the data (Figure 1); this is difficult when water contains suspended rock flour (common in fjords) as the water is then almost indistinguishable from land (Figure 7). Defining a threshold at which to mask flour-loaded water becomes a very delicate operation, to avoid losing land pixels.

General visualisation - A standard false colour composite mosaic of the entire area was constructed and used both for general visualisation and interpretation, and also for field reconnaissance planning. For optimum general visualisation and use in the field, image data which still contains at least the ice masses should be used since it is very difficult to navigate using an image from which the glaciers and ice-capped peaks have been removed. Individuals not so familiar in working with remotely sensed data (e.g. helicopter pilots) often find it difficult to navigate using imagery in its processed and rather abstract form. The best image for such purposes should be as simple as possible so that image features can be readily correlated with real objects on the ground.

Targeted spectral image processing - we cannot see the small, dark metalliferous mineralisations and so instead target the spectral characteristics of the host lithologies noted above and illustrated in Figure 8.

Fig. 7: Skjoldungen penninsula (looking NW) note deep shadows on N-facing slopes, well illuminated S-facing slopes, summer ice & snow-fields & rock-flour-laden fjord waters with scattered icebergs.

Fig. 8: Synformally folded suite of supracrustal rocks consisting of mafic (and ultra-mafic) units, high in Fe and often with oxidised Fe (gossans) at the surface, contained within granitic gneisses.

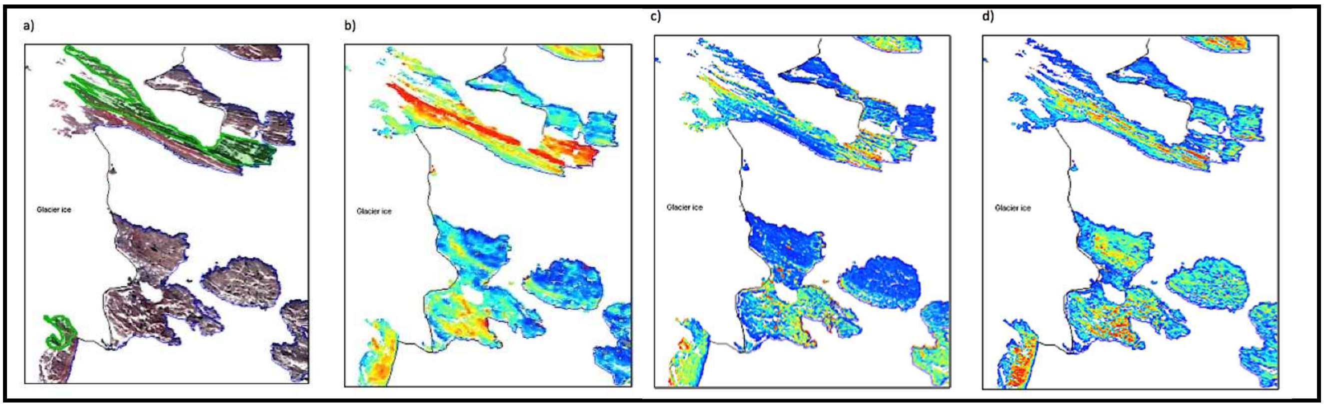


Fig. 9: Graah islands, SE Greenland: a) Standard false colour composite showing two supra-crustal packages identified in published maps (green polygons); b) mafic silicates displayed as a pseudocolour layer with increasing value from blue through to red (0-255); c) MgOH spectral index (e.g. epidote, chlorite, talc) indicating altered mafic volcanic rocks, displayed with the same colour table as (b); and d) Fe^{3+} in silicates index (FeMg minerals). The field of view is ca 14 km. See also Figure 10

Values from the spectral bands can identify diagnostic absorption features, which can be used to highlight Fe-oxides and hydroxides, in weathered goassaniferous areas of high Mg-OH content and of silica paucity i.e. mafic and ultramafic rocks where these are large enough or extensive enough to be detected.

Four key spectral indices are illustrated in Figure 9 for a very small part of the Survey area. We see that there is variation within the packages: some zones are more mafic than others (Figure 9c) and some zones are altered (Figure 9d). The reflectance spectroscopy in Figure 9c indicates the presence of silicate minerals, characteristic of mafic rather than the acidic igneous rocks; here red colours indicate the mafic igneous zones within the supra-crustal packages, against the acid crystalline background of gneisses (blue).

The geochemical data used here comprise laboratory analysis results from rock samples collected in 2006, 2007 and data from the Ujarassiurit database. Samples from the 1960s and those from 2006 were also analysed using a field spectrometer, the results of which have been very useful in characterising both the background spectral signatures and those of altered samples from known mineralised localities. This provided an ‘intelligent’ geochemical database.

For each particular deposit model, certain pathfinder elements were selected, here, Ni, Cu, Cr, Au, Pt and Pd. The sample point data for each pathfinder element were then interpolated to produce a representation of estimated element concentration over the entire area.

It is the patterns in the data that are important - relative rather than absolute values. Histograms showing a single, normally distributed population without skew (or a slightly positive skew), is highly likely to represent background levels of that element. It is better to see a negatively skewed histogram that has several peaks (i.e. representing multiple populations), as shown in Figure 11b.

Regional geophysical data (gravimetric point samples), corrected for anomalies, were interpolated to produce regional gravity for the project area and used for relative interpretations of anomalies; but not within the spatial modelling as they had not been corrected for Greenland’s ice sheet - a ‘make-shift’ correction had to be made before the results could be used within the spatial modelling.

Multi-criteria spatial modeling, combining all the input data and using known mineral occurrences in the Reference area, enabled us to produce a regional prospectivity assessment as the final step. Probability estimates (prediction maps) and new targets have been produced to identify economically favourable areas for further detailed ground validation.

One of the results, for the deposit model described here (komatiitic hosted Ni-Cu-PGE) is shown in Figure 12. It reveals a series of high value areas, at various locations throughout the Survey area. Some of which we have confidence in, others we suspect to be exaggerated by the overwhelming presence of a few high Au values; in addition to areas that we think should appear more significant than they do here. Clearly further iterations and development are required.

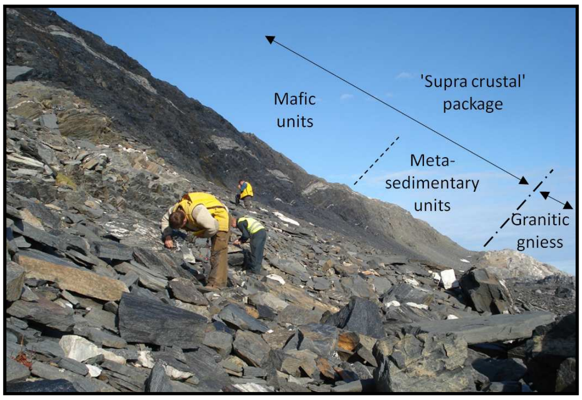


Fig. 10: Fieldwork, Graah Islands. The dark colour of the Fe-rich mafic supracrustal rocks are clearly distinguishable from the paler (felsic) granitic gneisses exposed on the horizon (far R). View looking SE along strike.

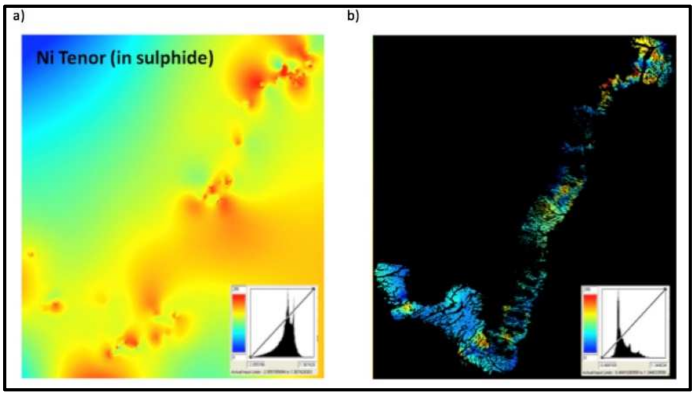


Fig. 11: a) The interpolated Ni tenor grid of entire area & histogram; b) the same grid and histogram after effective masking out sea and ice. The masked histogram clearly shows several significant populations, indicated by the smaller peaks on R.

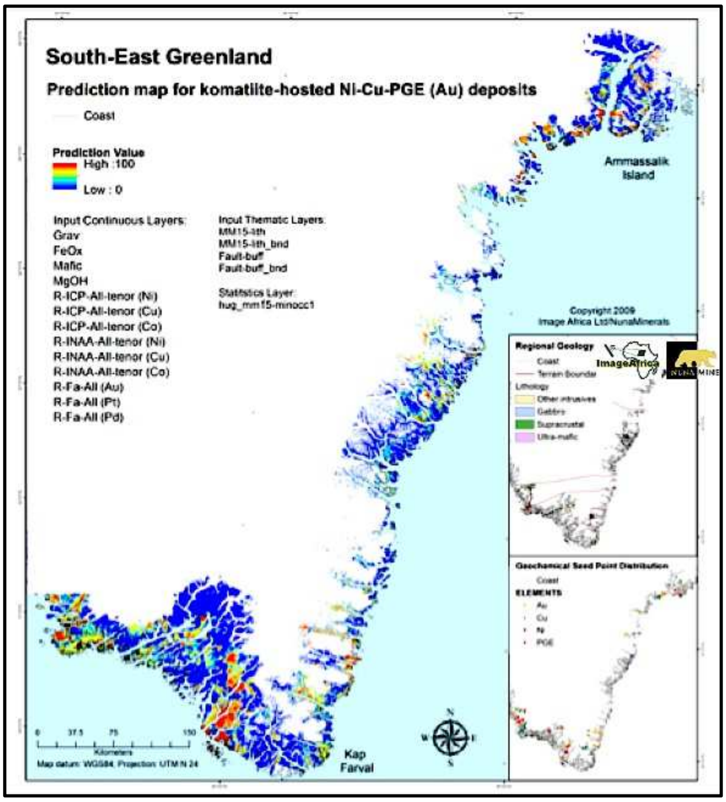


Fig. 12: Prediction map of prospectivity for Komatiitic hosted Ni-Cu-PGE deposits in the Reference and Survey areas. Produced by kind permission of Nunaminerals A/S

In conclusion - The purpose of this regional study is to demonstrate potential in a few target areas, which will then become the subject of further, more focused predictions since we expect that the vast majority of the project area will be shown to be non-prospective. One key driver for this work is to prevent ourselves and others from wasting valuable time and funds in those areas.

For each deposit model, we have a certain expectation of where the most predictive locations are likely to be, on the basis of our own field experience. In other words, the 'truth' is partly provided by our own observations, even though we have only visited a tiny fraction of the area. If our results can predict the locations known to be prospective, we can have more confidence in the map's ability to predict previously unknown locations as prospective.

The ideal next step in remote sensing exploration is the acquisition of airborne hyperspectral imagery but this is costly and likely only to be undertaken for a much smaller area about which considerable knowledge already exists.

Acknowledgements - This work was funded by NunaMinerals A/S and by Image Africa Ltd. We are grateful to GEUS for regional geophysical data, and to Dr Bo Muller Stensgard for his technical advice.

Reference

Van Gool, J. A. M., Connelly, J. N., Marker, M. & Mengel, F., 2002. The Nagssugtoqidian Orogen of W Greenland: tectonic evolution and regional correlations from a W Greenland perspective. Canadian Journal of Earth Sciences, 39, 665–686.

Relocating ancient sources of gold and tin in Ireland

Summary of May lecture given by Dr. Norman Moles, University of Brighton

The lecture was mainly about the history of gold working in Ireland and recent discoveries in the Mourne Mountains (Figure 1). However, Dr Moles began by showing photographs of nuggets and crystalline gold, and outlining the reasons for studying river-borne grains of this metal, referred to as alluvial or 'placer' gold (Figure 2). A naturally occurring mineral in hydrothermal veins and other mineralization, gold is released by weathering into soils and sediments. As it is chemically inert and ductile, the particles are progressively deformed during transport. However, the gold particles can contain tiny inclusions of other minerals, such as sulphides, with which it was deposited in the bedrock mineralization. These are shielded from the oxidizing environment of the soil or stream sediment. Furthermore, the gold itself is not usually chemically pure but comprises an alloy of variable composition. Silver is usually the main alloying element, but sometimes the alloy includes detectable copper, mercury or platinum group elements.

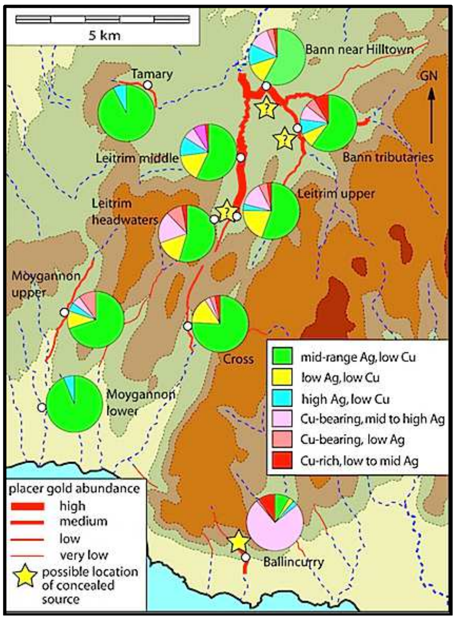


Fig. 1[1]: Alluvial gold abundance & alloy compositions, W Mournes. Pie charts show proportions of gold grains with compositional ranges at each site or cluster of sites. Stars indicate general location of possible bedrock source areas - these may now be eroded.

Fig. 2: Alluvial gold from the River Bann; the largest grain is 4 mm in length. Photograph by Rob Chapman.

The method of studying sets of alluvial gold grains collected by sluicing and panning stream sediment was described; this is known as 'microchemical characterization'. Ideally at least 30, and preferably over 50 gold grains at each site are collected by gravity separation techniques, involving sluicing and panning large volumes of sediment, typically about 1 tonne. Gold grains are embedded in resin blocks and cross-sectioned to allow the original alloy composition to be measured using an electron microscope. Studying placer gold can provide useful information such as whether there are single or multiple sources of bedrock mineralization, the style of the source mineralization, and even constrain the physiochemical conditions during mineralization.

Alloy compositions vary geographically - in the south of Ireland the gold has low silver contents but further north the proportion of silver is significantly higher. Metallic mineral inclusions encapsulated within the gold grains can be very useful indicators of the original style of bedrock mineralization e.g. whether associated with igneous intrusions or generated during regional metamorphism ('orogenic').

Bronze Age gold ornaments such as lunulae (collars shaped like a crescent moon) have been found throughout Ireland and were treasured and buried in mounds of local chiefs or leaders. Similar lunulae found in Cornwall originally came from Ireland around 4,000 years ago. The evolution in styles of Irish gold ornaments help in dating items from the Early to Late Bronze Ages. There is a debate as to whether the gold was obtained from sources in Ireland (possibly the Gold Mines River, Co. Wicklow) or imported from overseas. Since 1980, further finds of alluvial gold throughout Ireland support the theory that gold was extracted there in the Bronze Age.

Since 2006 bedrock gold has been mined in an opencast operation at Cavanacaw, near Omagh in County Tyrone. The ore is ground in mills and separated using froth flotation, producing a sulphide-rich concentrate, which is shipped to Morocco where small batch smelters separate the gold. This is returned to Tyrone and fabricated into Celtic design jewellery marketed as 'genuine Irish gold'.

The silver and copper contents of alluvial gold found in the Mourne Mountains of Northern Ireland match the majority of gold in early Bronze Age artefacts from Ireland, whereas most natural gold found elsewhere in Ireland does not match the artefacts. Caution is necessary as later in the Bronze Age, copper appears to have been added to the gold used in ornaments, either deliberately to enhance the colour of the gold or accidentally by contamination during the manufacturing process.

This type of copper-bearing gold seems to be limited to the Mourne Mountains region where granite plutons of Palaeocene age intrude through Lower Palaeozoic greywackes and shales. Inclusions of bornite and chalcocite in the copper-rich gold indicate formation from hydrothermal-magmatic fluids, which correlate with the granitic rocks found in the region. Using sluicing equipment, alluvial gold is relatively easy to obtain in the Leitrim and Bann River valleys in the western Mourne Mountains. However that is not to say it is abundant - two people panning all day at the most abundant sites with the equipment used in this study may result in only 100 sand-sized grains of gold!

Evidence of Bronze Age activity in the area is suggested by the discovery of an axe hoard at Ballinvalley within a few miles of the Leitrim River. Cassiterite for the production of the bronze alloy, as well as copper-rich gold, are found together in river sediment in the Leitrim-Bann area, which suggests that gold may have been recovered as a by-product of tin extraction in the region.

River sediment profiles in the Leitrim valley show enhanced levels of tin, which may have been caused by early mining activity. The Ballincurry River valley in the southern Mournes shows geomorphological evidence for possible metal working activity in the form of leats, where water was channelled to be used for hydraulic mining. An ancient wall with vertical rock slabs appears to have diverted water to an extraction pit approximately 60m long by 20m wide. Cassiterite is scarce in stream sediments in the Ballincurry River and therefore the ancient workings here were exclusively for the recovery of gold.

No radiocarbon dating has yet been carried out but would be of help in future studies of the Ballincurry leats, and Leitrim River sediment profiles, to date the periods of mineral extraction. Archaeological investigations are planned in the Ballincurry valley including bulk sampling of glacial sediments to determine their gold content. Analysis of cassiterite compositions and tin isotope ratios (a highly specialized technique) may be able to characterize particular bedrock source types, which would help differentiate between Cornish and Irish bronze.

To sum up, evidence can be found to support the theory that some 3,000 years ago gold and tin were extracted in the Mourne Mountains area and artefacts made from these metals may have been traded with Britain and possibly further afield. In the future, gold and tin mineralization may be located in bedrock in the Mourne Mountains. But this is an area of outstanding natural beauty so the ore is unlikely to be mined!

[1] *Map (Fig. 1) created by R. Warner and reproduced here by permission of The Geological Society, London.*
Many thanks go to Ingrid Lock of the Brighton & Hove Geological Society for her assistance with this summary.

FGS trip to Gower coast 29 March to 1st April, 2015 - Collisions, Castles and Cyclones

On April 1st, on a windswept beach once frequented by a Dr Who, a Dr Williams and Jack, his assistant, summarised the structural story he had been telling us in the last few days by drawing lines in the sand. The earliest rocks we saw in Gower were the Devonian Old Red Sandstone (ORS) (mud, sand and conglomerate) eroded from the Welsh mountains of the Caledonian orogeny.

During the Carboniferous, marine trangressions deposited a sequence of limestones up to a thickness of 1000m, and at the end of the Carboniferous, the Rheic Ocean closed and a collision between Armorica-Iberia and Gondwana, and S. Britain formed an E-W mountain range which was eroded throughout the Permian and Triassic.

As the Atlantic opened towards the end of the Triassic, crustal stretching formed basins into which sediments were deposited. At the end of the Triassic, the sea inundated S. Britain at which time the Liassic sequence of mud and limestone was deposited. What evidence had we seen for this?

Day 1 Mumbles Head: At Limescale Bay fissures, filled with calcite crystals sometimes reddened by the desert sands laid in Triassic times, trend N-S; were these Hercynian fissures or the result of the extending crust in the Triassic? To the east at Bracelet Bay the islands of the headland are the result of more easily eroded N-S faulting. Here, also, the folded limestones trend E-W. (Figures 1, 2)

Figs. 1 and 2: Folded and fissured Carboniferous Lsts. With red staining from the Triassic rock cover

Fig. 3: Folding and thrusting at Caswell Bay

Fig. 4: Wadi deposits

Day 2 At Mewslade: A very large piece of rock, whose strata appear to match those of a westerly limestone exposure about 50m away, sits in the dry valley perhaps dropped down as successive summer melts of surface frosts eroded the rocks beneath. Discounted, was the theory that the valley results from the collapse of an undergound river as little debris from above can be seen. An example of which is found further E in Paviland Cave, where the skeleton of 'The Red Lady' was found which the most recent dating puts at approximately 33,000 years BP.

North of Rhossili we saw Devonian rocks with limestone on top and a terrace before the bay is reached. Here the question of raised beach or glacial deposits was posed and lack of a cliff landward moved the decision to glacial deposits (solifluction).

By now our local cyclone was delivering rain as well as wind as we climbed up to the summit of Cefn Bryn to look over the Loughor Estuary and the syncline of the coal measures beyond. To the N is Cil Ifor, an Iron Age hill fort/earthwork, which was occupied into Roman times. On top of Cefn Bryn sits Arthur's stone, an enigmatic dolmen of Neolithic origin whose conglomerate capstone is broken and beside which lies a large stone of different origin. Local legends of its origin abound!

Day 3: We started with a recitation of the mantra for Caswell Bay from old to young: Caswell Bay Limestone (Oolite), Caswell Bay Mudstone and High Tor Limestone. By the café the rocks dip S and across the bay dip N suggesting the limbs of an anticline. Further towards the sea on the cafe side, triangular shaped slabs and mashed up rocks suggest an E-W thrust zone. The chaotic crumbling of the rocks being the result of the thrust decreasing the available volume in which they lie (Figure 3).

At Three Cliffs Bay the Caswell Bay mantra persists. A N-S fault displaces the E side of the bay northwards. Here the Caswell Bay Oolite has light and dark interbeds suggesting slighty muddy conditions, also minute zig-zag styolites indicate pressure and elsewhere we saw chert/flint material.

In the 13th/14th C the bay was swamped by sand dunes and, 12th C Pennard Castle, a ring-work castle with surrounding ditch and bank which overlooks it, was abandoned.

Day 4: At Ogmore the exposed surface of Carboniferous Limestone shows fossils of abundant marine life - crinoids, brachiopods, large solitary and colonial corals and we also saw a lone example of a proto-ammonite, a goniatite, which must have lived in deep warm water.

Fig.5: Carboniferous Limestone thrust over Lias.

To the E was an impressive wadi, its large unsorted boulders of Carboniferous Limestone mixed with red mud and sand had been swept by flash floods and filled eroded limestone valleys (Figure 4).

Lastly, at Bad Wolf Bay, we saw a long section of a Blue Lias cliff face resting on a Penarth Group beds wave cut platform. At the opposite side of the bay we were stunned by a spectacularly folded section of the Lias, folded into a small anticline, where a reverse fault had thrust the Sutton Stone (Carboniferous Limestone) above the Lias, Figure 5.

Many thanks to Graham for his, patiently explained, geological expertise and to Mike and Chris for archaeological interpretations. Finally the sea came and swept away the story but then that's geology for you.

Christine Norgate, FGS Member

Sill emplacement and evolution into a shallow magma chamber

February 2015 lecture given by Dr Zöe Barnett, RWE Dea UK Ltd

The Eyjafjallajökull eruption, S Iceland, in 2010 was an eruption to remember causing disruption to European air travel, grounding many flights due to the dispersal of ash. The magma that fed the eruption was from a shallow magma chamber, and prior to the eruption in April 2010 there was ground deformation (uplift or doming of the volcano) by approximately 3cm. This deformation was measured by the Iceland Meteorological Office using GPS (Global Positioning System) satellites, which also detected sill emplacement at great depth inside the volcano. Such a geophysical technique along with InSAR (Interferometric synthetic aperture radar) measurements and seismic detection have also been used to identify sill emplacement at El Hierro, Canary Islands, 2011-12, Etna in Italy, Kilauea in Hawaii, and many other volcanoes worldwide.

Geodetic, geochemical, and field data give evidence that shallow magma chambers have a sill-like geometry, which is maintained throughout their lifetime. There is also increasing support that large magma chambers form from sill clusters. However, within the scientific literature attention has so far been given mainly to individual sills; sill clusters or complexes have received little attention in comparison. Sills can be seen in the field within volcanic areas and also in sedimentary basins exhibiting a range of geometries, most commonly either straight or concave upwards. For geologists, and volcanologists in particular, a fundamental question is: how can these sills evolve into shallow magma chambers?

Magma chambers can be defined as totally or, most commonly, partially molten bodies within the Earth’s crust that, from time to time, receive batches of new magma from a deeper reservoir. These shallow magma chambers then act as a source for volcanic eruptions that we witness in tens of volcanoes every year on our planet. My research involves using numerical modelling to understand how a sill is initially emplaced and how it may evolve into a shallow magma chamber.

Classic cartoons of volcanoes show a vertical feeder dyke (a magma-filled fracture) running up through the centre of the volcano. However, many of these cartoons do not depict that volcanoes and the Earth’s crust consists of many different layers of rock, and the chances of a dyke reaching the surface to feed an eruption are normally not very great. That is, most injected dykes, most magma-driven factures injected from a chamber, stop or become arrested below the Earth’s surface and never feed volcanic eruptions. Or to put it differently: most dykes are failed eruptions. We call them non-feeders to distinguish from the much less common feeder-dykes.

The non-feeders have the ability to deflect laterally along contacts or boundaries between rock layers in the crust to form a sill – a horizontal magma intrusion. This is because within the upper crust the rock layers have widely different properties: in particular, some layers are very soft or compliant (like clay or sand) and easily deformed, whereas others are very stiff or springy (like lava flows) and difficult to deform. Where stiff and soft layers come together, such as where a stiff layer is on top of a soft one, they form a ‘trap’ for dyke propagation. That is, contacts between stiff and soft layers form barriers that tend to stop or arrest the dykes that are trying to reach the surface (so as to erupt). Sills tend to form along a contact between an overlying stiff rock, for example a basaltic lava flow, and an underlying soft rock, for example a sedimentary or pyroclastic rock layer. Thus, the traps for vertical dykes are the most common locations for sill formation and, therefore, for the development of shallow magma chambers.

More specifically, after the sill has been initiated it grows laterally, and then becomes thicker through upward bending of the overlying rocks. While the sill remains liquid, subsequent magma injections through dykes are absorbed by the initial sill, hence allowing it to expand and grow further. However, for the sill to remain at least partially molten there must be a high rate of magma injections from the deeper source reservoir in order for the sill to have a chance to evolve into a shallow magma chamber. Shallow magma chambers may also form by the amalgamation of sill complexes depending on the size of the individual sills that make up the complex.

To conclude, volcanoes are the manifestation of a powerful force of nature, but the building blocks of a volcano are far more complex than meets the eye. Only recently have these building blocks and their behaviour received due attention. In particular, the processes involved in the formation of shallow magma chambers and the arrest of dykes are currently of great scientific interest to volcanologists and the focus of many of their studies today.

Author’s note: For further reading please refer to ‘Numerical modelling of dykes deflected into sills to form a magma chamber’, Journal of Volcanology and Geothermal Research, 2014.

Looking back: FGS trip to Ireland, May 2001

During this trip we visited the Lower Carboniferous Limestone pavement landscape of the Burren, and inspected the Poulnabrone dolmen (Figure 1a, 1b). There is evidence that the first farmers arrived in the Burren in the Early Neolithic Period, at least 6,000 years ago. Farming activity appears to have been on a small scale. There were sporadic clearances, followed by abandonment and subsequent regeneration of the woody vegetation.

We saw a legacy of these early settlers in the shape of the famous Poulnabrone portal tomb/dolmen. Supporting evidence shows that this was built some 5,800 years ago, and on excavation within it signs of early agricultural activity have been recovered. The location of this type of tomb demonstrates a bias towards areas of lower altitude, mostly close to the coast or to water sources. Other types are more widely distributed at altitudes up to ca. 275m, and may indicate exploitation of thinner soils for stock raising (Ó Nuallain, 1983). There are only two known portal tombs in the Burren: one on the S periphery at Ballycashin, and this one, in the very centre, at Poulnabrone.

Fig. 1a: Poulnabrone Dolmen from front

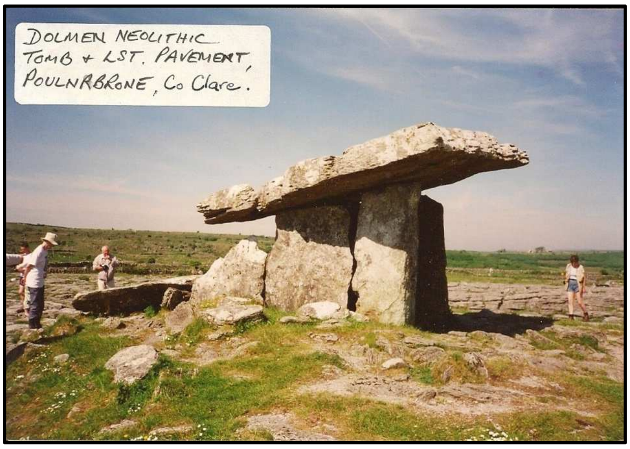


Fig. 1b: Poulnabrone Dolmen from side

Results from an excavation of this tomb reveal that it contained the remains of up to 22 people, interred over six centuries. High levels of stress and physical attrition due to diet and work were noted, as was evidence in one case of injury by a chert arrowhead in the hip. Early demise was common, with analysis of the adult remains indicating life spans of less than 30 years. Dental analyses revealed high levels of wear and tear consistent with a diet that included ground cereal. Other evidence recovered from this site indicated that these people were farmers of cattle, sheep and goats, and that cereal was cultivated.

In the late Neolithic and early Bronze Age, farming developed significantly; a phase of more concerted, structured and settled agricultural activity seems to have developed. In the Burren, the presence of more than 75 of Ireland's 400 wedge tombs*, and proof of numerous farm settlements, indicates the scale and extent of this prospering agricultural-based economy; an organised society in control of its resources.

**Wedge tomb: Irish megalithic tomb consisting of a rectangular, trapezoidal, or D-shaped cairn with a long, narrow chamber opening into the cairn from a wider, higher side. With no separate entrance passage, the chamber is typically constructed of orthostatic walls supporting massive capstones forming the roof. Generally the chamber decreases in height towards the back. Many face W. Burials are mainly multiple cremations. Grave goods are rare. Dated examples cluster in the late Neolithic, although many were later re-used as burial places. (Oxford Dictionary of Archaeology.)*

References:

Jones, C., 2004, The Burren and the Aran Islands, exploring the archaeology.

Ó Nuallain, S., 1983, A Location analysis of the Megalithic Tombs of the Burren, Co. Clare.

Weddell, J., 1998, Prehistoric Archaeology of Ireland.

Joan Prosser, FGS Member

Slaty cleavage and other forms of cracking, including that arising from hydraulic pressure

Several pieces of slate that exhibited cube face fractures such as that shown in Figure l, have been microscopically examined. The front face shown in this illustration could be readily identified as the principal (slaty) cleavage plane from the silky texture caused by the plane parallel alignment of the microscopic platelets in its structure. The other two fractures, planes A and B, needed a closer examination to discover the cause of their particular weakness. Figure 2 shows, in section, a B face that exhibited a number of deformation bands and in Figure 3, a B face fracture. It can be seen that within these bands the aligned platelets had been rotated by a shearing action, in some cases by as much as a right angle. Figure 4 shows how this extreme rotation led to shear de-cohesion, or what is commonly described as strain-slip cleavage. This accounts for the A face weakness and, incidentally, why the slaty cleavage surfaces in this particular slate were corrugated.

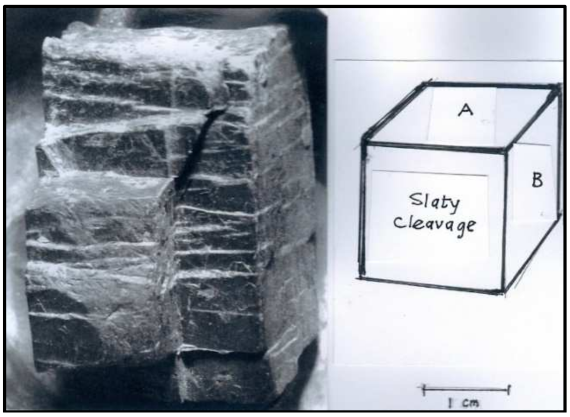


Fig 1

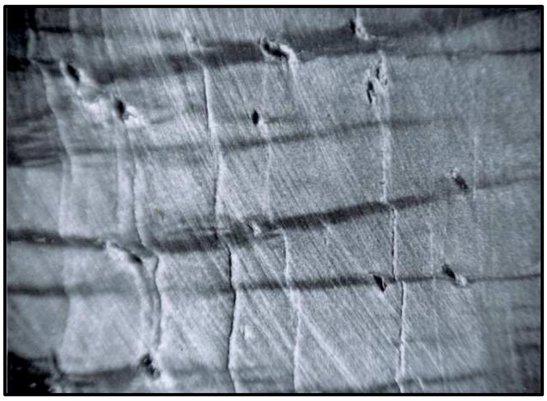


Fig 2: B Face

--- 1 cm

Fig 3

B Face

Fig 4

--- 1 cm

The B face fracture followed a plane path, yet there was no properly oriented feature in the slate's microstructure to account for this, thus it qualified as a joint. However, because of the layered form of the microstructure in slate the growing crack had attacked material containing vertical splits, as can be seen in Figure 3. These splits along the slaty cleavage plane would arise from the accompanying transverse tensile stress acting to open these weak interfaces. Thus the main crack grows by rupturing unsupported ligaments, and because the transverse stress trajectory lies in the main fracture plane, level growth is maintained

Joints have been a matter of considerable speculation. Where they appear in the context of thermal or de-hydration shrinkage they can be attributed to the forces involved in volume change. However, there are more general cases, particularly noticeable when quarrying fine grained sedimentary rocks, where the paths of fracture are distinctly cubic. It was this geometric exactitude of the fracture paths that seemed to puzzle the early geologists and, having the shrinkage cases in mind, they sought to attribute all such regular fractures to pre-existing residual stress. What was not known at that time was that a plane was the stable (minimum energy shape) for fracture, but only in a uniform tensile stress field, a fact that became clear from Griffith's work published in 1920.

Engineers are used to non-uniform stress, working with monolithic pieces in the centimetre to metre range, whereas rock formations are likely to be measured in kilometres where greater uniformity of stress can be expected. Under these conditions natural elastic strain energy release will happen by the formation of relatively plane smooth -faced joints. However, if high pressure water should enter these joints, this uniformity is upset, and cracks branch and grow along tortuous paths under the hydraulic (tri-axial) pressure within them.

This slate contained a number of well-formed cubes of pyrites which seemed to have played no part in the fracture process. There were also a number of smaller lens- shaped particles that must have been present in the slate's formative period. As can be seen in Figure 2, these were directly associated with the deformation bands (none were ever found elsewhere). This indicated that their presence had been the cause of this localised deformation, or, conversely, that they had obstructed what would have been, in their absence, uniformly distributed shear strain. Although these particles were small, about O.5mm in diameter, their sphere of influence must have been much greater. Their presence caused deformation banding which in turn resulted in slaty cleavage plane corrugations.

Peter Forsyth.