in California, sent for his family and took up permanent residence. There, he worked with a young chemist, Glenn Seaborg, to isolate an unusual, metastable isotope of his new element[5].

Two pieces of news arrived soon after. In November, Fermi won the Nobel prize for his discovery of elements beyond uranium. Fermi, whose wife was Jewish, used the prize as a pretext by which to escape Italy, too. Then, two months later, word came from Germany that Fermi's 'elements' were a mistake: a group led by Otto Hahn and Lise Meitner had shown that Fermi's discoveries were the result of an atom breaking apart, and were probably barium, krypton and fragments of other elements[6]. This revelation would eventually lead to the development of nuclear weapons — and meant that Segrè and Perrier's eka-manganese was the first true synthetic element. In 1947, ten years after its discovery, they named it technetium, after 'technetos', the Greek word for 'artificial'[7]. By then, all the other empty spaces in Mendeleev's table had been filled, with Segrè also contributing to the creation of element 85, astatine.

The lab-created elements opened up a search for elements heavier than uranium (transuranium elements). In 1939, Berkeley researcher Edwin McMillan approached Segrè about an unusual atom that he'd discovered in the cyclotron, which he believed to be a new element. Segrè dismissed the finding, even going so far as to write a paper[8]: 'An unsuccessful search for transuranic elements'. In fact, McMillan had discovered element 93, which he called neptunium. Then, in February 1941, taking over McMillan's work, Seaborg discovered element 94. With Segrè's help, Seaborg soon proved that his creation — plutonium — could be used in an atomic bomb. It was the first of ten synthetic elements that he would go on to discover; another, seaborgium (element 106), was named in his honour.

Technetium proved that the exploration of the periodic table was not limited to the elements found on Earth. Today, we have extended the table as far as the superheavy element 118, oganesson. With the new elements have come applications few could have imagined: smoke detectors, power for space probes and the most devastating weapons known.

But arguably the greatest discovery remains technetium, and the metastable isotope of the element that Segrè discovered with Seaborg. With its short, six-hour half-life, it is an ideal radioactive tracer. Today, technetium is the most commonly used medical radioisotope in the world (go.nature.com/2t4iqq8), accounting for 80% of procedures in nuclear medicine, and helping to save millions of lives every year. Not bad for something first seen in a discarded piece of metal plate. ■

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PALAEOANTHROPOLOGY

# Dating of hominin discoveries at Denisova

**Denisova Cave sheltered hominins at least 200,000 years ago, and excavations there have illuminated our understanding of early hominins in Asia. New dating analyses now refine this knowledge.** SEE ARTICLE P.594 & LETTER P.640

ROBIN DENNELL

Denisova Cave lies in a valley in the Altai Mountains of southern Siberia. Excavations began there 40 years ago, focusing on layers of material from the Middle Palaeolithic period (about 340,000 to 45,000 years ago) and the Initial Upper Palaeolithic (which is defined by the identification of types of stone tool, and often by the presence of items such as ornaments, and which corresponds to 45,000 to 40,000 years ago at this site). The excavations have provided many key insights into the lives of hominins belonging to branches of the evolutionary tree close to that of our own species, *Homo sapiens*. Douka *et al.*[1] (page 640) and Jacobs *et al.*[2] (page 594) now report their use of the latest dating techniques, which lead to a revised timeline of hominin-associated material in this cave.

Previous excavations had uncovered types of ancient ornamental artefact that are often associated with early *H. sapiens*, such as bones shaped into pendants (Fig. 1) and decorative items made of mammoth ivory. However, the cave hit the news headlines in 2010 when analysis of ancient DNA[3] from a bone in a Middle Palaeolithic layer indicated that the specimen was a previously unknown type of hominin from a branch of the evolutionary tree near *H. sapiens*. Such hominins were named Denisovans, and, on the basis of DNA analysis[4], they are probably a sister taxon of Neanderthals.

Analyses of ancient DNA from the site[4–6] indicated the presence of Neanderthals and Denisovans there during the Middle Palaeolithic. However, no signs of *H. sapiens* being present during that time have been found. Neanderthals and Denisovans existed there at too early a time for radiocarbon dating of the specimens, which is usually effective only for dates up to about 50,000 years ago. Other dating techniques, such as thermoluminesence and optical stimulated luminescence, have been the main approaches used to date such remains, although each of these methods has its own drawbacks.

Knowing accurate timings of occupation at the cave would help to shed light on the presence and activities of early hominins, and might address whether the different species overlapped there. However, analysing ancient deposits is tricky. Layers can be disturbed by animal burrowing, subsidence or freeze–thawing cycles. Small items, such as fossil bones or stone tools, might be displaced from their original positions and not be the same age as that of the layer of deposits in which they were found. Douka *et al.* report their dating of Neanderthal and Denisovan fossils of hominin specimens, as well as artefacts fashioned from bones. Jacobs and colleagues report dating information for the cave sediment deposits, obtained using optically stimulated luminescence, and presenting the most comprehensive dating work yet attempted for the deposits at Denisova Cave.

Jacobs and colleagues present 103 dates for sediment deposits that range from more than 300,000 years ago to 20,000 years ago, and that extend across glacial and interglacial episodes spanning timescale stages termed marine isotope stage 9 (MIS 9) to MIS 2. Deposition of sediments at the site was episodic, with numerous gaps indicating periods when either there was no sedimentation or sediments were removed. There is some evidence of post-depositional disturbance, but the crucial late Middle Palaeolithic and Initial Upper Palaeolithic layers show relatively little sign of disturbance. This is the time frame that might mark the appearance at Denisova of our own species. However, when *H. sapiens* first appeared at the site is unknown.

The authors analysed the remains of 27 species of large vertebrate, 100 species of small vertebrate (such as mammals and fishes) and 72 species of plant to make a reconstruction

Figure 1 | Ancient hominin-made items from the Denisova Cave. Douka *et al.*[1] and Jacobs *et al.*[2] report a revised timeline for the ancient occupation of this site by hominins. Artefacts found there have included rings (a), pendants (b) and a needle (c).

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of the environment at Denisova. This reveals that the cave surroundings varied from being a broad-leafed forest in the warmest episodes to a tundra–steppe habitat during the coldest times. The authors' results broadly agree with those from detailed climate reconstructions for the same time frame made at Lake Baikal[7,8], located 1,600 kilometres to the east. The one exception is for the climate approximately 150,000 years ago, when pollen from Denisova indicates vegetation characteristic of warm, humid conditions, whereas the Lake Baikal data indicate cold conditions at that time. As Jacobs and colleagues point out, this discrepancy might be because the dates obtained using optical dating techniques have wide margins of uncertainty, and climatic conditions might have been unstable.

Douka and colleagues focused on dating the hominin specimens and material from the Initial Upper Palaeolithic. Their results highlight the current capabilities of ancient-DNA analysis. Ancient DNA can be extracted from cave sediments[4], and DNA from both Neanderthals and Denisovans has been detected previously[4] at the site. But it is now possible to identify the taxon to which an otherwise unidentifiable bone fragment belongs by analysing a protein called collagen and using a technique known as zooarchaeology by mass spectrometry (ZooMS). The ability to use ZooMS to analyse thousands of bone fragments from cave excavations across Eurasia could enable the distribution of Neanderthals, Denisovans and our species to be mapped at a level of detail that would have seemed like science fiction just a few years ago. A total of 4,527 bone fragments from Denisova have been analysed in this way, with 2,212 of these being reported by Douka and colleagues.

Because of the specimens' ages, only a fossil named Denisova 14, which Douka and colleagues dated to around 46,300±2,600 years ago, could be analysed by carbon dating. And the authors could not determine the species to which Denisova 14 belonged because insufficient DNA was available. Most of the hominin samples were dated using a method that uses DNA sequences from cellular organelles called mitochrondria, to make comparisons between a sample and reference sequences from other hominins. The authors then generated a relative sequence of the ages of the Denisova fossils. This revealed that a specimen named Denisova 2 (species identified as being Denisovan) is the oldest fossil identified at the site (estimated to be 122,700–194,400 years old). Two Neanderthal fossils, Denisova 5 (90,900–130,000 years old) and Denisova 15 (91,400–130,300 years old), were dated to a similar time interval and are both older than Denisova 11 (79,300–118,100 years old), which is a fossil from an individual that had both Denisovan and Neanderthal individuals as parents[9]. There are uncertainties over these attempts at dating using genetic analysis, as the authors point out. Nevertheless, this is the first time that we have had this type of information about the pattern of occupation of Denisova Cave by Neanderthals and Denisovans.

Douka and colleagues dated the Denisovan specimens using an approach called Bayesian modelling. Their favoured version of this approach incorporated radiocarbon and optically stimulated luminescence ages, information about the excavated layers, and timing based on genetic data. Their modelled ages of some hominin specimens did not always match the age of the sediments in which the fossils were found. Although the DNA-based estimated ages for Denisova 5 and Denisova 8 are consistent with the optical ages for their associated layers, Denisova 3 and Denisova 4 are older than expected compared with the layers in which they were found, and Denisova 2 and Denisova 11 are younger than expected compared with the layers in which they were found. These discrepancies might indicate uncertainties in the genetically obtained age estimates, or that some fossils were redeposited from their initial site of deposit.

Although there might still be some uncertainty about the detailed ages of the remains — given the nature and complexity of the deposits and the dating methods used — the general picture is now clear. Deposition of sediment deposits at Denisova was episodic, but extends from MIS 9 to MIS 2, and the site was occupied by Denisovans and by Neanderthals in both cold and warm periods from approximately 200,000 to 50,000 years ago.

The challenge will now be to identify the hominin(s) associated with the Initial Upper Palaeolithic. The timing of the onset of the Initial Upper Palaeolithic period assemblages at Denisova was estimated by radiocarbon dating by Douka and colleagues — with two bone artefacts dated to 42,660–48,1000 and 41,590–45,700 years old. On the basis of human DNA identified at a site called Ust'-Ishim, it is estimated that *H. sapiens* reached Siberia at least 46,880 to 43,200 years ago[10]. This raises the possibility that our species contributed to the deposits in the Initial Upper Palaeolithic at Denisova. Some researchers argue on archaeological grounds[11] that the Initial Upper Palaeolithic in the Altai Mountain region was an indigenous development that followed on from that of the preceding local Middle Palaeolithic, whereas others argue that it represents an intrusive development of those arriving from outside the region. One possibility is that the Initial Upper Palaeolithic development at Denisova was made by hybrids of Denisovans and *H. sapiens*, given the evidence for interbreeding between Neanderthals, Denisovans and *H. sapiens* in MIS 3 (see go.nature.com/2cenz62). A way of testing these hypotheses would be to find and analyse ancient hominin DNA in the Initial Upper Palaeolithic layers.

There is still much to learn from Denisova. The work by Douka, Jacobs and their respective colleagues creates an important foundation for such efforts by providing a rigorous and compelling timeline for the cave sediments and its contents. ■

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