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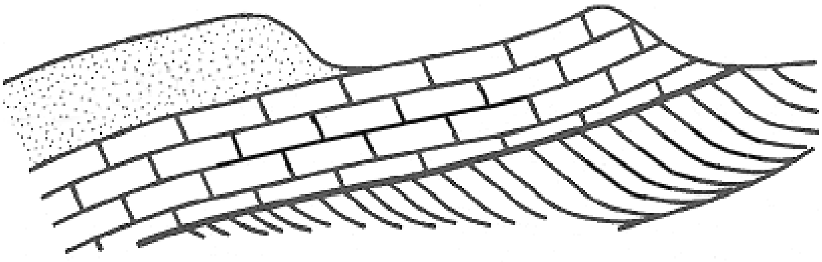

A local group within the GA

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Newsletter

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Editorial

This issue of the newsletter includes very different topics – the resume of a talk on Jade and a summary from one of our members who attended a symposium tackling 'climate change' and an interesting discourse on Lunar Geology, which I hope you will find both interesting and leave you thinking hard about the topics.

There has been an unexpectedly good response to the 'Introduction to Geology' Course with the necessity to split the group into two sessions.

Christine Norgate and Jean Davies are now assisting Graham and Susan Williams with the organization of the Field Trips, details of which are included both in your membership card and on the FGS website.

Liz Aston

Jade: its tectonic formation, geochemistry and archaeology in East Asia

Summary of October 2015 lecture given by Dr Gina Barnes, SOAS, University of London

As an archaeologist of East Asia, my interest in geology was stimulated by wanting to know more about jade – an important and valuable mineral in East Asian prehistory. To clarify: jade is a green gemstone, jadeite is a pyroxene mineral; jadeitite is a metamorphic rock.

East Asian Jade

Traditionally, the highest prized jade in China was (and still is) that called "mutton fat" jade, a white nephrite. In 1990, it cost US$3,000/ounce to buy. Since 1784, however, a jadeite from Myanmar (Burma) called "imperial green jade" began to be exported and has gained great popularity in China.

Myanmar, however, is in SE Asia, not East Asia, and its jadeite was unavailable to China until the late 18th century. Before that, only nephrite was known in China, especially that from Khotan (Hetian) of Silk Road fame in the Tarim Basin of W China (Figure 1). The only source of jadeite in East Asia is from the Jade Coast in Niigata prefecture of Japan and known as "Itoigawa jade"; however, it was not distributed to China – only as far as Korea. Two early jade cultures on the China Mainland are Hongshan in the N and Liangzhu in the SE.

Fig. 1: Location of Khotan & Itoigawa, Hongshan & Liangzhu, East Asian Jade Sources.

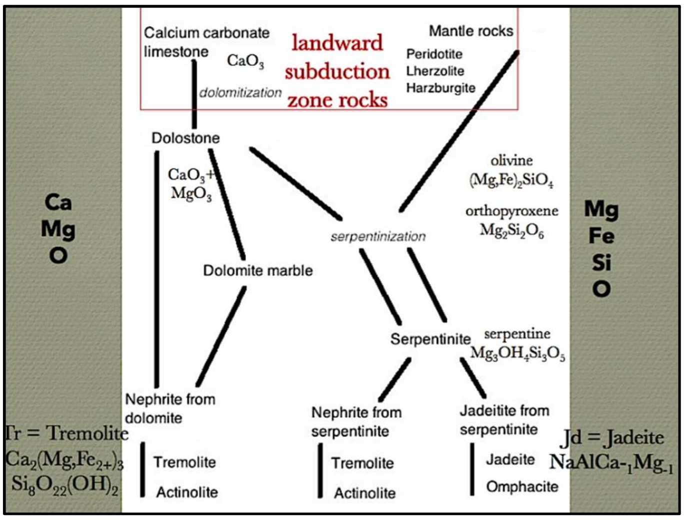
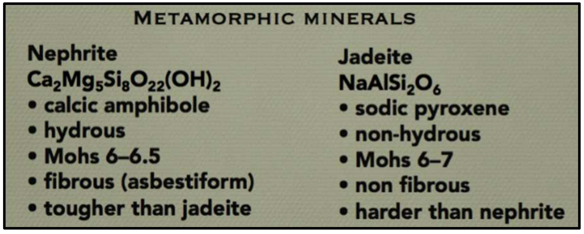


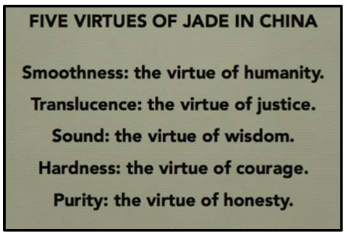
Fig. 2: The Transformations of Jade



METAMORPHIC MINERALS

Nephrite	Jadeite
$Ca_2Mg_5Si_8O_{22}(OH)_2$	$NaAlSi_2O_6$
• calcic amphibole	• sodic pyroxene
• hydrous	• non-hydrous
• Mohs 6–6.5	• Mohs 6–7
• fibrous (asbestiform)	• non fibrous
• tougher than jadeite	• harder than nephrite

Fig. 3: The Types of Jade



FIVE VIRTUES OF JADE IN CHINA

Smoothness: the virtue of humanity.

Translucence: the virtue of justice.

Sound: the virtue of wisdom.

Hardness: the virtue of courage.

Purity: the virtue of honesty.

Fig. 4: The Five Virtues of Jade in China

Jade for working is mostly collected as cobbles from riverbeds or beaches. Hetian nephrite from Khotan is mostly collected from the White Jade River, while Itoigawa jadeite from Niigata is collected from the Hime River emptying onto what is called the “Jade Coast”.

Both kinds of jades are metamorphic minerals. Nephrite is a hydrous calcic amphibole, $Ca_2Mg_5Si_8O_{22}(OH)_2$, while jadeite is a non-hydrous sodic pyroxene, $NaAlSi_2O_6$, Figure 3. Although nephrite is tougher than jadeite because of its fibrous (asbestiform nature), it is slightly softer (6–6.5 on Moh scale) than jadeite (6–7 on Moh scale). The toughness and hardness of these jades respectively have required special forming techniques: they can be flaked like normal stone tools but only grossly. To shape them, they are usually cut using what’s called a “flexible string” (maybe leather or bamboo) together with an abrasive, usually quartz sand.

Cutting slabs of nephrite in prehistoric China led to most artefacts being flat or flat-sided. They could then be rounded off by grinding with abrasive, and features could be applied by flexible string, as the wedge-shaped notches in early Hongshan jades illustrate. Today, all jade working is done by electric grinding machines; since nephrite is asbestiform, I wondered if jade workers suffered from mesothelioma; but a health analysis of workers in a Hong Kong jade workshop found silicosis from the quartz power used in abrasion, rather than mesothelioma.

Towards the end of the Neolithic period in China, fine engraving techniques were developed. These incised lines have been investigated by Margaret Sax of the British Museum with scanning electron microscopy (SEM); she discovered that each line was composed of fine tool notches as the line was created pushing forwards rather than drawing the tool across the jade. The tool used might have been one of the quartz-based rocks (flint, chert), because small flakes of silica have been found at one of the Late Neolithic jade-working sites. Today, again, drills as fine as dentist drills are used to shape and incise the fine details of Chinese jades.

Given this background, the big questions surrounding research on jades that are discovered in archaeological sites entail:

- Where were the geological sources of the raw materials?
- Where were the raw materials transformed into artefacts?
- What were the producer-consumer relationships vis-à-vis the distribution network?

These are not easy questions to answer, as we shall see.

The earliest jade use in the world is currently known from NE China in the Neolithic Xinglongwa culture, 8,000–7,000 BC. These jades consisted of slit earrings and three pendants. The same area developed into the Hongshan culture, 4,600–2,800 BC, which has given us unique shapes and styles of jades, especially what are called “pig dragons”, but also flared tubes, cloud-shaped ornaments, etc. These are often rounded, bevelled, and finely incised, while flexible string forming is known from turtle totems.

The apex of Neolithic jade-working was the Liangzhu culture in the 3rd millennium BC. In the region of the Shanghai delta, jade workshops are known to have produced flat *bi* disks and jade *cong* tubes with square outer walls but circular core. Both these forms occasionally have fine designs engraved on them, most notably the beast & man with headdress motif. Some archaeologists believe the round *bi* and round/square-shaped *cong* relate to the historic Chinese cosmological iconography where the circle is Heaven and the square is Earth. But it is difficult to prove that Neolithic peoples, without writing, thought this way.

Jade was used extensively in burials in early historic China, in the Zhou to Han periods between 700–100 BC. It is thought they preserved the body, hence the creation of jade suits and the placing of jade pieces on all the orifices of the body to keep in the spirit. Jade ornaments and artefacts were symbols of power, ritual, morality, wealth, and immortality.

In historic times, the Five Virtues of Jade (Figure 4) were constituted as: Smoothness = the virtue of humanity; Translucence = the virtue of justice; Sound = the virtue of wisdom; Hardness = the virtue of courage; and Purity = the virtue of honesty.

Shifting from China to Japan and Korea, jade usage was somewhat different.

Itoigawa jadeite was used in Japan from Jomon times, particularly in the 1st millennium BC. The ornaments of these hunter-gatherer-horticulturalists consisted of slit earrings and pebble pendants. In the Kofun period of state formation (250–645 AD), curved beads became an important insignia of the elite, and the curved bead (*magatama*), bronze mirror and sword comprise the imperial regalia of the Japanese emperor. The Korean Peninsula has sources of nephrite, but they were not intensively exploited. Instead, amazonite (a meta-feldspar called microcline) was primarily used in the Neolithic and Bronze Ages. However, during the Silla period (300–668 AD) of state formation, curved beads made of Itoigawa jade were used in royal crowns; whether the raw materials or the finished beads were imported is not yet confirmed – maybe both.

Jade geochemistry

Both jadeite and nephrite are metamorphic minerals; however, they formed not from pressure/temperature metamorphism but from metasomatism. That is, they are solid-solution minerals that precipitated from *fluids*. Solid-solution minerals exhibit a continuous distribution of exchangeable elements, and their variable chemical constitutions form different minerals within that distributional range.

Nephrite

Nephrite belongs to the tremolite-actinolite-ferroactinolite (T-A-F) solid solution series; this series has, as its basic elements, Ca, Si, O and H, with the addition of either Mg, or Fe. Pure nephrite jade is the mineral tremolite $[Ca_2Mg_5Si_8(OH)_2]$, the solution end member with magnesium; the opposite end of the series is ferro-actinolite $[Ca_2Fe_5Si_8(OH)_2]$. Between them is actinolite. “The idealized actinolite chemical formula, $[Ca_2(Mg,Fe)_5Si_8(OH)_2]$, is rarely encountered with natural samples. There are generally appreciable amounts of Al^{3+}, Fe^{3+}, Mn, Cr, and Na” (Mustard 1992:345)”. In fact, it is difficult to find pure end members as well, so that most Chinese nephrites can be classed as tremolite-actinolite.

The Ca-Mg-Fe solid solution chemistry has other outcomes besides the T-A-F series: from anthophyllite ($Mg_1Si_8O_{22}[OH]_2$) to grunerite ($Fe_1Si_8O_{22}[OH]_2$) with cummingtonite ($[Mg,Fe]_7Si_8O_{22}[OH]_2$) in the middle. Again, these minerals are rarely pure, with other elements, as named above, substituted in for Mg and Fe. The fact that there are two different solid solution series for the same elements means that depending on availability of elements in different liquid mixtures, up to six different minerals may form, giving nephrite chemical relatives that might occur with it as neighbours in geological settings.

In just looking at tremolite alone, the mineral may consist of major elements of over 1% each (that are represented in the ideal chemical formula: Si, Mg, Ca, H, O), minor elements of between 0.1–1% (Fe, Na, Mn), and trace elements of less than 0.1%. These figures come from an Italian study of almost pure (98%) tremolite discovered in road construction. Despite the possible variablilty in minor and trace elements, however, Chinese studies of archaeological nephrite were not able to identify sources because the chemical compositions were so similar. The analysts said that to make further progress in nephrite sourcing, it would be necessary to do isotopic analyses of the artefacts, but there is no comparative collection from jade sources as yet.

Jadeite

Jadeite is much more complicated than nephrite as it belongs to a solid solution that is continually graded among several different minerals. The nearest relatives of jadeite ($NaAlSi_2O_6$) are omphacite ($[Ca,Na][Mg,Fe,Al]\ Si_2O_6$) and aegirine ($NaFe^{3+}Si_2O_6$). Their relatives are aegirine-augite, augite and other Ca-Fe-Mg pyroxenes: orthoferrosilite, eulite, ferro-hypersthene, hypersthene, bronzite, enstatite, diopside, salite, ferrosalite, ferroaugite, and hedenbergite. Thus again, several minerals can precipitate from the same solution if the elements are temporally or spatially differentiated, and jadeite might coexist with some of these minerals as neighbours in a geological deposit.

Moreover, jadeites are rarely pure: most have some diopside (Ca,Mg) molecules or augite group minerals ($[Ca,Na][Mg,Fe,Al,Ti][Si,Al]_2O_6$) in them (Harlow 2012).

Given the variety of minerals that can occur and be found together in geological settings, it is necessary to distinguish rock from mineral. Nephrite, a term well used in the archaeological literature, is not a valid mineral name according to the IMA (International Minerological Association). The mineral instead should be referred to as tremolite or tremolite-actinolite; the rock it occurs in (possibly together with other minerals such as actinolite or ferro-actinolite) can be called nephrite. Jadeite, on the other hand, is a mineral that occurs in the rock called jadeitite, defined as 90vol.% pyroxene - NB that pyroxene contains an average of 90%wt. jadeite. Thus, a jadeitite may be composed of Jade Jd100–Jd80+Aegirine 1-10, with an omphacite overgrowth and some presence of diopside.

Archaeological jades: are they jade??

In addition to difficulty in identifying jadeite from jadeitite, and tremolite from nephrite, other minerals masquerade as jades in the archaeological records. Some of the more common are: pounamu (New Zealand greenstone), serpentine, prehnite, aventurine quartz, grossular garnet, chrysoprase, and dolomite marble. In addition, glass, plastic and more minerals are often passed off as jade. How does one identify true jade? Wikihow gives 14 ways – not including colour, since dyes can be used to approximate historical jades.

Scientifically, x-ray diffraction and Raman spectroscopy are used. One study on Lantian jade (Wang, Chang & Gao 2012) discovered that it was lizardite jade, a variety of serpentinite, that consisted of calcite and serpentine with traces of talc, dolomite and tremolite. Note that nephrite can also occur together with calcite, grossular, talc, serpentines, and marble. Thus, all these minerals may be available together in geological deposits, which may explain why many of them are used as jades.

Petrogenesis

So far, we have looked at how elements combine to make minerals and minerals into rocks. Next, we must look at how rocks are formed in geological processes, resulting in specific mineral combinations.

There are two host rocks from which the jade rocks and minerals are formed through metamorphism: the first is common limestone, loaded with calcium ($CaCO_3$), and the second is mantle rock (whether peridotite, lherzolite, hartzburgite) that contain varying amounts of olivine ($[Mg,Fe]_2SiO_4$). Each of these host rocks can undergo metasomatism or P/T metamorphism. In addition, one mineral, albite, can undergo P/T metamorphism into jadeite, complicating the picture.

- First, limestone can be turned into dolostone (a rock) through the substitution of Mg for Ca, comprised mainly of dolomite (a mineral, $MgCO_3$). Dolostone can be acted on directly by fluids to produce nephrite and its constituent minerals tremolite and actinolite. Or, dolostone can be P/T metamorphosed into dolomitic marble and then acted on by fluids to produce nephrite and its constituent minerals tremolite and actinolite.
- Dolostone can also be metasomatized into serpentine, resulting in serpentinite, which can further be metasomatized into nephrite and its constituent minerals tremolite and actinolite.

How to tell by which path a jade made of nephrite came into being? By looking at the variety of serpentine mineral.

- Starting with mantle rocks, these can be metasomatized and serpentinized into serpentinite, then further metasomatized into jadeitite and its constituent minerals jadeite and omphacite.
- In addition, the mineral albite can undergo solid-state recrystallization during P/T metamorphism, producing jadeite and quartz.
- Thus, we have three different routes for the formation of nephrite, one directly from dolostone, but one via dolomitic marble, and one via serpentinite. And we have two different routes for the formation of jadeite: one from mantle rocks via serpentization, and one from solid-state recrystallization of albite. All these require varying geological processes, localities, and compositions.

The problem today is that the process by which metasomatism transforms these minerals is not completely known. Was there a "ready fluid", or did it gain elements during circulation? Were the elements in metamorphic fluids or drawn from country rock (seawater, meteoric water)?

Geological settings

Limestone in association with metamorphosed mantle rocks that are found on dry land today have arrived there via subduction. They are commonly incorporated into obducted ophiolites, slices of ocean floor that have formed in a back-arc basin setting. Mantle rocks and ocean crust together with overlying shallow water limestones are compressed, folded and metamorphosed when subduction ends with the collision of the plates.

The co-occurrence of nephrite sources and ophiolite locations around the world, have been mapped by Harlow (2014). Notice that two types of nephrite are distinguished: that formed from dolomite (dolostone) and that from serpentinite; however, whether that serpentinite came from metasomatized dolostone or mantle rock is not stated/known. Some of these ophiolite zones are exceptionally long, many with no apparent (as yet) nephrite sources.

One of the longest sutures containing a discontinuous string of ophiolites and mélange is the Bangong suture of the Himalayas. It is 20–50km wide and 1,200km long. It contains the Bangong Lake ophiolite, the Shiquanhe Lake ophiolite, and the Yarlung Zangpo ophiolite.

In contrast, the occurrences of jadeitite around the world correlate with blueschist zones, where deeply buried blocks have been metamorphosed to blueschist facies and then exhumed.

Jadeitite forms in subduction zones where the dehydration of the downgoing oceanic crust releases fluids into the overlying mantle, serpentenizing the peridotite into serpentinite and further formation of jadeitite. The latter process is most problematic, but the fluids are known to contain large-ion lithophile elements (LILE) and high field strength elements (HFSE).

Three case studies in Myanmar, Japan and Guatemala demonstrate that jadeitite is formed in association with several other surrounding minerals in zoned layers within serpentinite.

The mineral assemblages in jadeitites from Japan show vast differences in the numbers and combinations of minerals in different samples.

The geographical correlation maps show that for Chinese nephrite, there are 15 known locations for jade from carbonate (especially from the Altun belt, which is 1,100km long), and seven locations for jade from serpentinite.

A look at the geological maps for the East Asian region shows that the orogenic zones containing ophiolites and blueschist rocks are concentrated in the Central Asian Orogenic Belt between the North China craton and the Siberian Craton in the paleo-Tethys region.

Several individual locations of nephrite discovery have been found along the S edges of the Tarim Basin, and in the accreted arcs between there and Tibet.

Also, examination of granite masses across China, which indicate prior subduction zones, are highly represented in the SE and NW. The jades from the Hongshan culture have been sourced to an outcrop in the E Manchurian Basin, and those from Liangzhu are sourced to the nearby Meitian deposit. The latter were discovered to match by comparing the formation dates of the jade in the artefacts and in the source. Thus it seems that the Hetian jade sources at Khotan were not employed during the Neolithic but were developed later with the Silk Road trade.

In conclusion, it can be said that jade mineralogy is extremely complicated, but several avenues of research can be followed:

- Focus on orogenic zones to search for jade sources
- Build comparative source collections
- Pay attention to artefact rock and mineral types occurring with monomineralic jades
- Test artefacts, don’t assume rock/mineral type
- Begin isotope analyses and jade dating programs

One problem in carrying out analyses remains the stricture that non-destructive techniques must be used in Japan.

Gina Barnes

What moon rocks reveal about the geology of the moon

Summary of June 2016 lecture given by William Joyce, Birkbeck College

Our planet provides plenty of rocks, minerals and field structures, plus a wealth of active processes like sedimentation, earthquakes and volcanic eruptions, creating a fascinating puzzle to unravel the history and evolution of the planet. So geology has always enjoyed a uniquely terrestrial focus. But Earth is, of course, just one member of a large family of other worlds and other objects, each with their own geological story to tell. Furthermore, the origin and formation of the Earth can only be completely explored by understanding the geology and geochemistry of many of these other worlds.

Just one of these worlds, our Moon, has been clearly visible over millennia as a likely rocky world beyond our own. Its closeness enabled human beings to examine its surface for thousands of years, as even with the unaided eye it shows distinct bright and darker areas, and around the time of a full Moon, very bright, spot-like features. It was realised that the Moon could not be a smooth sphere because it didn’t reflect sunlight the right way, but the nature of its surface was unknown and ideas were wide-ranging, including rocky land, deep dust, and liquid seas. So geology became concerned to an extent with the geology of the Moon.

The first planetary scientist, Galileo Galilei, used the newly invented telescope to observe the Moon several times during the winter of 1609, and more surface features became apparent, particularly a variety of craters covering all surfaces at a wide range of scales and densities, rugged mountainous terrain, and smooth plains. Galileo even estimated the heights of mountains from the lengths of the shadows they cast, obtaining a correct value of several kilometres. The Moon could now be thought of as a rocky world rather like our own, with real geology to offer.

A lot of telescopic mapping efforts ensued to characterise and understand the Moon's surface features over the subsequent three-and-a-half centuries, but since the Moon always keeps the same side facing the Earth, only the near side could be examined by telescopes, and our knowledge was restricted to surface feature mapping, low-resolution spectroscopy, basic properties of density, temperature and composition, and lunar orbital mechanics. This astronomical work using telescopes to explore the near side of the Moon was all that could be done, and nothing whatsoever was known about the far side until 1959 when spacecraft began to be sent to the Moon to explore it close-up (Figure 1). Interestingly when space probes were sent to the Moon, and also Venus and Mars in the early 1960's, appeals by space agencies to astronomers to help analyse images and data were largely ignored. It was the geologists who stepped forward to help!

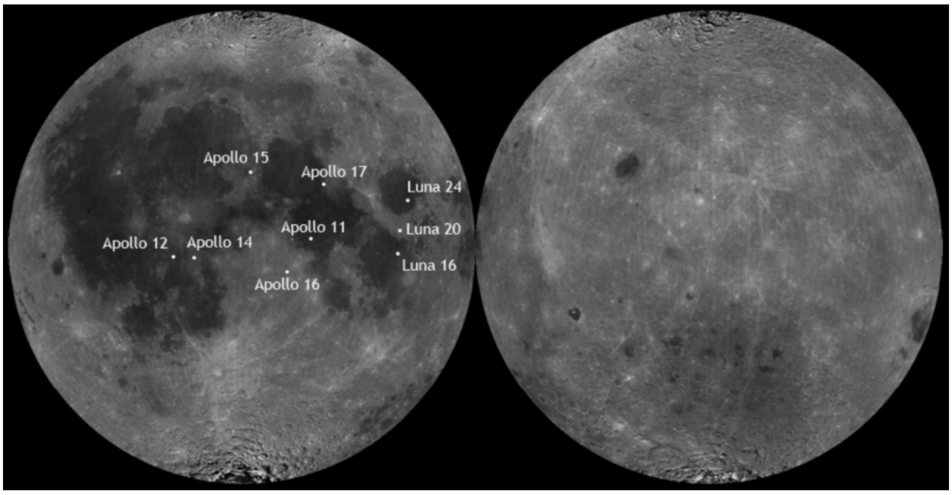


Fig. 1: The Moon as imaged from an orbiting spacecraft. The near side (left) contains almost all the dark basaltic lava 'seas' while only a few lava outcrops occur on the far side (right). The locations where rock samples have been returned to Earth are shown: six by Apollo and three by Russian automatic spacecraft.

In the early 1960's, geologist Gene Shoemaker correctly interpreted the large crater in Arizona now known as 'Meteor Crater', as an impact crater and not a volcanic crater. He subsequently applied the Principle of Superposition to telescopic images of part of the lunar near side.

A key area for his lunar stratigraphy scheme was around the southern rim of Mare Imbrium, where impact ejecta from the large, fresh-looking crater Copernicus overlies that of a slightly smaller, more weathered crater Eratosthenes which, in turn, overlies Imbrium impact basin deposits which form prominent arcs of mountains (see Figure 2).

A 'lunar stratigraphic column' based on impact sequences was developed from this work, and geological maps could be drawn.

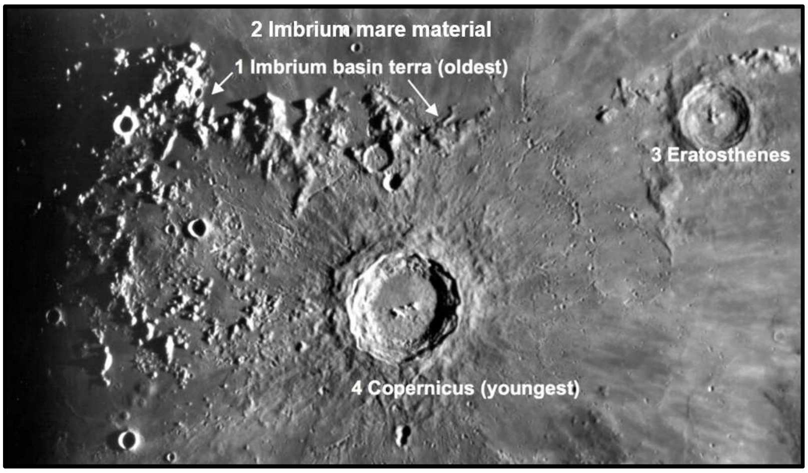


Fig. 2. Lunar superposition. The southern periphery of Mare Imbrium (top) was used to define a lunar 'stratigraphy'. Impact ejecta from the fresh-looking crater Copernicus overlies ejecta of the more eroded-looking crater Eratosthenes, which in turn, overlies Imbrium impact basin formations (the arc of mountains). The flood basalt lavas filling the Imbrium impact basin form Mare Imbrium, and as the lavas embay the mountains, they are younger than the Imbrium basin itself. Therefore, in order of decreasing age, we have the mountains forming the rim of the Imbrium basin, then Mare Imbrium, then Eratosthenes, and finally Copernicus

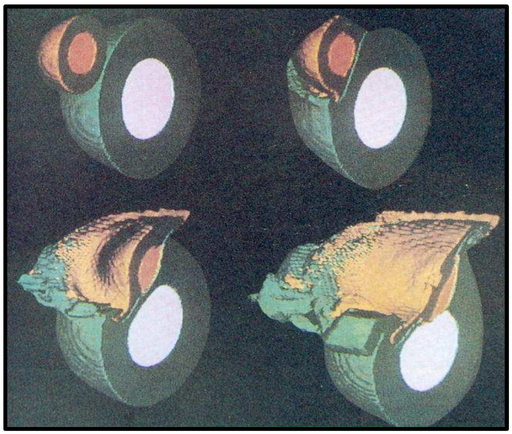


Fig. 3: The original 'giant impact' theory of the formation of the Moon – see Page 9 Computer simulations of the impact show how the cores of the 2 bodies combine while material from the mantles of impactor and the early Earth partially combine & eject material into orbit, which accreted to form the Moon.

Theories about the formation, bulk composition, internal structure and evolution of the Moon were developed but were relatively unconstrained prior to the 'Space Age'. The lunar formation ideas were:

(1) Rotational fission of the Earth, proposed by George Darwin in 1880, suggesting that the early Earth was rapidly spinning with a 'day' of only a few hours. Material flung off the equatorial regions into orbit, either in many chunks followed by accretion in orbit, or as a single splitting of part of the Earth, produced an orbiting Moon. However, this is unlikely to occur, as it does not agree with the rotational energy currently observed in the Earth-Moon system, and also it produces a Moon with an identical composition to Earth.

(2) Binary accretion theories suggested that both Earth and Moon formed together from a disk of material orbiting the Sun. This would also produce identical compositions in both bodies.

(3) Capture of the Moon from elsewhere was also proposed but this is also rather unlikely to happen as it is difficult for an approaching object to enter orbit around Earth unless a drastic reduction in its speed is achieved near closest approach, and such an object is far more likely to swing past the Earth or collide directly with it. However, the composition of the captured Moon would probably be quite different from that of Earth if the Moon had originated elsewhere in the Solar System.

None of these ideas of lunar formation could really be tested unless some field geology was performed, including the analysis of lunar rock samples. The Apollo space programme was in part conducted to do this and select the most likely theory based on the mineralogy and geochemistry of returned rock samples.

With the dawning of the 'Space Age' the Moon became a natural target, and in 1959 the Soviet Union successfully sent three spacecraft to the Moon. This ushered in a 'Space Race' between the two superpowers, and intense exploration and scientific study was performed in lunar space and on the surface between 1959 and 1976, including twelve automated landings, and also six manned landings by the United States between July 1969 and December 1972.

Rock and soil samples were returned to Earth from a total of nine sites, and geological fieldwork performed at all six Apollo landing sites (Figure 1). Another automatic landing was achieved by China in December 2013 (some 37 years after the previous landing), and more are planned, although no human missions to the surface are planned until at least the mid-2030's.

Modern lunar science developed during this period, based on spacecraft observations, automated samples from three sites, geological fieldwork and numerous samples from six sites, and these refined Earth-based telescopic observations. After 1976, active exploration ceased for almost two decades, although the analysis of data and samples continued. The results greatly improved our knowledge of the Moon and led to new geological models of its formation and subsequent evolution. However, many questions remained unanswered, and many more new questions arose.

Currently there is renewed interest in lunar exploration and several spacecraft have recently visited the Moon, with more planned in the near future. Modern lunar science also developed new, more refined instruments and data analysis methods, including the analysis of over 240 lunar meteorites which have been identified on Earth. Remote sensing from lunar orbit continues to provide valuable science, but ideally surface landers and sample return missions are now required to make great leaps in progress. This new phase of lunar exploration is likely to increase significantly during the next decade, partly because many common ideas are now being challenged by new discoveries, with consequences for planetary formation in general.

What do we know from this early phase of exploring the Moon?

The Moon is the only long-term natural companion to the Earth. It is a fairly large planetary body in its own right, over a quarter of the diameter of Earth, and is about 60 Earth radii away. The two bodies are often considered to be a 'double planet' rather than planet and satellite. The Moon is a small, geologically diverse terrestrial planet from a geological perspective, with two global-scale geological units on its surface:

(1) The 'highlands' – these are extremely ancient (samples are 4.2 to 4.5 Ga old), bright, heavily cratered, rugged, and mountainous. Two-thirds of the near side and almost all the far side are highlands;

(2) The 'maria' (or 'seas') – these are darker, much more sparsely cratered, low-lying flat plains. They are rather younger than the highlands, but still ancient. Samples from Apollo missions are 3.1 to 3.9 Ga old, and meteorite samples of maria basalt exist which are significantly older and younger than these ages.
These are basalt flood lavas. One-third of the near side and only around1% of the far side are maria.

On regional scales, many large impact basins have been recognised. They are also very ancient (the youngest is 3.8 Ga old), and many were filled with lavas to form the maria at a later stage. The largest, and oldest, lunar impact basin is the South Pole-Aitken basin, which is 2,600 x 2,100 km in diameter, almost 13 km deep, and is probably the largest impact crater in the Solar System.

On smaller scales, impact craters dominate the Moon. Almost all lunar craters were formed by impacts and show well-defined morphologies according to their size, from small, simple craters, through large, complex craters, to ringed basins, and finally to multi-ringed basins. Impact craters occupy all scales from regional to microscopic, and a surface ‘rubble’ or ‘soil’, called ‘regolith’, covers all surfaces with a loose, powdery layer of rock fragments and dust formed by meteorite bombardment and continual ‘sandblasting’ from micrometeorites.

Few exposures of ‘bedrock’ outcrop. The Moon does, however, also have some craters, which are believed to be volcanic in origin.

Basic geological thoughts

Geologically the Moon possesses some similarities with Earth but it also differs markedly in many important respects. Like Earth, during its history the Moon has undergone extensive volcanism with flood basalt eruptions, fire fountains and even central volcanic pyroclastic eruptions, and been subjected to intensive and non-intensive bombardment by asteroids, comets and meteorites.

Unlike Earth, the Moon lacks an appreciable atmosphere and its surface is directly exposed to the space environment, so surface erosion results from continual micrometeoroid and energetic particle impacts, which smooth the landscape. The Moon also generally lacks water (but recently it was discovered it does not lack water as much as originally thought), and is highly depleted in volatile elements compared to Earth (notably sodium and potassium). This scarcity of water or volatiles results in lunar rocks being mineralogically much simpler than terrestrial rocks.

Due to its relatively small size and volume, the Moon has rapidly lost most of its original internal radiogenic heat sources so volcanic activity is believed to have mostly occurred during its very early history, with probably no major activity over the last billion years.

The Moon also lacks any plate tectonics so the largely complete rock record of early volcanic and bombardment processes is preserved today, unlike Earth’s geological record where evidence of almost all its early history has been destroyed by plate tectonics, erosion and deposition.

The Moon offers an opportunity for geologists to study evidence of planetary formation and early evolution processes ,which have been completely lost from the Earth’s geological record.

Lunar Rocks and Minerals

The lunar highlands form most of the crust and are composed of anorthositic rock containing over 95% of the mineral plagioclase (the calcium-rich variety known as anorthite), and a few % of orthopyroxene.

The maria are basaltic lava flows containing approximately 50% plagioclase mixed with clinopyroxene and the opaque mineral ilmenite (an iron-titanium oxide), often with olivine and sometimes orthopyroxene.

Mineralogically lunar rocks are much simpler than terrestrial rocks. Almost all lunar samples analysed to date are composed almost entirely of one or more of the five minerals listed above, though they can contain dozens of simple trace minerals such as spinel. This relative simplicity is mainly due to the Moon’s almost totally anhydrous nature and depletion in volatile and siderophile (iron-seeking) elements.

By analogy with terrestrial igneous rocks, lunar rocks can be broadly classified into six types based on mineral content, in order of increasing formation depth:

Lunar rock type:	**Main minerals:**
anorthosite	plagioclase (anorthite) (+ orthopyroxene in minor amounts)
basalt / gabbro	plagioclase (anorthite) + clinopyroxene + ilmenite (+ olivine is often present)
norite	plagioclase (anorthite) + orthopyroxene
troctolite	plagioclase (anorthite) + olivine
peridotite	olivine + orthopyroxene + clinopyroxene
dunite	olivine

Generally the upper crust is anorthositic in the highlands and around impact basin rims, and basaltic lava later erupted in many episodes to resurface large areas, forming the maria, or intruded to form gabbroic ‘cryptomare’ (subsurface maria). The mid- to lower crust is expected to be noritic and then troctolitic with increasing depth, and the lunar mantle is probably similar to that of Earth, composed of peridotite and dunite. Impacts excavate deep rocks and bring many of them to, or close to, the surface.

The bright areas of the lunar surface consist of anorthite rock (almost entirely composed of calcium-rich plagioclase, anorthite, since sodium and potassium are highly depleted on the Moon), which is a rare rock type on Earth. The dark areas are basaltic lavas somewhat similar to terrestrial basalts but more iron-rich and lacking water-bearing minerals, which made lunar basalts extremely fluid. Lunar basalts contain clinopyroxene, plagioclase (again mostly anorthite), the opaque mineral ilmenite (compared to terrestrial lavas which contain mostly magnetite as the opaque mineral, but the anhydrous Moon excludes formation of magnetite), and often olivine as an accessory mineral.

In many cases, basalt samples obtained near the rim of the Imbrium impact basin show enhanced geochemical signatures of potassium (K), the rare earth elements (REE) and phosphorus (P), and are therefore called ‘KREEP’ basalts. They contain higher levels of the heat-producing elements uranium and thorium.

Norite rocks occur in the highlands in ridges and as boulders, and troctolite boulders also occur on the surface. These are lower crustal rocks that have been excavated by large impact cratering events.

No lunar peridotite has been found to date, and dunite is extremely rare in our sample collection, but we expect the lunar mantle to be composed of peridotite since the basaltic lavas filling the near side ‘seas’ would have formed by partial melting of such a mantle, similar to Earth.

How did the Moon form? Ideas after geological fieldwork and rock sample analyses

By 1977, after much analysis of rock samples returned by Apollo astronauts, it had become clear that none of the three proposed theories of lunar origin could explain the findings, and an alternative theory was published. This was the ‘giant impact’ (or ‘big whack’) theory (Figure 3 on Page 6).

The analysis of lunar rocks indicated that the Moon appears to have a similar bulk composition to the Earth’s mantle, and the lunar average density is only slightly greater than that of basaltic rocks, implying a very small iron core. Lunar rocks contain only a few minerals, but these are very similar to equivalent terrestrial minerals, except the rocks are generally iron depleted and most volatiles are greatly depleted compared to terrestrial rocks.

The giant impact idea suggests that the young Earth had quite quickly developed a mantle and an iron core, and was then struck by an incoming smaller planet which had also differentiated into a mantle and iron core. The core of this impactor merged with that of the Earth, while much of the material from both mantles was placed into an orbiting disk, from which the Moon accreted. The formation of the Moon from such a disk of material would have created a very hot environment as impacts continually occurred as material was swept up into the growing Moon, and this is believed to be sufficient to create a global ‘magma ocean’. The cooling of this magma ocean over time would result in a particular sequence of minerals being crystallized, and this process is supported by the analysis of lunar rocks (Table 1).

This idea quite well explains the relatively iron-poor Moon and its bulk composition similarity to mantle material, giving a global average density similar to rock, while also explaining the loss of volatiles during the hot collision and aftermath. Furthermore, it is dynamically possible, and it is believed that impacting bodies were a common feature in the early Solar System. The impact may have added or subtracted spin depending on the geometry. This theory predicts a similarity in composition except for bulk iron and volatiles.

The giant impact theory does not predict an identical composition because much of the Moon would have originated from mantle material from the impacting planet, which came from elsewhere in the Solar System. In particular, oxygen isotopes (which are used to distinguish material from objects originating in different regions of the Solar System) should be different between Earth and Moon. However, the minerals in lunar rocks are very similar to terrestrial rocks, and they have identical oxygen isotope signatures. This shows that the original giant impact theory has some difficulties even though it is better than the earlier three ideas.

In recent years there have been a number of ‘tweaks’ to the original giant impact theory to try to account for the close similarity in mineralogy and identical oxygen isotope results. Some of the newer versions include:

(1) The coalescing of two moons to produce a single Moon with the observed shape and crustal thickness;
(2) Two giant impacts occurring in sequence, the first impact spinning up the early Earth to an oblate sphere which could shed material from its equator, and sometime later a second impact launching this material into an orbiting disk, resulting in a Moon forming mostly from the Earth’s mantle material;
(3) A giant impact where the early Earth was much smaller, about half its current size, with a similarly-sized impacting planet, resulting in the merging, separation and re-impacting of both bodies to produce a blended disk of material from which both Earth and Moon subsequently formed, and therefore accounting for the similar mineralogy and identical oxygen isotopes observation;
(4) The impacting planet already possessed a near-identical composition to the early Earth due to it being formed in an area of the Solar System close to where the Earth formed.

In order to decide which is the best theory we must obtain data from rock sample analysis on the isotopic composition of other objects in the inner Solar System, and obtain samples of the lunar mantle for analysis, perhaps from deep impact basin ejecta or from xenoliths in lunar basalt lavas.

The lunar magma ocean

After innumerable collisions increased the size of the Moon as it swept up surrounding debris, it would have become a large sphere of superheated magma orbiting the Earth. Within the hot, dense, mobile interior of this magma ocean, dense elements (iron- and magnesium-bearing minerals) would sink under gravity to form a small core and a lower mantle. Lighter minerals would have formed crystals in the global magma ocean overlying the core and lower mantle. Minerals condensing in the magma which had a lower density than the magma, particularly plagioclase, would have floated to the surface, forming a thick, insulating crust very early on, and seen today as the lunar highlands. Dense minerals (olivine, pyroxenes and ilmenite) would have sunk and formed the mantle, and later erupted as lava, forming the basaltic maria.

The last remaining molten magma would have become trapped between the solid crust and mantle. This thin liquid layer would then become enriched in elements that do not easily enter into any minerals (known as incompatible elements). These final dregs of magma were the very last to cool, forming basaltic rocks rich in potassium (K), rare earth elements (REE) and phosphorus (P), thus creating a thin KREEP layer with high amounts of incompatible and radiogenic elements like uranium and thorium (Figure 4).

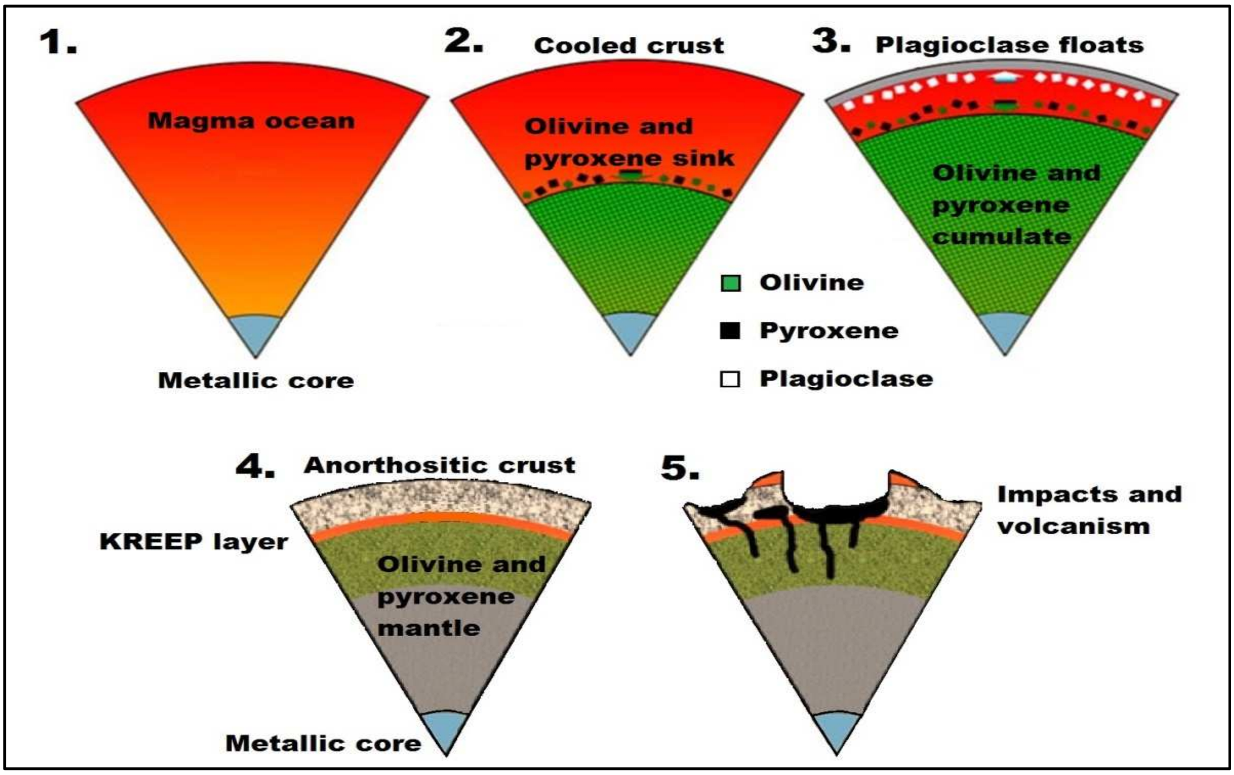


Fig. 4: The formation of a lunar magma ocean and its evolution to produce the interior of the Moon. Layers of the upper mantle and crust form after solidification of a global magma ocean. A thin KREEP layer forms from the last remnants of the magma to solidify. Later mantle overturn of Fe-rich minerals sinking below magnesium-rich minerals, and dense ilmenite attempting to sink to the bottom, disrupts this layering.

Crystallisation sequence:	Mineral type:	Mineral name and formula:	Density:	Motion in magma ocean:	Rocks formed:
1	Mg-rich olivine	Forsterite Mg_2SiO_4	High	Sinks	Deep dunite
2	Mg-rich orthopyroxene	Enstatite $Mg_2Si_2O_6$	High	Sinks	Deep peridotite
3	Mg-rich clinopyroxene	Diopside $CaMgSi_2O_6$	High	Sinks	Deep peridotite
4	Fe-rich olivine	Fayalite Fe_2SiO_4	Very high	Sinks	Intermediate depth dunite and gabbro
5	Fe-rich orthopyroxene	Ferrosilite $Fe_2Si_2O_6$	Very high	Sinks	Intermediate depth peridotite and gabbro
6	Fe-rich clinopyroxene	Hedenburgite $CaFeSi_2O_6$	Very high	Sinks	Intermediate depth peridotite and gabbro
7	Ca-rich plagioclase	Anorthite $CaAl_2Si_2O_8$	Low	Floats	Top primary crust. Subsurface gabbro
8	Ti- and Fe-rich oxide	Ilmenite $FeTiO_3$	Extremely high	Tries to sink but is stopped	Ti-rich gabbro and Ti-rich mare basalt

Table 1: Mineral crystallization sequence within the lunar magma ocean. Minerals continue to crystallize concurrently when a new mineral starts to solidify. The order listed refers to the sequence of the first crystals to

solidify from the magma. When mafic minerals and plagioclase crystallize together (since plagioclase starts to form while mafic minerals are still crystallizing from the magma) they can form gabbroic suite rocks (gabbro, norite and troctolite). Ilmenite forms at a very late stage, producing a relatively thin layer.

The densest iron-rich layers would have crystallized after the slightly less dense magnesium-rich layers, and therefore be emplaced on top, forming a gravitationally unstable situation and forcing convection-like movements or ‘mantle overturn’ to occur. This encourages partial melting and volcanism, and the dense iron-rich layers are subsequently intruded into the upper crust or erupted to form mare basalts.

Remote Sensing of the Lunar Surface

Modern spacecraft images have demonstrated that lunar surface mineralogy can be distinguished by using reflectance spectroscopy, and therefore remote sensing from lunar orbit can provide mineralogical and elemental maps of the whole Moon, providing a wealth of new information about the Moon. Reflectance spectroscopy measures reflected sunlight from just the very top of the lunar surface for each image pixel. This spectrum is examined for diagnostic mineral absorption features to obtain mineralogical information. Certain spectral features, particularly absorption lines, can be used to identify the dominant mineral present in an image pixel and can help distinguish between minerals.

However, the effects of the space environment on these spectra must be compensated for when identifying minerals. This enables lunar geologists to compare orbital remote sensing data for locations on the surface from which samples have also been returned to Earth and analysed, and then extrapolate the remote sensing coverage to the rest of the surface for which we do not yet have any samples. Many unusual rock types have been identified from orbit in this way, which assists with selecting scientifically valuable sites for future sample return missions.

Meteorites from the Moon

The Apollo missions returned 2,415 samples of lunar rocks and soils weighing a total of 381 kg (840 lbs.), all from the near side. The Russian Luna sample return missions returned 0.33 kg (11.5 oz.). So the geology of the whole world of the Moon has largely been derived from non-representative samples from very limited parts of the lunar surface, mostly before global remote sensing maps were available.

However, we also have additional lunar samples from random (usually unknown) parts of the surface, in the form of meteorites that originated from the Moon. Since 1980, about 240 lunar meteorites representing about 120 different falls have been collected on Earth, with a total mass of 137 kg (303 lbs.), just over 1/3 the mass of the Apollo sample collection.

Lunar meteorites are likely to have originated from high near side latitudes as well as areas close to the equator where most spacecraft samples were obtained, and also the far side. They therefore provide a wealth of new information about the Moon even though their precise point of origin is unknown in most cases. Many are types of material, which are geochemically different from Apollo or Luna samples so they provide samples of new lunar rock types.

Maria basalt meteorites have been found that pre-date and post-date the basalt ages obtained from Apollo and Luna samples, providing new upper and lower time limits on the occurrence of lunar volcanism.

Final thoughts

The Moon has a surface area of 38 million square kilometres, about equal to that of Africa and the Arabian Peninsula combined, and we have only sampled nine localities and performed geological fieldwork at six of these. Therefore much more needs to be done in order to understand the Moon’s geological origin and evolution. Despite recent advances in global orbital imagery and rock sample analysis, clearly many more samples and more fieldwork are required. Lunar science is a highly active research area, and I hope a flavour of this exciting field of planetary geology has been given in this article.

William Joyce is a Chartered Physicist and a Fellow of the Royal Astronomical Society. He has a BSc in Astrophysics and a BSc in Planetary Geology, and gives talks on astronomy and planetary science topics while studying for a PhD in lunar geology at Birkbeck, University of London.

Out of the ice ages: our past, present and future

Summary of lectures given at the Geography Department, Royal Holloway College on 9th January 2015

The first lecture, titled '***Are humans causing global warming? What past climates tell us about our role in current climate change***', was given by Dr Ian Candy. He began by stating the IPCC's changing statement on global warming:

1) 66% sure greenhouse gases alter global warming.
2) 90% sure the causes are anthropogenic
3) 95% sure humans vastly affect global warming

He used data from palaeoair in air bubbles trapped in ice cores and foraminifera in deep sea cores to indicate the changing rate of global warming. This showed that the effect of global warming wasn't explained by volcanism/sunspots/orbital variations and cycles, all of which only show slight variations.

The second lecture was led by Dr Bethan Davies, whose talk was called '***Glaciers and Climate change: the changing face of Antarctica***'. She showed a worrying animation about Antarctica growing and shrinking over time. The effects were most evident in the W where most of the land lies below sea level, so the base is eroded by circumpolar currents from below. The E is more mountainous so shows less shrinkage during interglacial warms. Her talk showed mostly that Antarctica has had many growths and collapses that have affected global sea levels.

After lunch, Professor Danielle Schreve and Dr Alice Milner led a talk entitled; '***From reindeer to rewilding: the past, present and future of flora and fauna in Britain***'. Their talk focused upon the organisms that inhabited the glacial/interglacial periods of Britain's history. Overall, each change led to a major reorganisation, meaning that no species survived all the changes.

An impressive fact they gave was that 450km of ice covered Britain during the glacial maximums; enough to put ice down to N London. Also the European rivers filled a lake in the North Sea that burst to carve the English Channel, leading to the isolation of Britain during the interglacials.

Then they went on to talk about the organisms that dominated the glacial and interglacial periods.

- The glacial periods were dominated by big bears, bison, reindeer and wolverines, all of which had thin skin, but up to 9cm of fat, guard hairs and under-wool that kept them warm.
- The interglacial periods were dominated by straight-tusked elephants, boar, aurochs and hippo. These had more lamellar teeth suggesting that they ate the harder vegetation indicative of the maple-Mediterranean type-flora that dominated the interglacial period.

They also talked about the many ways to manage the environment today so as not to damage it anymore. These included 'rewilding' Britain by reintroducing lynx (which limit deer populations so preventing overgrazing) and beavers (which slow river flow with dams, so reducing flooding).

The fourth and final lecture was '***Climate change, human evolution and adaptation: from the earliest humans to future challenges***' led by Dr Simon Blockley. His lecture focused on the evolution and spread of humans from the origins in Africa as H. heidelbergensis to their radiation into the Homo neanderthalensis and Homo sapiens. He suggested that the Neanderthals evolved from the European Homo heidelbergensis whilst the modern human evolved from the African Homo heidelbergensis. This suggests that there were many migrations from Africa from 120ka to 60ka, led by the fluctuations in the Sahara to a Green Sahara, therefore allowing easier migration northwards.

Dr Blockley also gave reasons for why the Neanderthal disappeared and modern humans survived – H. sapiens and Neanderthals lived side by side for a while, but H sapiens had more tools suggesting that the cold-adapted Neanderthals were driven out in localised extinctions by Heinrich cold events and/or outcompeted.

Between lectures, the Department held demonstrations in the adjoining rooms. These varied from fossils showing the fluctuation between interglacial fauna (deer/horse/aurochs) and glacial fauna (bears/arctic foxes/lemmings); to microscopes set up with glacial ash samples that are used to date the glacial periods. In the hallway, a model glacier was set up using a plastic mountainous layer mould, with PVA enriched in resins (representing moraine) that flowed down the valley, simulating the flow of a glacier in time-lapse.

Many of the lectures had displays, with more detail on their work, lining the walls of the rooms, giving guests a chance to ask questions and chat with the lecturers about their work.

Finally, an ice block was displayed in the foyer, which demonstrated the melting of glaciers. It was amazing to see just how fast the ice melted, even on a cold January day, clearly demonstrating just how little temperature rise can lead to the melting and retreating of global glaciers. Overall, it was a very interesting day where everyone learnt a lot about the Ice Ages and our climatic future, even if the day was more tailored to geographers than geologists.

Peter Searle, FGS Member