PHYSICS AND ARCHAEOLOGY

Physics-based techniques are yielding more accurate dates for our prehistoric ancestors, profoundly affecting our understanding of the past.

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Traditional archaeology has not been a field that suffers science easily. Only gradually have archaeologists accepted physics as a tool for archaeological research. Perhaps as a result, the physicists who work in archaeology, their methods, and their theories, are neither well known nor numerous. Archaeometry, as the wider field of scientific archaeology is known, has no Heisenbergs or Einsteins, uncertainty principles or relativity theories. The only physical discovery to truly revolutionize archaeology has been radiocarbon dating. Willard Frank Libby won a Nobel Prize in 1960 for developing the technique.

Although physics has yet to produce as dramatic an advance as radiocarbon dating, it has nevertheless left its mark on modern archaeology. To see why, consider the definition of archaeology offered by William H. Stiebing Jr: "Simply put, archaeology is the study of mankind's past through the recovery and analysis of its material remains."[1] The very nature of archaeological materials—fragmentary, incomplete, and, in many cases, wholly unknown to modern eyes—makes their study and interpretation difficult and prone to error.

The reason for this state of affairs is patently simple. The further back in time one goes, the fewer the remains of materials and the less likely that they will survive natural forces. Indeed, one of the major problems in demonstrating how humans and their cultures have evolved from their simplest and oldest beginnings is the paucity of evidence. When they do find artifacts, archaeologists ask: How old is it? What is it made of? Where did it come from? These are questions that science, particularly physics, can help answer. And it is the archaeological question that determines the choice of a particular physical technique.[2]

Radioisotope dating

Radioisotopes have characteristic decay probabilities, commonly expressed as halflives, which render them more or less useful in dating the objects that contain them. Carbon-14, for instance, has a relatively short halflife of 5730 years. In the first archaeological demonstration of radiocarbon dating, Libby determined the age of wooden items found in an Egyptian pharaoh's tomb.

With the discovery of increasingly ancient fossils, the date of the earliest human horizons has moved steadily backward to the Pliocene–Pleistocene boundary 5 million years (5 Ma) ago—well beyond the 50-ka limit of radiocarbon dating. Breaching that limit was a knotty problem until the late 1940s, when Alfred Nier confirmed Carl Friedrich von Weizäcker's prediction that argon-40, a decay product of potassium-40, would accumulate in volcanic minerals such as micas, feldspars, and hornblendes.

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When lava spews out of a volcano, argon gas trapped within the lava is forced out. But potassium, in a naturally occurring mixture of radioactive ^{40}K and nonradioactive ^{39}K, remains. ^{40}K decays into ^{40}Ar, which then starts to accumulate. At 4.1 billion years, the halflife of ^{40}Ar is ideal for dating ancient humans. Measuring the amount of accumulated argon in the rock yields the rock's age, as well as that of any fossils found in the same stratum.

One such fossil is the *Homo erectus* known as "Java Man." The famous relic was found in 1891 by the Dutch paleontologist Eugène Dubois on the Trinil terraces of the Solo River in Java. From its discovery onward, Java Man has been controversial. Even up into the late 20th century, its precise placement in the human evolutionary tree was debated, largely because of the inability to obtain completely reliable dates for the archaeological and geological context of the Java fossils.

Dubois himself, an eccentric in his later years, always maintained that his finds were extremely ancient, an argument he based on their stratigraphic context and on a strong prejudicial desire to demonstrate a non-European origin for humanity. In the late 19th century, the discoveries of Cro-Magnon and Neanderthal fossils in France and Germany were originally thought to place ancient humanity's origin in Europe. Now, thanks to ^{40}K/^{40}Ar dating, we understand that Africa—not Asia, as Dubois advocated—is the genetic cradle of early humanity. Still, Dubois was not completely wrong in his presumption of great antiquity for his fossils. How much older may have surprised even the opinionated old man.

Early attempts using the radiogenic ^{40}K/^{40}Ar method yielded ages of around 0.6 Ma, but, in 1993, Carl Swisher and his coworkers at the University of California, Berkeley redated two pumice deposits from Java Man's cranium as having originated 1.81 Ma and 1.66 Ma ago.[3] This new finding was indeed a surprise—but one whose validity seemed secure, given the proven reliability of the newest radiogenic potassium method (^{40}Ar/^{39}Ar) and the rigor by which the new dates were obtained. Why is this such a landmark finding?

The *Homo erectus* taxon to which the Java finds belong is intermediate between the oldest fossil finds of south and east Africa (4 Ma to 1.8 Ma) and the later archaic and modern *Homo sapiens* varieties of Europe, Africa, and the Middle and Far East (around 0.5 Ma ago to the present). Before the ^{40}Ar/^{39}Ar dating, the Java fossils seemed to fit conveniently into the later part of the erectoid sequence, both chronologically and in terms of theoretical models for the dispersal of those hominid types out of Africa in the mid-Pleistocene. But the new dates call those models into serious question. Statistically speaking, the east African (1.6 Ma) and Java (1.8 Ma) dates are the same. How, then, did *Homo erectus* get from

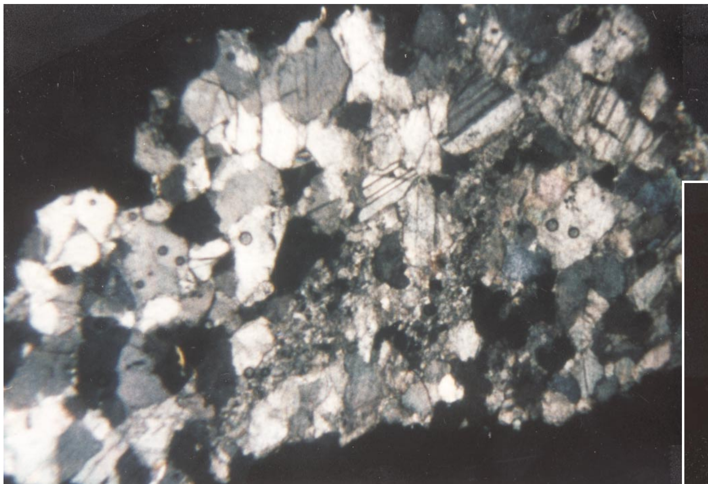

FIGURE 1. CRYSTALS that have been exposed to ionizing radiation reveal their age through the heat-induced emission of photons, an effect called thermoluminescence. The image on the left shows a marble sample under natural light. The image on the right shows the same sample's thermoluminescent glow.

east Africa to the Far East so quickly?

New fossil evidence from China and the Caucasus indicates that *Homo erectus* left Africa around 2.0 Ma ago, arriving in Asia 0.1–0.2 Ma later. At that time, the sea level was lower, shortening the most likely coastal dispersion routes. The fossils also indicate that, compared with their African forebears, the humans who arrived in Asia possessed larger brains, longer legs, more varied diet, reduced sexual dimorphism, more complex cultural behavior, such as social groups and tool manufacture, and, very likely, better regulation of body temperature through more efficient musculature and perspiration. All these changes pre-adapted the *Homo erectus* taxon to broader climatic conditions, more diverse environments, and greater territorial dispersal that became, when the opportunity arose, intercontinental.

The Gap

Between the upper limit of radiocarbon dating (about 50 ka) and the lower limit of radiogenic potassium dating (about 0.5 Ma) there used to exist a chronological lacuna that I call the Gap. This temporal range encompasses the transition of archaic humans into fully modern forms, so the lack of a reliable means of dating fossils from the Gap was disconcerting. Luckily, several dating methods developed in the past few decades now effectively bridge that previously undatable half-million years.

Foremost among these new physical dating methods are three that rely on detecting accumulated radiation damage to assess the age of both minerals and organic remains. These methods, each named after the physical phenomenon that makes detection possible, are thermoluminescence (TL), optical stimulated luminescence (OSL), and electron spin resonance (ESR).

First observed by Robert Boyle in 1663, TL and its younger cousin OSL measure the photons emitted when electrons are freed from traps within feldspar and quartz crystal lattices (figure 1). In the case of TL, photons are emitted when the sample is heated. In OSL, photon emission occurs when the sample is exposed to narrow-band blue–green or infrared light. In both TL and OSL, the basic data product is a plot of cumulative energy release versus temperature and is called a glow curve (figure 2).

Interpreting glow curves requires physics. When ionizing radiation is incident on a crystal, a population of trapped electrons is created between the conduction and valence bands. The depth of the trap, in energy terms, determines the amount of thermal (TL) or optical (OSL) energy necessary to free the electron so that it will return to an energy level within the regular orbital structure of the atoms in the crystal. Once there, it can emit a detectable photon. Not all traps are what are termed luminescence centers, but enough are created by naturally occurring radiation for TL and OSL to be the basis of an increasingly popular method of dating.

Laboratory experiments show that TL varies linearly with radiation dose until it saturates at a dose that, if delivered at the natural exposure rate, would take 500 000 years to administer (see figure 2). Age determination is therefore a straightforward matter of comparing the TL of the artifact in question with that of a representative piece of the same material that has been given a dose equivalent to one year's worth of natural exposure. In practice, the method readily yields ages with an accuracy near 10%.

Because they can be used on single grains of a mineral, TL and OSL are practically nondestructive and have been applied to crystal grains within those most commonplace of artifacts, pottery fragments, as well as to sediments and chert (a silica mineral).

In the case of TL and ESR, the clock resets to zero when the sample is heated and starts ticking once the sample cools. Pottery, which is fired in its manufacture and heated when used for cooking, can therefore be dated with TL and ESR. For OSL, exposure to sunlight resets the clock. Sediments, such as dune sand or loess, are bleached by the Sun until covered over, which is when the OSL clock starts to tick.

ESR, the third dating technique based on radiation damage, is similar to TL and OSL in that it depends on the presence of trapped electrons. Crystals naturally contain defects called vacancies, in which an atom is missing from a lattice site. When the crystal is exposed to ionizing radiation, unbound electrons are created that can occupy the vacancies. The longer the radiation exposure, the more vacancies are filled.

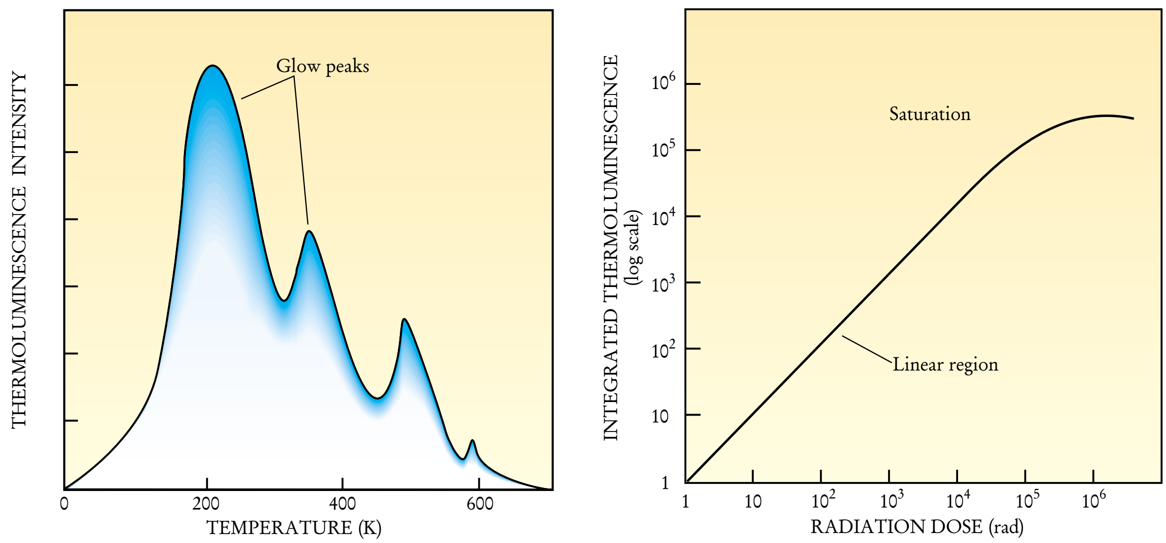

FIGURE 2. AT CHARACTERISTIC TEMPERATURES, electrons dislodged from the lattice by ionizing radiation gain the right amount of thermal energy to return to their former bound states, emitting thermoluminescent photons in the process. The plot of spectral intensity against temperature is known as a glow curve (left). The total amount of thermoluminescence (TL) depends linearly on the radiation dose for a wide range of values (right), a fact that makes TL suitable for archaeological dating.

Quantifying the filled vacancies is where ESR, a close cousin of nuclear magnetic resonance (NMR), comes in. The first step is to apply a static magnetic field B, which splits the two spin levels of the trapped electron by $2\mu_B B$, where μ_B is the Bohr magneton. To measure the splitting, a second oscillating field of variable frequency ω is applied. When $\hbar\omega = 2\mu_B B$, a detectable resonant absorption occurs. The deeper the absorption, the greater the number of filled vacancies. The precise location of the resonance depends on the trapped electron's magnetic environment, which is characterized by the nuclear spins of the surrounding atoms. Calculation and calibration can therefore reveal not only the number of trapped electrons, but also the identity of the trapping atoms.

Eve and the Neanderthals

TL and the other Gap-spanning dating techniques have proven crucial in elucidating what has become known as the Eve hypothesis. According to this theoretical model, which is based on the study of female-line mitochondrial DNA, all modern humanity (that is, *Homo sapiens*) shares descent from an African ancestor termed Eve who lived some two hundred thousand years ago. Although the method used to derive Eve's antiquity is somewhat questionable, most scholars of early human evolution accept the overall outline for the Eve hypothesis. Correctly dating hominid sites of an antiquity approximating the age of hypothetical Eve assumed a greater importance.

Although the Eve hypothesis has not been conclusively vindicated, ESR dating of teeth and TL dating of heated flints from the Middle East and OSL dating of soil samples from the Katanga region of Africa have established that a tool-using variant of *Homo sapiens* lived in Africa and the Middle East well before the Cro-Magnon period (30 ka ago) of western Europe.

The Eve hypothesis isn't the only archaeological problem that the Gap-spanning dating techniques have illuminated. Since their discovery in Germany's Neander Valley in 1856, the hominid taxon *Homo sapiens neanderthalensis* has provoked discussion and controversy as to its exact place in humanity's genesis. This long-running debate has been renewed by interest in the Eve hypothesis and by Middle Eastern and Mediterranean discoveries in the late 20th century.

The exact phyletic position of *Homo sapiens neanderthalensis* has been a somewhat uncomfortable fit within the late Quaternary forms of the genus *Homo*. Neanderthals are different from modern humans; the unanswered question remains: How different? Do Neanderthals form a separate species, a subspecies, or what?

Until the advent of age-determination methods such as TL and ESR, the accepted scientific explanation for Neanderthals was as predecessors to modern (Cro-Magnon-type) humans. Such a view was understandable

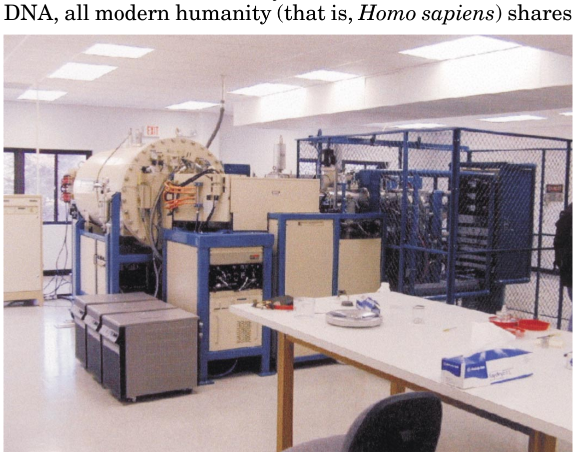

FIGURE 3. ACCELERATOR MASS SPECTROMETRY SYSTEM. This example, an NEC Model 1.5SDH-1 Pelletron, is based at the University of Georgia's Center for Applied Isotope Studies.

given that archaeologists and biological anthropologists had demonstrated that Neanderthals were anatomically and culturally different from their successors and that the best available dating had the last of the Neanderthals dying off around 35 ka ago.

The dates obtained, particularly in the Middle East and Mediterranean, challenged the conventional wisdom. They proved that modern and Neanderthal sites overlapped for tens of millennia. Indeed, modern humans first appeared, not in the 40 ka time range, but as early as 92 ka! Eve's children, with their great art and culture, reached Europe faster than any had supposed. We know now that Neanderthals and the ancestors of modern humans were living side by side for millennia, perhaps apart or perhaps mixing culturally and biologically with their modern neighbors.

Accelerator mass spectrometry

Another physics-based dating technique is accelerator mass spectrometry (AMS). Developed in the 1970s, AMS works like any other mass spectrometry in that it exploits electric and magnetic fields to separate and identify ions by their mass-to-charge ratios. The particle accelerator (typically a 2– to 10–MeV Van de Graaff) is needed to rip apart the carbon atoms from whatever other atoms they are bound to (usually hydrogen).

AMS is an astonishingly sensitive technique. Current AMS systems (see figure 3) can detect a single ^{14}C nuclide among 10^{15} ^{12}C neighbors. This enhanced sensitivity allows the use of milligram samples for the direct dating of archaeological materials such as bits of hair. Using such small samples is out of the question for traditional radiocarbon dating, which relies on counting enough beta decays to reliably establish the decay rate.

The ability of AMS to date small samples was crucial for dating the Turin Shroud, an artifact believed by many to be Christ's burial cloth. The Roman Catholic Church, which owns the shroud, considered it far too valuable to allow the removal of portions large enough for conventional radiocarbon dating. But in 1988, the church consented to the first dating tests of the shroud. Strands were sent to seven different laboratories for AMS and gas-counter dating. The results consistently placed the manufacture of the shroud in the Middle Ages, around 1300, as indicated by the earlier analyses of the image and its mode of production.

Interestingly, given the controversy surrounding the shroud, the AMS-determined date is also consistent with an injunction from Pope Clement VII, dated 1389, that used to be displayed with the shroud:

> . . . The aforesaid form or representation is not the true burial cloth of Our Lord Jesus Christ but a kind of painting made as a form or representation of the burial cloth.

AMS figured prominently in another important archaeological find. In 1991, the public was fascinated by the discovery of a perfectly preserved mummy (see figure 4) at an altitude of 3000 m in Italy's Tyrolean Alps.[4] Nicknamed the Iceman (and later Ötzi after the mountain pass in which he was found) this unique archaeological discovery at a wholly unexpected altitude led to archaeometric studies that have recast ideas on the prehistory of humans and their early exploitation of metals. Although perhaps not as epochal as the redating of the Java and Neanderthal materials, the archaeometric analyses of Ötzi and items found along side of him yielded surprises, not the least of which were his antiquity and the composition of the metal axe he carried at the time of his death.

FIGURE 4. ÖTZI THE ICEMAN was found 10 years ago by hikers in Italy's Tyrolean Alps. Accelerator mass spectrometry puts his date of death between 3300 and 3200 years BC.

When first found, the axe was thought to be bronze, placing Ötzi in the Bronze Age and suggesting that he lived around 1800 BC. However, the axe was of a cast technology, which led archaeologists to suspect a date of manufacture, and hence a cultural affiliation, no later than 2300 BC. AMS put his date of death between 3300 and 3200 years BC.

Another physics-based technique, x-ray fluorescence (XRF), was brought to bear on Ötzi's axe. XRF showed that the metal it was made from was copper, not bronze. The metal also contained 0.22% arsenic and 0.09% silver, indicating that the original ore was probably malachite or azurite.

Ötzi, then, was a man of the late Neolithic period, a time characterized by early experimentation with metal manufacture. Most of the Neolithic cultures of Western Europe were based more on stone than metal. In fact, Ötzi was carrying items both new and old—an axe of the latest technology along with stone artifacts that fit comfortably into a Neolithic cultural milieu that lasted a millennium at the very least.

Shallow geophysical techniques

Since the end of World War II, archaeometric prospectors have made extensive use of what are known today as shallow geophysical techniques. Currently, the three most prominent prospecting devices use electrical fields, magnetism, or microwave radiation to detect and characterize underground objects.

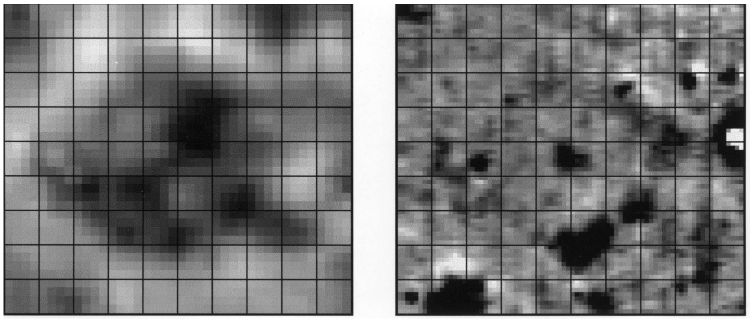

Figure 5. The buried remains of a 14th-century American Indian house from the Whistling Elk archaeological site in South Dakota. The electrical resistivity map on the left reveals the size and shape of the house (a 10 × 10-meter square) and its linear doorway. The magnetic anomaly map on the right reveals the house's central hearth and support posts. (Courtesy of Kenneth L. Kvanne, University of Arkansas.)

Geophysicists had used electrical and magnetic techniques in mineral exploration long before European archaeometrists began adapting these devices to archaeological search in the 1940s. In 1946, Oxford University's R. J. C. Atkinson adapted resistivity surveying so that he could study sites in Oxfordshire. Another pioneer was J. C. Belshé. The Oxford-based archaeometrist became the first to use a proton precession magnetometer for archaeological purposes when, in 1957, he monitored the magnetic signature of a reconstructed Roman kiln when it fired. Although the 1990s saw a renewal of interest in electrical methods such as resistivity and conductivity meters, the portability and sensitivity of magnetometer and ground-penetrating radar (GPR) systems (which I don't have space to discuss here) have made magnetometers and GPR systems more and more popular in archaeology.

In archaeological prospecting with a magnetometer, local contrasts (termed anomalies) in the magnetic character of a site are measured. LeBorgne showed that soil magnetization is a product of Earth's field strength and the magnetic susceptibility of the soil, which arises from the iron-bearing minerals magnetite, hematite, and maghemite. Additionally, heated objects, such as clay brick and pottery, can exhibit thermoremanent magnetism, in which the object retains its magnetism in the absence of an external field. Typical anomalies are about 10 nT (the intensity of Earth's magnetic field ranges from 30 000 to 60 000 nT).

Irwin Scollar, formerly of the Rhineland State Museum in Bonn, singles out the proton precession magnetometer (PPM) as the physical device that has had the most impact in archaeological prospecting. The physics behind the PPM is straightforward. Protons, and other nuclear magnetic moments, tend to align with Earth's magnetic field. Introducing a stronger field with a different orientation causes the protons to realign with the new field. If you then turn off the new field, the protons will return to their original alignment. As they do so, they precess with a frequency (of around 2 kHz) that is proportional to the local value of Earth's magnetic field.

In actual devices, the effect is realized by coiling wire (to make an electromagnet) around a bottle of distilled water or other proton-rich substance. When the electromagnet is turned off, the precessing protons induce a weak current in the coil. Measuring that current yields the local magnetic field.

The sensitivity of the first PPMs was about 1 nT for absolute measurements and about 0.5 nT for relative measurements. Later devices, such as optically-pumped, single (optical) cell cesium vapor magnetometers, are about twice as sensitive. The device I use exploits the Overhauser effect—a double resonance of electrons and nuclei—to achieve an operational sensitivity of 0.01 nT. This magnetometer uses a solvent, like methanol, in which free radicals, such as triscetone-amine-nitroxide are dissolved. These radicals have available free electrons, which couple with the protons to raise the net magnetic polarization of the fluid by a factor of 4000–5000 compared to that of a typical proton magnetometer. Such sensitivity is nice on paper, but in practice, older PPMs are more than adequate for finding buried features of archaeological interest.

Magnetometer sensitivity falls off with the third power of the distance. An anomaly measuring 64 nT with the sensor directly over it will therefore produce a reading of 4 nT when the sensor is moved a distance of 1 meter away. This distance dependence might seem to be a serious limitation, but in fact it works to help localize the feature or object spatially. For electromagnetic devices such as metal detectors, the sensitivity distance depends on 6th power of the distance. One can readily understand why the search coil of metal detectors has to be right on top of the buried coin.

Magnetometers have led to several significant discoveries. In 1968, Elizabeth Ralph used a cesium magnetometer of her own design to locate buried houses of a Balkan Neolithic culture known as the Vinča. In the 1970s, Sheldon Breiner, who developed the digital-display proton magnetometer at Geometrics Inc, located gigantic pre-Columbian basalt sculptures—heads, in fact—in Mexico's Tabasco state. And in the 1980s, Scollar located and saved from destruction, the remains of the previously unknown 2nd century AD Roman town of Colonia Ulpia Trajana in western Germany. Another example is shown in figure 5.

This brief discussion of physics and archaeology has mentioned only a fraction of the varied contributions that could be discussed. Among the well-established fields omitted are electron and optical microscopy, archaeomagnetism, and optical, Mössbauer, and IR spectroscopy. Fascinating new areas include NMR spectroscopy and resonance ionization spectroscopy, together with scanning tunneling microscopy and atomic force microscopy.

The use of physics in archaeology is now firmly established and the lively and productive dialog between the two fields continues. At many institutions around the world, archaeometrists are being trained at both the master's and doctoral levels. From the ballistics of a Paleolithic spear to the trajectories of carbon isotopes in an AMS accelerator, physics provides answers to archaeological questions.

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