traces an ellipse rather than a perfect circle. But this eccentricity would rapidly diminish if the moon's interior could readily respond to gravitational forces exerted on Mimas by other bodies. This indicates that the ocean or the orbital eccentricity — or even both — must have been around for only a short time, of the order of tens of millions of years.

A young ocean also matches constraints derived from Mimas's geology; in particular, the large crater, known as Herschel, could not have formed in an ice shell that is as thin as Lainey and colleagues (and others[2]) predict. Rather, the ice shell must have thinned by tens of kilometres since Herschel formed[3]. A thinning ice shell might also explain why Mimas lacks the heavy fracturing observed on ocean moons such as Europa and Enceladus[4]. In this way, geological features can help researchers to pin down the timing of ocean formation and the orbital conditions that stimulated the growth of an ocean.

The idea that Mimas's ocean could have formed relatively recently also has implications for other features of the Saturnian system that remain mysteries, in spite of clues retrieved by the Cassini mission. Saturn's bright icy rings are apparently young in geological terms[5], but not all scientists agree[6]. The heavily cratered icy moons seem ancient, but the source of the bodies that made the craters is disputed[7,8], and there are suggestions that the moons themselves are also geologically young[9]. The clues provided by Mimas and its ocean could help to resolve some of these conundrums.

Finally, adding Mimas to the catalogue of ocean worlds changes the general picture of what these moons can look like. The idea that relatively small, icy moons can harbour young oceans is inspiring, as is the possibility that transformational processes have occurred even in the most recent history of these moons. Lainey and colleagues' findings will motivate a thorough examination of mid-sized icy moons throughout the Solar System. Most notably, there is a suite of mid-sized icy moons orbiting Uranus, which was selected as the highest-priority target of a NASA flagship mission by the Planetary Science and Astrobiology Decadal Survey.

Mimas also has an important lesson to teach scientists: intuition is excellent for generating hypotheses, but not sufficient for drawing conclusions. The Solar System will always have surprises in store, and researchers must be open enough to new ideas and unexpected possibilities to recognize them.

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Archaeology

Ancient toolmakers in north Europe identified

William E. Banks

DNA analyses of skeletal fragments from a site in Germany provide evidence that humans, rather than Neanderthals, were responsible for a particular stone-tool industry called the Lincombian–Ranisian–Jerzmanowician. **See p.341**

Analyses of stone tools and human skeletal remains can help to determine whether specific excavated levels at archaeological sites are associated with Neanderthals or anatomically modern humans (with a body form similar to ours) during the period when both groups were present in Europe. Mylopotamitaki *et al*.[1], on page 341, and Pederzani *et al*.[2] and Smith *et al*.[3], writing in *Nature Ecology & Evolution,* report their analyses of Ilsenhöhle, an archaeological site from this period near Ranis, Germany. The findings shed light on the environmental conditions there and identify the inhabitants linked to a widespread stone-tool industry in the region, for which the associated population was previously unknown.

The arrival of anatomically modern humans in Europe has long been of interest to scientists because this migration did not take place in a previously uninhabited landscape. Neanderthals (*Homo neanderthalensis*) with their classic anatomical form occupied Europe from at least 200,000 years ago[4] and were related to individuals who had a subset of Neanderthal anatomical features and were present in Europe by approximately 400,000 years ago. *Homo sapiens* arrived in southeastern Europe by 46,000 years ago[5]. Neanderthals subsequently disappeared, leaving only *H. sapiens*. The reason why Neanderthals were replaced by humans is the source of often-heated debate. To understand the factors in this population replacement, termed the Middle to Upper Palaeolithic (MUP) transition, we must learn exactly when *H. sapiens* arrived in Europe and for how long the two populations occupied the landscape.

Mylopotamitaki and colleagues used a protein-analysis technique (a proteomic method) to determine that the remains of individuals found at Ilsenhöhle (Fig. 1) were hominins (members of the genus *Homo*, which includes humans and close relatives). The authors also analysed DNA from mitochondrial organelles to demonstrate that these individuals were *H. sapiens*, and carried out statistical analyses of radiocarbon-dating evidence to show that the remains are approximately 45,000 years old. Studies by Pederzani *et al*. and Smith *et al*. provide a window into the environmental conditions at the site during its occupation, reveal the ecology of the recovered prey species and offer insights into how the human groups that frequented Ilsenhöhle incorporated this site into their use of the region.

Archaeologists have defined a number of regionally specific stone-tool technological traditions for the MUP transition, but skeletal remains in association with these industries are sparse, and most sites have contextual problems — the archaeological relationships between the few remains and the MUP transitional stone tools with which they are associated are difficult to determine. As a result, it is unclear who created these technologies, but working this out is essential to infer the cultural dynamics of populations of late Neanderthals and early modern humans in Europe and to determine whether interactions between these groups, which are known to have occurred[6], might have influenced the technologies and objects used by a culture. Two archaeological levels excavated by Mylopotamitaki and colleagues at Ilsenhöhle are associated with one of these MUP transitional industries, termed the Lincombian–Ranisian–Jerzmanowician (LRJ).

Mylopotamitaki *et al*. demonstrate that the LRJ-associated levels are clearly separated

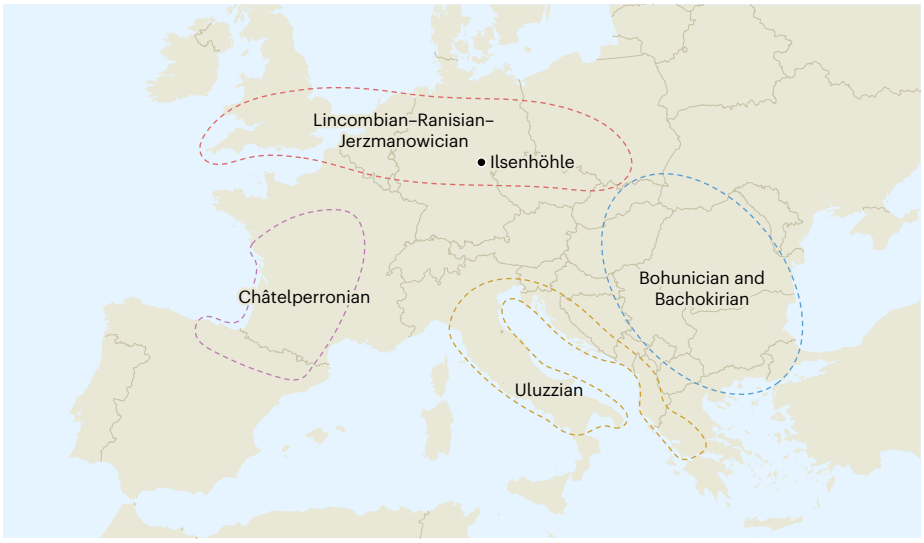

Figure 1 | Regions associated with distinctive stone-tool industries in Europe during the period when *Homo sapiens* and Neanderthals were present. Mylopotamitaki *et al.*[1] present evidence from the Ilsenhöhle archaeological site indicating that the stone tools there, of a type described as Lincombian–Ranisian–Jerzmanowician, were associated with *H. sapiens*. *H. sapiens* is also associated with Bachokirian stone tools[5]. The identity of populations associated with other types of stone-tool industry — Bohunician, Châtelperronian and Uluzzian — remains to be determined. Circled regions reflect previous evidence about Châtelperronian[14], Lincombian–Ranisian–Jerzmanowician[15], Uluzzian[15], Bachokirian[15] and Bohunician[16] sites.

from the underlying level, which is linked to a type of stone-tool industry termed Mousterian (made by Neanderthals), and from the overlying Upper Palaeolithic levels (the period that represents the end of the last ice age and is associated with modern humans). The authors established that the LRJ levels were intact and did not contain materials from adjacent ones, which would cause problems in terms of archaeological interpretations. Mylopotamitaki and colleagues performed proteomic analyses of a number of skeletal remains from these levels. Limitations in the existing proteomic reference databases prevented more precise identification than the remains being hominin.

To remedy this, the authors turned to ancient mitochondrial DNA, and the results revealed that the remains are *H. sapiens*. The four remains of modern humans from the excavated LRJ levels had radiocarbon dates that are 'stratigraphically coherent', which means that the oldest specimen comes from the lower level and the younger specimens from the upper level. These dates fall roughly between 47,000 and 44,000 years ago.

This timeframe indicates that *H. sapiens* LRJ occupations occurred sometime between the tail end of a period of cold conditions (described as Greenland Stadial 13) and the initial stages of the Greenland Interstadial 12, a period that was less cold than the previous one but still had a mean annual temperature of less than 5 °C. The site was situated in a steppe or tundra habitat, indicating that the human groups that occupied it were adept at preying on fauna in a cold, open environment.

In 2020, scientists found that modern human remains were associated with another MUP transitional stone-tool industry, the Bachokirian, in southeastern Europe[5]; therefore, with Ilsenhöhle, we now know of two sites from the MUP transition with *H. sapiens* remains that are associated with two different transitional industries.

Mylopotamitaki *et al.* point out that the majority of the mitochondrial-DNA genomes from Ilsenhöhle show similarities to the mitochondrial DNA extracted from the Zlatý kůň *H. sapiens* skull from the Czech Republic, and point out that this skull's purported age of about 45,000 years old[7] overlaps with the date range of another MUP transitional industry called the Bohunician. This echoes the conclusion, based on technological characteristics, reached by others that the LRJ has its roots in the Bohunician[8]. However, in the absence of human remains, as well as the fact that the techniques used to produce projectile tips in the Bohunician are reminiscent of the technique used by Neanderthals to produce a type of projectile tip called a Levallois point, the Bohunician's association with modern humans remains to be demonstrated with certainty.

As an archaeologist, I find that my colleagues and I are conducting our research during an interesting time. We have at our disposal methods that the discipline did not possess just a couple of decades ago — which enables us to examine the archaeological record at a better level of detail and improves our capacity to pinpoint when specific levels at a site were occupied. Furthermore, there is now an appreciation for the often-regional nature of cultural trajectories, and the need to examine them as such[9].

Another development is the recognition that Neanderthal groups were culturally complex[10–12], so we should not necessarily assume that all MUP transitional industries, because they differ from those of the preceding Middle Palaeolithic, must have been made by modern humans. Although Mylopotamitaki and colleagues' discoveries provide another important piece of the puzzle of this culturally and demographically complex period in Europe, we must be careful not to generalize findings from one or two sites — or even one or two transitional industries — to other contemporaneous, regional transitional industries. For example, a lack of consensus[13] surrounds the identity of groups (Neanderthal or modern human) associated with two transitional industries — the Châtelperronian in present-day France and northern Spain, and the Uluzzian in the Italian peninsula and immediately adjacent areas — clearly indicating the need for further objective investigation.

What is the way forward? I argue that at least two things are needed. First, researchers must rigorously examine archaeological association and archaeological context — factors that are the basis on which all of our inferences are founded. Second, we must assess all available data from reliable contexts as objectively as possible, and do our best to not try to fit data into a preconceived idea of how this culturally complex period played out. In so doing, I am convinced that, in a decade's time, we'll have a much clearer picture of the European MUP transition.

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