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Digging deeper in human history: The role of mining natural resources in Big History

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ABSTRACT

This paper is focused on the "paths of human history" in relation to the geological occurrence patterns of the following natural resources: stone, copper, tin, iron, gold, and coal. The abundant occurrence of flint in the Near East has influenced toolmaking and maybe the moment when early men discovered how to control fire. The scarcity of tin stimulated an early long distance trade during the Bronze Age. The abundant occurrence of iron, on the other hand, offered tools for everyday agriculture and "democratized" weaponry. The scarcity of gold, plus its durability, made it perfect for money, and therefore mining of gold strongly influenced economic history. The use of coal revolutionized the use of energy and industrialization. From making knives to controlling fire, from developing world trade to stimulating agriculture and war, from creating a global economy to increasing, as well as highlighting, the great differences between haves and have nots, from forming societies to destroying environments, the role of ores and their occurrences were essential.

1. INTRODUCTION

Big History is, according to Spier (2015, p. 1), "the approach to history that places human history within the context of cosmic history, from the beginning of the universe up until life on Earth today." Therefore, Big History tries to combine the regimes of cosmos, Earth, life, and humanity (Alvarez, 2017). Christian (2004) suggested that there is a growing sense across many scholarly disciplines that we need to move beyond the fragmented account of reality that has dominated scholarship (and served it well) for a century. While specialization is still the leading rule in the world of science, interdisciplinary knowledge is needed to solve the challenges our global world faces. Looking at deep time means focusing on long-term changes.

Although this paper is not about cosmic history (the big bang, the making of stars and galaxies, or the making of the chemical elements), it is still important to realize that humans, as well as everything around them, are made of "star stuff" (Sagan, 1980). In this chapter, we do mention a little about Earth history (plate tectonics and volcanism, or impacts), without elaborating on it. Nor do we write a lot on the influence of life on Earth, (e.g., the Great Oxygenation Event or the Geological Carbon Cycle, which have shaped Earth's crust). Still the premise is that Earth history set the stage for humans and their ancestors. Often

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without realizing it, humans in turn strongly influenced Earth and life on Earth. Out of the intricate woven fabric of Big History, just one thread has been chosen.

In history, archaeology, and physical anthropology, the three-age system (Stone Age, Bronze Age, Iron Age) is a methodological concept—adopted during the 19th century—according to which human artifacts could be broadly ordered into a recognizable chronology (Thomsen, 1836). Therefore the first three resources to look into are stone (from the Stone Age), bronze—copper and tin—(from the Bronze Age), and iron (from the Iron Age). The other two resources are gold and coal. Gold, next to silver, is an ongoing symbol of monetary and economic development, and coal, because of its large exploitation (and later that of oil), can be seen as an important trigger for the industrial ages of the last few centuries and the enormous growth in energy use by ever growing numbers of humans. The following sections on stone, gold, and coal are in part a review of previous publications with a similar approach (Alvarez et al., 2011; García-Moreno et al., 2017, 2019). For non-geologists, it is helpful to understand the geology of these ores, while elaborating on human history.

This chapter is a contribution honoring Walter Alvarez's vision of a Big History perspective and his confidence in the importance of Big History teaching (Alvarez et al., 2011). And, it is an attempt to give an example of how a Big History approach to the role of mining natural resources can stimulate students to connect the interdisciplinary dots.

The painted "shovels" shown in this chapter are from the current artistic project *Dig History* by Metallo (2022). The shovel figures (Figs. 3A–3H, 5I–5P, and 7), along with extensive captions, intend to show a Big History investigation of digging. It is a study depicting how humans drill, dig, and mine, and take from the earth what geological processes took millions of years to make. The artwork is not necessarily meant to be a visual explanation of the text, but is an artistic reaction, which can add a critical attitude to reading "objective" facts and propose questions with benefits for science and art. Ranis (2021, p. 13) states, "There is a long tradition of merging Art with Science originating from both fields of study, with good reason." And, "Projects merging Geoscience, in particular, with art can also serve as an effective link between natural history and human history" (p. 13). The beauty of an interdisciplinary frame of mind is to show different approaches that can make students dig deeper. Metallo (2016, p. 139) observed, "Studying only our history, as living things on this planet, is like observing no more than the width of a single tessera in a mosaic. Art can encourage openness to stretching the brain to comprehend this interconnectivity and become active describers and comparers of our stories, thus illuminating our small, patterned part of the universe."

2. THE STONE AGE

Some 3.4 million years ago, pre-human hominids such as *Australopithecus afarensis*, represented by the famous skeleton of Lucy (Johanson and Edey, 1981), lived in East Africa. Archeological finds show that these hominids made stone tools. The first members of the later genus *Homo* dated from ~2.6 Ma. That date is usually chosen as the start of what we call the Stone Age of human history, which, in the geological time scale, is equivalent to the Pleistocene (Gibbard and Head, 2020).

Geologists, of course, know that Africa went through a number of tectonic cycles of breaking and merging plates, and breaking up and subduction in different places, over and over again for billions of years. In short, one could say that plate tectonics worked somewhat like a giant chemical processing plant; colliding subduction plates heat up rocks until they melt, forming molten magma. When the magma erupts at the surface and quickly solidifies, sometimes obsidian or volcanic glass is formed (e.g., Alvarez, 2017; Dartnell, 2019). One of the most recent breakups on this continent is situated in the East African Rift, where Lucy lived and her human descendants originated. The uplifted rims of the East African Rift are the source of many rivers, and the rifting itself caused magma to rise to the surface and erupt frequently.

Using rocks as tools was not a uniquely human or even primate invention. Elephants, dolphins, sea otters, birds, and rodents are known to also use pebbles as tools. However, early humans developed a more specialized way of using these rocks. Once they found a stone that fit best in their fist to crush nuts or animal bones to extract the marrow, early men may have empirically found that hitting a pebble on something hard might cause the pebble to split, producing sharp cutting edges. What makes Hominids and early humans special is that they were learning beings who passed their knowledge on to following generations (e.g., Christian, 2004). They realized that granite would not work due to its granular texture, and that while basalt might be strong, it was hard to shape. Quartzite is also strong and leaves conchoidal cut surfaces with sharper edges when split. Still, quartzite is a relatively coarse-grained rock, and shapes cannot be further refined. Naturally glassy rocks like obsidian, however, can provide perfect conchoidal fractures, which can be further refined. This would have been the preferred material of more experienced stone toolmakers. The earliest hominids from Olduvai Gorge used basalt rocks or quartzite at first, but later discovered obsidian to make better tools (Merrick and Brown, 1984).

The best material to make stone tools, beside obsidian, was chert (or flint, as archaeologists usually call it). It is a microcrystalline precipitate of dissolved SiO_2, usually found as nodules or layers in carbonate rocks. Being mechanically and chemically more resistant than the embedding limestone, chert nodules are easily separated from the rest of the limestone mass by the natural processes of weathering. However, Cretaceous limestone is quite scarce in the East African rift area. Some older chert may have been found in these regions, e.g., around Magadi Lake in Kenya (Brennan, 2016), but there seem to be few examples of tools made from chert in East Africa (Fig. 1). Non-geologists usually only mention "stone" tools, without geological specifications (e.g., de la Torre, 2011). Already around 300,000 years ago,

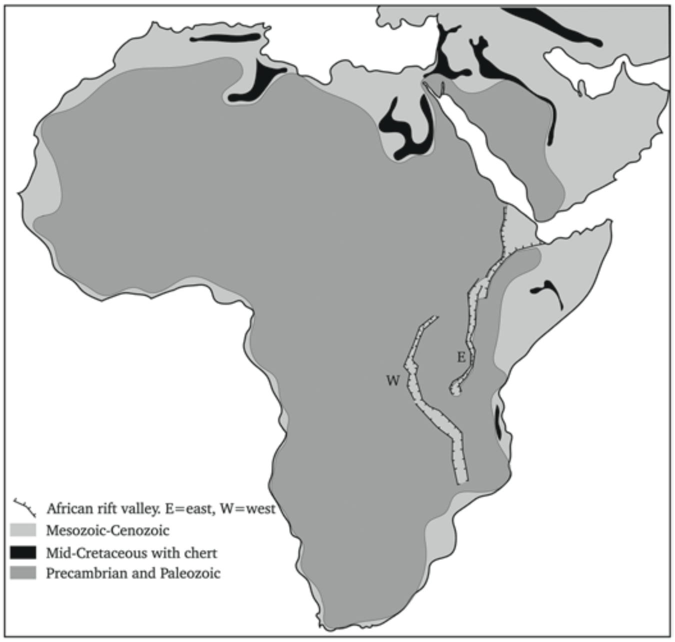

Figure 1. Geological map of North Africa and the Near East (modified after Commission for the Geological Map of the World, 1985–1990). Dark areas: chert/flint-bearing, mid Cretaceous limestone formations.

42% of the recovered tools in a site in the East African Rift could, however, be specified to have been made of obsidian, not chert. Obsidian must have been brought in from volcanic sites, often up to 25–50 km away (Deino et al., 2018).

Around 300,000 years ago, anatomical and archaeological changes took place in combination with ecological challenges (Spikins et al., 2021). Alternating periods of dry and wet conditions placed particular pressure on human populations in arid corridors, prompting dispersions along wetter corridors. Between 300,000 and 200,000 years ago, groups of *Homo erectus* living in East Africa migrated northward toward Egypt and the near East (Fig. 2).

These early humans may have tried to find obsidian for toolmaking in this area, as they had used in Eastern Africa. The search for obsidian stimulated what could be considered as the first trade in history. Obsidian can only be mined in volcanic provinces (as in some parts of Turkey and Northern Iran), but in many small settlements in the Near East signs have been found of obsidian toolmaking, and the obsidian could be traced to several volcanic sites (Dixon et al., 1986).

Chert is found in Cretaceous limestone layers from Egypt to the Levant (Fig. 1). So, contrary to Eastern Africa, chert could be found more easily than obsidian in Egypt and the Near East. Chert, being microcrystalline, has even better properties to make tools. It does not break easily, and it is tougher than obsidian glass, which is more brittle. Vermeersch and Paulissen (1993) describe examples of Palaeolithic chert quarrying and mining in Egypt, and Verri et al. (2004) show that the raw material used to manufacture flint artifacts of 300,000 yr BP at Qesem Cave (Israel) was obtained from shallow quarries. Delage (2007) edited a publication on chert availability and prehistoric exploitation of chert in the Near East, in which finds of prehistoric exploitation in Syria, Israel, Jordan, Turkey, and Cyprus are described.

This must have been a welcome discovery for the early humans arriving in Egypt and the near East. Carotenuto et al. (2016) developed a model that suggests that during their dispersal around the world, *Homo erectus* followed the large herbivores, while also keeping an eye on flint deposits. These early paths of *Homo erectus* were followed by waves of Homo sapiens (Fig. 1) thousands of years later. In museums all over the world nowadays, flint tools are shown as the most used everyday tools of the Stone Age. Flint tools have become the characteristic finds of the Stone Age epic (Figs. 3A and 3B).

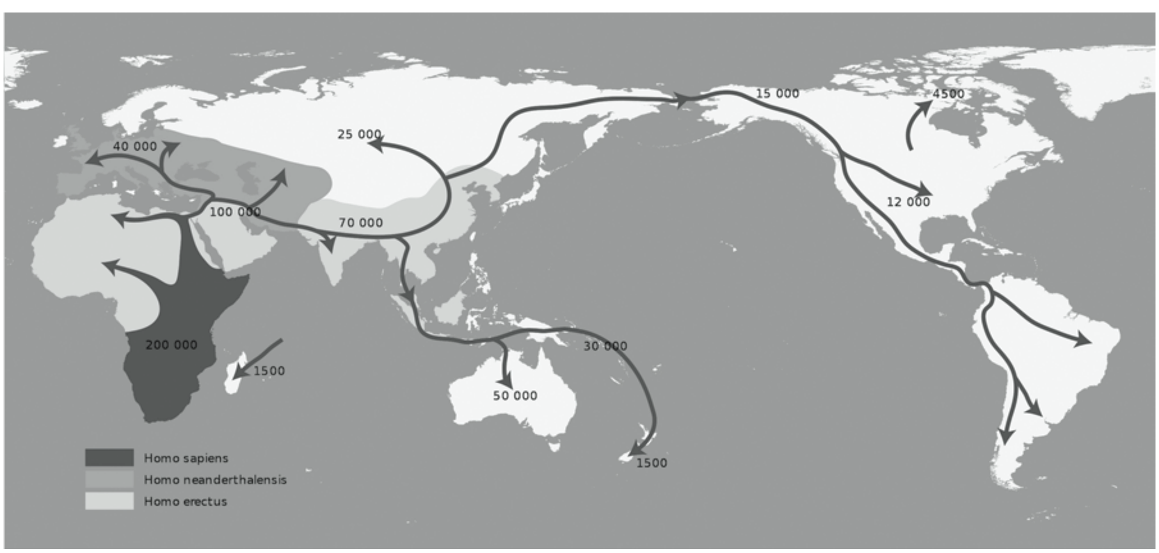

Figure 2. Map of early human migration. Image by NordNordWest (public domain), from Groeneveld (2017).

2.1 Tool Making and the Control of Fire

There is a firm empirical basis for considering natural fire to have been part of the ecology of early hominins. Geological evidence of fire on a Triassic tree suggests that fire played an important role in plant ecology by the Triassic (Chazan, 2017). While fire is a chemical reaction and a natural resource, in the human context, it is also a technology, an aspect of society, a necessity, and even an element of belief. So, there was a long prehistory of fire; it was not a sudden invention (Chazan, 2017).

Goudsblom (1992) stated that it was the control of fire more than anything else that was essential for the development of civilization. Herculano-Houzel (2012) concluded that the greatly enlarged modern human brain was energetically very

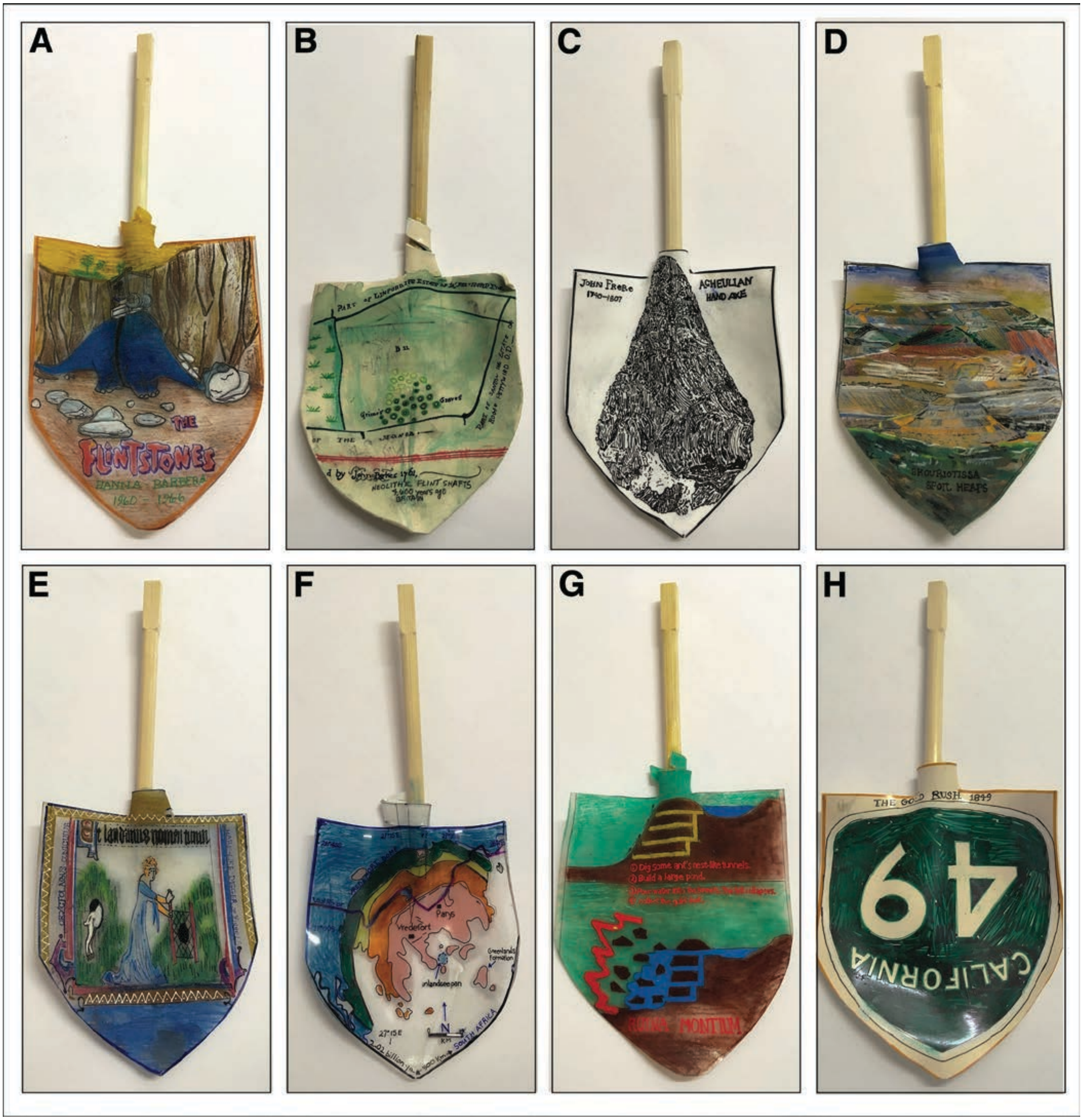

Figure 3.

unfavorable. Spier (2015) suggested that, after developing better hand-arm coordination and stereoscopic eyes, walking straight up would have stimulated humankind to start using and making tools. This would be crucial for brain growth. At the same time, the disadvantage of having a large brain is that it uses up a great deal of energy. Finding more efficient ways of food processing would make the development of larger brains possible. The knowledge of controlling fire could fulfill these needs. Combining archaeological, anthropological cooking hypotheses, and evolutionary perspectives about the human brain, Gowlett and Wrangham (2013) suggested a combined hypothesis on the earliest use and control of fire with three points:

1. Fire would have been used as a resource of nature by early *Homo* or even earlier hominid species, when early *Homo* spread out around the world, around 2.0 Ma. They may have been "consumers" of natural fire with limited active control. An argument against control of making fire by *Homo erectus* was the absence of evidence for the control of fire by *Homo neanderthalensis* in Europe (the descendants of *Homo erectus*).
2. In the drier zones of the tropics and subtropics, the familiarity with fire offered by regular lightning strikes and forest fires would give the benefit of cooking plants and small animals, as stated by the so-called "cooking hypothesis." In this context, fire control skills would rapidly improve until the use of fire was widespread in these areas.
3. Further north, the scarcity of lightning strikes and the severe costs of accidental fire loss would create far greater challenges to human occupation and selective pressures for dealing with these, the two factors perhaps operating to influence and constrain patterns of settlement.

In many languages, chert or flint is literally known as "firestone" (e.g., *vuursteen* in Dutch, *feuerstein* in German, and *pietra focaia* in Italian). These "firestones" have been used in modern times for making flintlocks and cigarette lighters. Chert will produce sparks of fire when it is hit with an equally hard stone (i.e., another piece of chert) or, even better, with a rock containing pyrite (iron sulfide). The working of flint and experience with pyrite might have triggered early humans to use these sparks of fire to control and make fire.

Evidence of the use of fire by early hominids was found in lower Paleolithic sites in Africa as old as 1.9 Ma (e.g., James et al., 1989). However, it is often claimed that these fires were remnants of natural wild fires, carefully kept in a protected place for several usages. Chert, when hit hard to make a tool, can spark like a "firestone." In the East African Rift valley, chert was scarce, and toolmakers used obsidian. Obsidian is brittle and breaks easily, so it must be hit gently and probably produces few sparks, if any at all. From a geological viewpoint, it would not be obvious that early human toolmakers, while still in East Africa without chert, would discover how to make fire. It is not impossible either, because quartzite can also spark when

Figure 3. (A–H) Dig History series, Paula Metallo (2022; www.paulametallo.com: HOLES section, New Works), Shrinky Dink® plastic, mixed media, and chopsticks, 8 × 18 cm. (A) *The Flintstones*' quarry. *The Flintstones* was an American T.V. cartoon produced by Hanna-Barbera Production in the 1960s. Thousands of years ago, a hominin of the "Flintstone Family" found a chert nodule, picked it up, and turned it into a flint-stone tool. The shovel shows how facts often are used falsely for commercial reasons. (B) Digging in Grime's Graves. Toward Grime's Graves near Norfolk, England, is a grassland pockmarked with over 430 prehistoric flint mine pits. The earliest pits were dug as vertical shafts some 2,600 years ago, to reach horizons of flint nodules. "The mysterious lunar-like landscape of Grime's Graves is the legacy of hundreds of years of activity by flint miners, to extract the fine quality, jet-black flint from which they fashioned tools, weapons, and ceremonial objects" (English Heritage, 2022). This illustration shows the results of the work of miners, not just the objects made out of it, but also that the earth can become "lunar-like" because of it. (C) The first published representation of an Acheulian hand axe was drawn by Antiquarian John Frere in 1790. Frere's drawing, which has become a basic "Horizon Marker" of the Lower Paleolithic cultures studied by archaeologists today, is an example of how a drawing can turn into an established "fact." (D) Skouriotissa spoil heaps. Skouriotissa, on the island of Cyprus, is one of the oldest operating copper mines in the world. In 1200 BCE, the forests of Cyprus were all cut to provide fire wood for smelting copper, and mounds of slag piled up around the mines that can still be seen today in the Troodos Geological Park (Given et al., 2007). Archeometallurgical studies record Cyprus's mining history through archaeological survey of the Anthropocene stratified mounds that dominate the landscape, pointing to the fact that humans have throughout history changed the Earth. (E) Oryctolagus cuniculus. The original European wild rabbits evolved ~4,000 years ago in Iberia. The Romans in Spain talked about hare-like diggers of underground tunnels (oryctolagus cuniculus). Visiting Phoenician merchants referred to part of Iberia as "I-shephan-im," which means land of the rabbits. This was translated as "Hispania" or Spain as we know it today. Mining was compared to the work of rabbits digging holes in the ground, and Spain actually owes its name to them. (F) The Vredefort Impact Crater in South Africa, which is one of the oldest (2023 ± 4 Ma) and most well-known impact structures on Earth with a diameter of roughly 250–300 km. It is named after the town of Vredefort, which is near its center, and hosts a productive mining industry. The shovel shows the enormous impact a meteorite like this had on the South African continent. (G) Ruina Montium. After Augustus had annexed the territory of Las Medulas in the northwestern region of present-day Spain as part of the Roman Empire around 25 BCE, the exploitation of that land began. Hydraulic mining, which Pliny the Elder referred to as *ruina montium* (ruin of the mountains), allowed precious metals to be extracted on a proto-industrial scale. Even this early, mountains were changed completely by mining. Or should we say ruined? (H) The Fourty-Niners, California Gold Rush (1848–1855). California's name became indelibly connected with the Gold Rush, as the 49er gold diggers and fast success in a new world became known as the California Dream. In the years after the Gold Rush, the California Dream spread across the nation. It was not the original American Dream of the Puritans, of men and women content to accumulate their modest fortunes a little at a time, or of Benjamin Franklin's "Poor Richard." The new golden dream was the dream of instant wealth, won in a twinkling by audacity and good luck, which became a prominent psychological character of the collective American society (Brands, 2002). The year 1849 turned the American dream upside down.

hit hard. At that time, however, toolmakers specialized in making obsidian tools.

Groups of *Homo erectus* left Africa around 300,000–200,000 years ago, moving toward Egypt and the Near East (Fig. 2). In these areas they started using flint or chert for making tools, instead of only obsidian. At that time, they may have discovered that hitting chert sparked fire. Especially when considered in combination with the second point of Gowlett and Wrangham (2013), who stress the growing use of fire for cooking food (the "cooking hypothesis"), and the argument of Spier (2015), who suggested the growing brains of these early humans increased their need for energy, it seems probable that by trial and error, fire control had already started in this period of *Homo erectus* in Egypt and the Near East. Zeigen et al. (2019) found proof of incinerated cherts and hearths from the Middle Paleolithic (around 200,000 yr B.P.) in Amud Cave, Israel, which suggests chert was deliberately used to keep fire going. In the Tabun Cave, Israel, in layers older than roughly 350,000 years, almost none of the flints are burned, but in every layer thereafter, many flints show signs of exposure to fire (Shimelmitz and Kuhn, 2013). If flint is hit with pyrite, fire sparks are produced even more easily. Pyrite is widely distributed and forms under extremely varied conditions. Also, it was used in upper Paleolithic times in Denmark and Holland (Stapert and Johansen, 1999). There seem to be a lot of arguments, from many different disciplines, which suggest early control of fire by *Homo erectus.*

The argument of Gowlett and Wrangham (2013), that *Homo neanderthalensis* (Neanderthal hereafter) could not make fire, and thus *Homo erectus* could not control fire either, has since been contradicted. Neanderthals supposedly made flint tools only for animal butchering, but Sorensen et al. (2018) have shown that the typical Neanderthal flint tools, such as bifacial hand axes from late Middle Paleolithic France, especially those attributed to the Acheulean (Fig. 3C) or the more recent Mousterian lithic industry, support the hypothesis that these bifaces were sometimes used as fire-making tools. Sorensen et al. (2018) suggests that Neanderthals were almost certainly making fire during the last glacial period, ~100,000–35,000 years ago. If indeed it is true that Neaderthals were able to make fire with flint tools, their ancestors, *Homo erectus* in Egypt or the Near East, might also have had these skills. When added to the geological occurrence and mining of resources like flint in these areas, these different arguments make it more plausible that *Homo erectus* in Egypt and the Near East had already gained some control over fire. However, the final proof has yet to be found.

Any knowledge of controlling fire by Neanderthals would surely have been conveyed to early *Homo sapiens,* who were contemporaries of the Neanderthal. Fire certainly could have helped early Sapiens to adapt to and survive the freezing cold climate of the last glaciation. People used fire for heating, cooking food, and baking clay to make pots (e.g., Rafferty, 2020).

Some of the DNA results by Fu et al. (2016) reveal big changes in prehistoric human populations that are linked to the end of the last Ice Age (Weichselian glaciation). One of these changes in DNA occurred ~19.000 years ago. As the ice sheets retreated, Europe became repopulated by prehistoric humans from southwest Europe (e.g., Spain). The other big change shown by the DNA results took place after 14,000 BP, at the time agriculture spread. It seems that groups of Sapiens from the East replaced the Sapiens in Europe at that time, and took agriculture with them (Fu et al., 2016). Fields were burned to start agriculture, while metal ores were smelted to find new uses for them. It marks the end of the Stone Age.

3. THE BRONZE AGE

Copper is a soft and weak metal, which was not quite suitable for making hard and durable tools such as spear or arrowhead points, knives, scrapers, or chisels, etc. Chert was still the preferred material in the transitional archaeological age between the Stone Age and the Bronze Age. This transitional period started around 7,000 years ago in Europe and the Near East, and lasted until ~5,000 years ago with the discovery of bronze. The addition of tin (or arsenic) to copper increased its hardness and made casting much easier, which revolutionized metalworking techniques, and signaled the start of the Bronze Age.

The concentration of copper in the crust of the Earth is much less than iron (50,000 ppm and 70 ppm, respectively), but still relatively large in comparison with silver (0.1 ppm) and gold (~0.005 ppm) (Valera and Valera, 2003). The discovery of copper probably happened serendipitously. Copper-rich carbonates such as malachite have an appealing leaf-green color, often associated with deep-blue azurite. The finds of beads suggest that Stone Age inhabitants liked these colored materials (Radivojević and Kuzmanović-Kvetković, 2014). The oldest dated record of copper smelting was reported by Radivojević et al. (2010) in a ca. 7000-year-old settlement near Belovoda and Pločnik in eastern Serbia. Archeological excavations in these sites revealed the presence of malachite ornamental beads associated with pieces of copper slag, as well as copper-casted objects such as axe heads, fishing hooks, fibulas, bracelets, and even figurines. Along with these copper objects, ceramic objects were found, used for smelting and casting copper from the abundant malachite found in the surroundings of these settlements (Radivojević and Kuzmanović-Kvetković, 2014).

Malachite contains no other metals than copper, and heating it over a very hot fire or in a well-ventilated oven would produce only molten copper. Therefore, copper was the first metal that humans used to make weapons, tools, and jewelry—a development that marked the end of the Stone Age. The famous 5300-year-old mummy known as Ötzi, found in 1991 in Val Senales in the eastern Italian Alps, carried an axe head made of 99.7% pure casted copper, indicating that the use of copper tools was common in this age (Bonani et al., 1994).

In Cyprus, copper started to be mined and smelted in the 5th millennium BCE. Cyprus is a geologically unique island, with massive volcanic sulfide ore deposits of the ancient obducted ocean floor (Given et al., 2007, and references therein). Cyprus is where the word copper, *cuprum* in Latin, originates. Copper mining on Cyprus reached a large, quasi-industrial scale around 2300 BCE and demand did not collapse until around 400 CE, when the decline of the Roman Empire was well under way (Fig. 3D).

Bronze is a copper alloy containing small quantities of other elements, including toxic metalloid arsenic and more workable metals such as tin. Melting down tin (or arsenic) together with copper and mixing it in small proportions would form a metal much harder than copper, but also more brittle and less malleable. Bronze was much better than pure copper for casting durable, sharp tools such as swords, knives, and spear and arrow points. This discovery revolutionized metalworking techniques, and signaled the transition of the copper period (sometimes called the Copper Age) to the Bronze Age.

The concentration of tin in the Earth's crust is ~2 ppm, so compared to copper (70 ppm), it is a relatively rare element (Valera and Valera, 2003). In the Earth's crust, tin is found as an oxide, chiefly cassiterite. Tin has a very low melting point of ~232 °C. About 85% of all historically mined tin, ~27 million tons, is from a few ore provinces within large granite belts. These are, in decreasing importance, Southeast Asia (Indonesia, Malaysia, Thailand, and Myanmar), South China, the Central Andes (Bolivia and southern Peru), and Cornwall, UK. Alluvial placer deposits were usually the starting point for tin mining, and have provided at least half of all tin ever mined (e.g., Lehmann, 2020).

3.1 The Euro-Asian Trade of the Bronze Age

The oldest production of tin-bronze is found in Anatolia, ~3500 BCE, and other evidence of tin used for making bronze around 3000 BCE appears in the Near East and the Balkans (Bailey, 2000). Around 2500 BCE, Europe's most important tin mining district appears to have been located in the Ertzgebirge on the border between Germany and Czech Republic. From there, tin was traded north to the Baltic Sea and south to the Mediterranean following the Amber Road trading route.

The Near East had historic trade relations in the eastern direction. In Assyrian trading settlements in Anatolia before 2000 BCE, a lively trade in tin existed, which probably originated in present-day Afghanistan. From 2000 until 1500 BCE, Uzbekistan, Afghanistan, and Tajikistan appear to have exploited their sources of tin, carrying these resources to the east (China) as well as the west (Middle East) along what was later known as one of the Silk Roads, crossing Central Asia (Cierny and Weisgerber, 2003). At that time, bronze was growing important in China. There have been discussions on the question of whether bronze making originated independently in China. It seems that the Indo-European tribes from the northern steppe in Anatolia and Eastern Europe may have been acquainted with the use of copper and bronze first, and introduced the technique of bronze making to China (Mei and Chan, 2017). Although bronze making was probably not a Chinese invention, and likely social appropriation instead, the way bronze was used in China (for vessels, for example) became very much a Chinese ritual (Mei and Chan, 2017).

Known sources of tin mining in Asia in ancient times include the southeastern tin belt that runs from Yunnan in China to the Malay Peninsula in Southeast Asia. Thus, it seems that around the 2nd millennium BC, a trade route network was in use between China and Central and Western Asia, long before the official Royal Silk Road of the Han dynasty. It was mostly a Pontic Steppe route controlled by nomadic horse riding tribes of the Yamnaia culture. From mines near the border of China and Afghanistan, jade and horses were being traded to China, and it is suggested that Afghanistan metals, like tin, were being traded to the Near East (Cierny and Weisgerber, 2003).

Berger et al. (2019) demonstrated that tin in the form of ingots from Egypt and the Near East did not come from Central Asia, as previously assumed, but from tin deposits in Europe. Tin artifacts from Israel, for example, largely matched the isotopic composition of tin from Cornwall and Devon in Great Britain. Copper and tin mining in Britain may have started ca. 2500 BC, although archaeologists suggest the Bronze Age culture began later. (The period from 2500 BC to 1900 BC has been called the "Late Neolithic/Early Bronze Age" [Pryor, 2003], in recognition of the difficulty of exactly defining this boundary.)

Early tin exploitation appears to have been centered on placer deposits of cassiterite, and was therefore easy to mine in the beginning. The tin from Cornwall seems to have been shipped by boat ~480 km northward to Great Orme in North Wales, where copper was found (suggesting that bronze, the mixture of tin and copper, may have already been known there at the time). The parent mineral used for copper smelting was chalcopyrite, which is relatively common in igneous rocks. There were not only signs of a thriving trade between Cornwall and Great Orme, but this was also a period of intensive connections between South England, Spain, and the mainland of Europe. The tin ores were brought over land to the Mediterranean, and probably sent by boat further to the Near East (Benvenuti et al., 2003; Valera and Valera, 2003). Because of the growing demand for tin from Cornwall, the people had to mine tin in larger quantities and dig deeper. Since 2006, 48,700 acres of Cornwall and West Devon's mining landscape have been a UNESCO World Heritage Site.

Discoveries of tin from Cornwall in ingots from Egypt and the Near East show that in the Bronze Age, complex and far-reaching trade-route webs existed between Western Europe and the Eastern Mediterranean. Raw materials like tin as well as amber, glass, and copper could have been the driving force of this early international trade network. The Uluburun shipwreck, a 14th-century BCE vessel discovered off the coast of Turkey, was carrying raw material trade goods, such as copper and tin ingots, ivory, and glass disks, and was likely on its way to workshops in Mycenaean Greece (Cartwright, 2017). Green (2020) states that in some Arabic and Persian accounts from the 13th and 14th centuries, the early export of tin from Cornwall to Egypt and Iran was also mentioned. These early trade movements suggest that during the Bronze Age, there were a series of trade routes in which tin played a role, likely from Britain to the Near East, as well as between China and the Near East, quite a while before the official and famous Royal Silk Roads of the Han Dynasty. In his research on the silk roads, Frankopan (2015) did not mention tin as an important trading item, perhaps because his study focused strongly on Persia, which seems to have used the poisonous arsenic instead of tin for making bronze. Tin "bypassed" the Persian plateau en route to Mesopotamia (Daniel et al., 2000). Both the Chinese trading routes to the Near East and the European routes between England and the Eastern Mediterranean were part of an Eurasian human web spanning between Western Europe and Eastern China (McNeill and McNeill, 2003). McNeill and McNeill (2003) suggested that this "Old World Web" started with the formation of civilizations from 3500 BCE and resulted in "an ever thickening web throughout most of Eurasia and much of Africa by 200 CE"(p. 41). Early tin trade from 2500 BCE may have played a bigger role in shaping this early trading web than was realized by most historians.

3.2 The Tinners' Hares

A glimpse of the oldest tin trade between East and West comes from the legend of the Three Hares (or rabbits), a circular motif or meme appearing in sacred sites from the Middle and Far East to the churches of Devon, England, as well as in historical synagogues in Europe. The iconography features three hares chasing each other in a circle (Fig. 4B).

The figure of the three hares has a threefold rotational symmetry. Each of the ears is shared by two hares, so that only three ears are shown. Some claim that the Devon name for this symbol, Tinners' Hares, is related to local tin miners adopting it. The mines generated wealth in the region and funded the building and repair of many local churches, and thus the symbol may have been used as a sign of the miners' patronage (Greeves et al., 2016).

The motif of the three hares is used in a number of European churches, particularly in England, France, and northern Germany, and especially in the churches of Devon (Fig. 4A). One hypothesis pertaining to the spread of the motif is that it was transported from China across Asia and as far as the southwest of England by merchants traveling the Silk Road, and that the motif was transported via designs found on expensive oriental ceramics. However, the fact that the majority of representations of the three hares is found in northern European churches supports the alternative view that the three hares occurred independently as English or maybe early German symbols. The hare frequently appears in the form of the symbol of the "rotating rabbits." An ancient German riddle describes this graphic as "Three hares sharing three ears, yet every one of them has two" (Singmaster, 2004) (Fig. 3E).

4. THE IRON AGE

Metallic meteoritic iron was used by various ancient peoples thousands of years before the Iron Age started. Meteoritic iron, a characteristic iron-nickel alloy, came from meteorite falls throughout the long history of Earth. Such meteoritic iron, in its native metallic state, required no smelting of terrestrial ores, but just forging (Fig. 3F).

The Iron Age, which followed the Bronze Age and started in different regions between 1200 and 600 BCE, is characterized by the preindustrial production of iron tools and weaponry through iron metallurgy. Iron's abundance in rocky planets like Earth is due to its abundant production during the fusion and explosion of

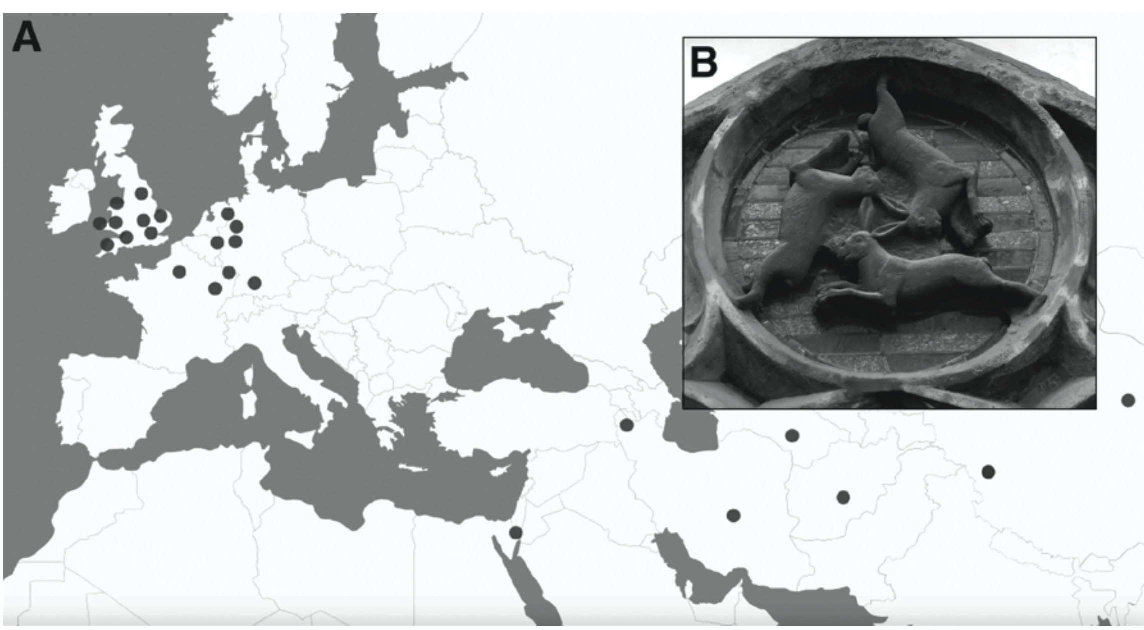

Figure 4. Three hares symbol. (A) Occurrence of the three hares symbol in churches, synagogues, and other sacred places from Britain to China (black dots). Image by Morn at the English-language Wikipedia. (B) Window of Three Hares in the Cathedral of Paderborn (Germany). Image by Wikimedia Commons, User: Zefram. See https://en.wikipedia.org/wiki/Three_hares.

several supernovae. The precipitation of iron on the deep seafloor in thick ferric layers is part of a crucial moment in the evolution of life on this planet, known as the Great Oxygenation Event (GOE). In early geologic time, there was very little free oxygen in the atmosphere. Ferric iron precipitates started to form some 3.7 billion years ago onwards, more or less at the same time as the first life (prokaryotes) appeared on Earth and photosynthesis began. The oxidized ($Fe3+$) iron precipitated on the seafloor in layers of banded iron formations (BIF) during the GOE. Widespread BIFs have been crucial for the enormous amounts of iron used in modern human history (e.g. Westbroek, 1992).

4.1 The Bronze Age Collapse

Minoan culture on Crete flourished from ~3000 BCE until ~1200 BCE. In 1430 BCE, the Mycenaeans from mainland Greece destroyed Knossos, and wrested control of maritime trade from Minoan Crete. It started a time of prosperity for mainland Greece that lasted nearly 200 years and weakened the position of the Minoans. However, before these changes in power, around 1600 BCE, the previously dormant Santorini volcano suddenly woke up, producing one of the largest explosive eruptions in historical time. Pyroclastic tuffs from the "'Minoan Eruption" in sediment core samples from the seafloor between Santorini and Crete demonstrated that the eruption of 1600 BCE produced at least 39 km^3 of ejecta, much more than was assumed before (Sigurdsson et al., 2006). The tsunami that destroyed Aegean settlements was caused either by the collapse of the caldera walls or by the large number of pyroclastic flows (Nomikou et al., 2016). The eruption of Santorini was comparable in force only to the eruption of Mount Tambora in 1816, an event that caused a global "year without a summer." There is a general consensus among historians that the Santorini event caused the end of Mycenaean dominance in the Mediterranean world, as well as almost the end of the Minoans of Crete.

Around 1250 BCE, moreover, several hundred years after Santorini's outburst, political unrest became evident in Greece and also in Asia Minor. At the same time, the so-called "Sea Peoples" arrived on the scene. The Sea Peoples appear to have been an alliance of Western Anatolian states, and maybe the Mycenaeans joined them. A wave of destruction spread across the Eastern Mediterranean, and many urban centers and in particular their palaces fell victim. Dozens of port cities in Cyprus, Syria, and Palestine were destroyed. Hattuša was also apparently wiped out, and with it the Hittite Empire. Later, Troy went up in flames, and despite partial reconstruction, was condemned to insignificance thereafter. Tiryns, Pylos, and other locations in mainland Greece also perished in the seemingly all-encompassing devastation that created the start of the "Greek Dark Ages" (Drews, 1997).

4.2 Iron technology

The Bronze Age collapse may be seen first of all in the context of a technological history that saw the slow, comparatively continuous spread of iron-working technology in the Eastern Mediterranean region. The combination of carbon dating, archaeological context, and archaeo-metallurgy indicates that it is likely that the use of ironware made of steel had begun in the 3rd millennium BCE in Central Anatolia (Akanuma, 2008). The development of weaponry was stimulated by bronze as well as iron—already in the Bronze Age, fortified settlements appeared in the area around 1800 BCE, showing the belligerent character of the times. These were the effects of the spread of metal-based developments in military weapons and tactics. Between the 12th and the 10th centuries BCE, iron took over bronze in the production of tools and especially weapons. Drews (1997, p. 97) stated that the catastrophe can most easily be explained as "...a result of a radical innovation in warfare, which suddenly gave to 'barbarians' the military advantage over the long established and civilized kingdoms of the eastern Mediterranean."

The Iron Age did not start because of the consideration that iron would have "better" properties than bronze. In the beginning, blacksmiths even thought of bronze as superior to iron. Iron has its disadvantages; iron smelting from iron ores is more difficult than tin and copper smelting. While tin and copper can be cold-worked or smelted in relatively simple furnaces, such as the kilns used for pottery, and cast into molds, iron requires much higher temperatures, and can be fused only in specially designed furnaces. Iron is a common impurity in copper ores, and iron ore was sometimes used as a flux, so metal blacksmiths knew the material. Still, humans mastered the technology of smelting iron only after several millennia of bronze metallurgy. The problem with melted iron was that it immediately starts rusting when the melting material cools in the air or in water. This changed when it was realized that the quality of iron could be improved by heating the raw iron ore in a bed made of charcoal (i.e., pure carbon), which, in a highly reducing and much hotter environment, led to the discovery of carbon steel. Only with the capability of producing carbon steel did ferrous metallurgy result in tools or weapons that are equal or superior to bronze.

The process of ferrous metallurgy in the Near East could have been stimulated by the greatly reduced availability of tin. Long-distance trade contacts built up during the Bronze Age were distorted by the developments around 1200 BCE. The invasions of the Sea Peoples not only destroyed palaces and monuments, but also influenced trade. Tin from southwestern England (Cornwall and Devon) was exported via southern France to the Mediterranean, and this trade must have suffered from it. It could have caused shortages of tin, which would emphasize the need for an alternative to tin-bronze. Iron, easily available, would have been a logical successor. Blacksmiths may have turned to iron as an alternative, which might have accelerated the use of iron instead of tin-bronze around the first millennium BCE.

Long-distance trade in Asia may have been temporarily frustrated because of the loss of riches in the Near East, but this does not seem to have caused a sudden change in Asia. In China and Southern Asia, there was enough tin to still make the bronze objects they wanted. In China, bronze remained important for a long time. The start of the Iron Age there is placed in the transitional period of ca. 500–100 BCE during which ferrous metallurgy was present, although not dominant. During the 8th century BCE, warriors from the steppe were often employed by nations in the Near East, and these returning soldiers may have brought knowledge of iron working back to their homeland, and by the start of the 6th century BCE, the practice was widespread in the Pontic steppes (Jettmar, 1971). In addition to bronze and iron working, gold and copper working were also present in Scythian society of the steppe. In Central Asia, the Iron Age is thought to have begun when iron objects appeared among Turkic Hyghur groups, in the present-day territory of Xinjiang (northwestern China) between the 10th and 7th centuries BCE. In southern India, however, iron immediately succeeded stone as a material for tools and weapons, skipping the Bronze Age; iron weapons began to come into use there ~500 BCE. Also in Europe, iron and steel began to play a significant role as a material for the manufacture of tools and weapons in the second half of the first millennium BCE. In Asia as well as in Europe, the Iron Age was a time of many small, warring states.

The technical revolution, accomplished by the spread of iron and steel, increased humankind's control over nature: it afforded the possibility of clearing large tracts of forest land for planting, expanding, and perfecting irrigation and land amelioration structures, and improving agriculture in general. The development of handicraft production accelerated, particularly of weapons and forged articles. Artisans, from shoemakers and stonemasons to miners, now had better tools at their disposal. Road construction was made easier, military equipment was perfected, commodity exchange expanded, and metal coins were used as exchange currency.

The end of the Iron Age, like the beginning of it, varies depending on the region under consideration. If we look at the use of iron to make tools and weapons, as well as the importance of other developments from that time, one might say we still live in the Iron Age now. The Iron Age stands much closer to our own than does the world of the Bronze Age. However, metallurgical progress—from bronze to iron—was only the most tangible of the innovations. More significant innovations following it, marking the end of the Paleolithicum, were the growth of national and republican political forms and the development and spread of alphabetic writing, monotheism, and eventually rationalism (Drews, 1997). The Iron Age, as defined by archaeologists, is considered as ending with the beginning of the historiographical record. For the ancient Near East, the establishment of the first Persian Empire ca. 550 BCE is usually taken as a cutoff date, while in central and western Europe, the Roman conquests of the 1st century BCE serve as a marker for the end of the Iron Age.

While humankind also profited from iron tools for agriculture and construction, McNeill and McNeill (2003) speak of "democratization of warfare," because using iron for weapons put arms in the hands of the masses for the first time. This set off a series of large-scale movements of peoples that continued for 2,000 years and changed the face of Europe, Asia, and the rest of the world.

5. GOLD

Like quartz, gold can often be found in mountain belts originating at former colliding plates. For example, many of the Iberian gold deposits are of this type, and were generated ~300 million years ago, when Gondwana collided with the northern continents to assemble the supercontinent of Pangaea. The easiest gold to find and mine is in placer deposits. In many gold-rich regions, gold can be found as nuggets and as smaller grains within the sand and gravel sediments of rivers, both modern rivers and ancient ones, often concentrated in placers at the bottom of the riverbed. Grains of gold are first eroded from older rock, commonly from gold-bearing quartz veins, then transported, and finally deposited as fluvial sediment. Gold has a much higher density than quartz grains, so it is density-sorted from quartz grains, accumulating at the bottom of sand deposits. Gold in quartz veins is mined in open pits and underground workings in many places around the world (García-Moreno et al., 2017).

Gold is normally not soluble, does not oxidize, is durable, and is chemically inert (it does not easily alloy with other non-noble metals). That makes it very suitable to use as money. When coins were made of precious metals, they had a certain real value in gold or silver. Gold has been the one material that is universally accepted in exchange for goods and services (although silver was long the standard medium of smaller payments in the world's trading systems) (Gregersen, 2017). Also, gold was a luxury article for jewelry for the rich. Gold discovered in the Nuba region made Egypt very prosperous by 1500 BCE, and it was there that the foundation for gold as an international trade standard was laid. In 1091 BCE, gold began to play an essential role in China. Small gold cubes were legalized as a form of money. Several hundred years later, in 560 BCE, the first gold coins were struck in Anatolia (present-day Turkey) shortly after the ancient Greeks started extracting gold from mines in the Near East and around the Mediterranean. Gold also played an important role in the Roman Empire for coins as well as jewelry. In 58–51 BCE, Roman general Julius Caesar captured an enormous amount of the coveted precious metal during his conquest campaign in Gaul. In this way, he could pay each of his soldiers 200 gold coins, and at the same time pay off all of Rome's debts. The gold coin *aureus* was originally a widely accepted means of payment for years until it was replaced by the *solidus* currency in 309 CE. A persistent feature was the inflationary debasement and replacement of coins over the centuries. People lost confidence in the coins legitimately issued by the central government. Despite Emperor Diocletian's introduction of the gold *solidus* along with monetary reforms, the credit market of the Roman Empire never recovered its former strong position. The Western Roman Empire collapsed in 476 CE; a weakening of imperial powers and increasing pressure from invading tribes outside

Roman culture contributed to the collapse (e.g., Montanari et al., this volume, Chapter 27).

5.1 Gold and Mining

The main valuable metal mining regions of the Roman Empire were in West Europe (Iberia, Gaul, and Britain) and in the Near East (Macedonia, Thrace, Anatolia, and Cyprus). Roman historian Gaius Plinius Secundus (Pliny the Elder, 23–79 CE) points out that the mining of gold, tin, iron, and lead underwent a radical transformation during the period of Romanization (Pliny the Elder, 1855). Romans conducted intensive, large-scale mining of alluvial deposits, by means of open-cast mining and underground mining, from the reign of Octavius Augustus up to the early 3rd century CE. An example was gold mining in Iberia. Fernández-Lozano et al. (2015, p. 356) wrote: "Hidden under the vegetation and crops of the Eria Valley, in León (Spain), there is a gold mining network created by the Romans two thousand years ago, as well as complex hydraulic works, such as river diversions, to divert water to the mines of the precious metal."

Miners would dig narrow cavities down into a mountain, and then fill the cavities with water, creating pressure high enough to fragment thick rock walls. Human enterprise and drive started to shape the landscape, creating forms analogous to the ones excavated by nature's actions, which took much longer periods of time. Pliny wrote about it with abhorrence. He felt that the Roman gold thirst was boundless, and he complained that engineers in Spain had developed the most impressive method of stealing Mother Nature's precious treasures (Lewis and Jones, 1970) (Fig. 3G).

5.2 Gold and Trade

There is evidence in the first centuries CE of the Roman Empire gold was already being traded between the western sub-Saharan Africa and the Mediterranean region. Trade items from northern Africa and the world prior to the 8th century CE were discovered at the eastern Bend (Magnavita et al., 2009). Since native gold is found there in abundance, it would be interesting to know whether gold from that area matches chemically with pre-Arab North African gold coins (Fenn et al., 2009). Wilson (2012) suggests that the Saharan trade in the Roman period consisted of trade networks, instead of long distance trans-Sahara trade. He argued that in focusing chiefly on trans-Saharan commerce, much previous research has misunderstood the nature and importance of Saharan trade in antiquity. Relatively few types of goods were traded all the way across the Sahara from south to north or vice-versa in the Roman period. Rather, we should be thinking in terms of a network of interdependent sub-webs of short-, medium- and long-distance exchange; the trans-Saharan traffic was only one part of this network.

The Islamic conquest of North Africa and Spain in the 8th century CE recovered contacts between West Africa and the West Mediterranean, from Morocco to Spain. From 711 to 718 CE, the Muslim conquest of the Iberian Peninsula, which was followed by a period of several hundred years during which most of the Iberian Peninsula was known as Al-Andalus and dominated by Muslim rulers. Eventually, this led to an influx of gold into Iberia via the trans-Saharan caravan trade from source regions in sub-Saharan West Africa. Arab merchants exchanged salt, extracted from sebka deposits at Taoudenni, in the middle of the Sahara in modern Mali, for gold, harvested from rich placer deposits called Wangara, probably along the Senegal River (Bovill, 1968).

The most active period of the *Reconquista* against the Muslims in Spain took place during the High Middle Ages, resulting in Christian control of most of Spain by 1250 CE. After the capture of Granada, the last Islamic kingdom in Iberia, in 1492, African gold no longer reached Spain in large quantities by the trans-Saharan route. The search for a way to outflank the Arab-controlled trans-Saharan gold caravan route may have been one of the motivations for Prince Henrique of Portugal, alias "Prince Henry the Navigator," to begin 15th-century Portuguese exploration along the west coast of Africa and maritime expansion (García-Moreno et al., 2017). Discoveries by Italian navigators Christopher Columbus and Amerigo Vespucci of American empires brought two whole new continents to the attention of the Spanish, who rapidly undertook exploration (and exploitation) of the New World. One of the goals, next to spices, was to find resources of precious metals. The most abundant gold resources were found in Nueva Granada, now Colombia, which seems to have been a richly endowed gold province in Andean South America. Gold placers were exploited in much of Colombia, and additional gold was taken from pre-Columbian tombs (García-Moreno et al., 2017).

The (Spanish) Price Revolution highlights the transition of agricultural society to monetary society. The high rate of inflation that occurred during this period across Western Europe caused prices to rise on average roughly six fold over 150 years. Economic and social historians offer different explanations for these changes, such as population growth and government measures, but many economists and historians believe this high inflation was started by the large influx of gold and silver of the Spanish treasure fleet from the New World, including Columbia, Mexico, Peru, and the rest of the Spanish Empire. Fisher (1989) tested the monetary interpretation, suggesting that American gold or silver coins (specie) drove European prices, a mechanism entailing the quantity theory of money buttressed by the specie-flow. Specie entered Spain, increasing Spanish prices, and then spread over Western Europe as a result of the Spanish balance-of-payments deficit, enlarging European monetary bases and price levels. The economic and social effects were felt strongly in Europe and America.

250 years later, something similar happened. When gold was found by James W. Marshall at Sutter's Mill in Coloma, California, USA, the population of San Francisco increased quickly from 200 in 1846, to 36,000 by 1852. During that time, roads, schools, churches, and businesses were built, along with other towns, eventually leading to the establishment of California as a state in 1850 (Fig. 3H). This Gold Rush had severe effects on the demography of the New World. Retrospectively, some historians today see it as

the start of capitalist society (e.g., Brands, 2002), and others stress the increasing social differences between rich and poor. While the Californian population increased, the Native American population dramatically decreased. Thousands of enslaved Native Americans were used as a free source of labor. All this was encouraged, carried out, and tolerated by state authorities and militias. Kroeber (1925) estimated that the indigenous population of California decreased from perhaps as many as 150,000 in 1848 to 30,000 in 1870 and fell further to 16,000 in 1900. (Fig. 5I).

6. COAL

Coal is particularly important for human history because it was a new external source of energy that influenced societal

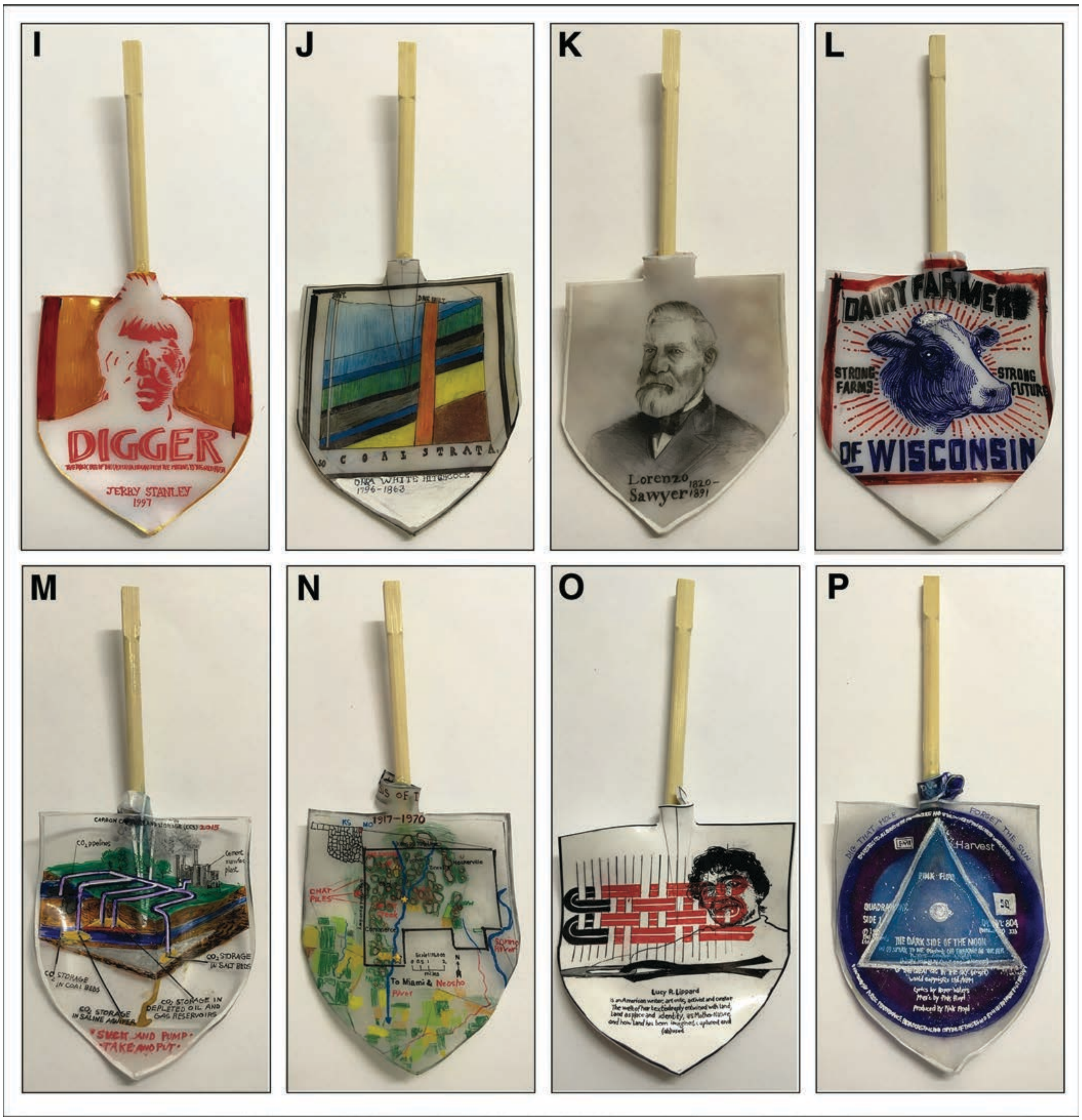

Figure 5.

developments on a global scale. In a human and economic historical account from traditional farming to industrial land use of the Nalon River in Asturia, García-Moreno et al. (2019) explained the natural evolution in the Nalón area and the recent environmental changes in the whole Nalón River basin following these developments. The geological carbon cycle formed big coal deposits in which much energy is stored. The evolution of life has influenced the carbon cycle for the last 3,800 million years, in particular since the Cambrian "Explosion" of life. At the end of the Silurian Period (420 Ma), plants conquered the land. During the Carboniferous period, enormous tree-sized plants and ferns grew and reproduced quickly, leading to an O_2 concentration in the atmosphere that may have been greater than the current concentration. Billions of tons of plant remains were buried in the bedrock over 300 million years, thus storing great amounts of energy acquired by photosynthesis (Fig. 5J). This energy buried in the earth over millions of years was suddenly released by the anthropogenic exploitation of coal (García-Moreno et al., 2019).

6.1 Coal Mining and the Industrial Revolution

The formation of coal usually takes place in one of two situations: (1) a rising water level that perfectly keeps pace with the rate of plant debris accumulation, or (2) a subsiding landscape that perfectly keeps pace with the rate of plant debris accumulation. Obviously, under these conditions the plant debris (peat) is not oxidized. Most coal layers are thought to have formed under condition 2 in a delta environment. "Although terrestrial plants necessary for the development of coal did not become abundant until Carboniferous time (358.9 million to 298.9 million years ago), large sedimentary basins containing rocks of Carboniferous age and younger are known on virtually every continent" (Kopp, 2020).

The history of coal mining goes back thousands of years, with early mines documented in ancient China, the Roman Empire, and other early historical economies. The Chinese used coal to produce iron and steel; in 1080 CE, their iron production exceeded that of Europe in 1700 CE. But Northern China,

Figure 5. (I–P; note: part labels continued from Fig. 3) Dig History series, Paula Metallo (2022; www.paulametallo.com: HOLES section, New Works), Shrinky Dink® plastic, mixed media, and chopsticks, 8 × 18 cm. (I) Jerry Stanley's Digger. Ironically, the Native Californians were contemptuously referred to as diggers for their practice of digging up roots to eat (Stanley, 1997). Digging can have different outcomes for people. Some win, some lose. (J) Orra White Hitchcock's shovel. Geologist Edward Hitchcock has made important representations of the coal strata of the Carboniferous Period, with "indispensable aids" from his wife, Orra White Hitchcock (1796–1863). She was America's earliest female scientific illustrator and artist. Her work is a time-focused chronicle of the scenic and botanically and geologically diverse Connecticut River Valley in western Massachusetts. Her art was integral to the work of her husband. Edward Hitchcock acknowledged her essential contributions for his lectures, citing her drawings as more powerful than his pen. Drawings can be more powerful than a pen. (K) Lorenzo Sawyer (1820–1891). During the Industrial Revolution in the United States, the environmental problem caused by mining was raised by Lorenzo Sawyer (1820–1891), a famous American lawyer and judge. In 1883, San Francisco Bay was estimated to be filling up with silt at a rate of 30 cm per year. Huge cliffs were carved by mighty streams of water, washing away entire mountains of gravel, imitating geological erosion that would have taken hundreds of thousand years. Debris, silt, and millions of liters of water used daily by the North Bloomfield Mining and Gravel Company caused extensive flooding, prompting Sacramento valley farmers to file the lawsuit "Woodruff v. North Bloomfield Mining and Gravel Company." On 7 January 1884, Judge Lorenzo Sawyer declared hydraulic mining illegal. Sawyer's decision is widely considered to be California's first environmental law. A turning point in history? (L) The Last Stand: Wisconsin dairy farmers' fate. In *The New Yorker*'s 17 August 2020 issue, Dan Kaufman interviewed dairy farmer Jerry Volenec, who stated, "It's not the farming I was brought up with. It's not really even farming anymore. It's mining. We're extracting resources and shipping them away, and they're not coming back. There's no cyclical nature to it. It's a straight line out" (Kaufman, 2020). In this article, Kaufman (2020) provided a poem by the farmer, who expressed his distressed sentiment toward industrialized farming. In the poem "Get Big or Get Out," Volenec uses the metaphor of being told to dig a hole for his neighbor and finally to dig a hole for himself. Neither of them were needed any longer. (M) The Big Suck, or DAC (direct air capture units, 2015). The machines suck carbon dioxide from the atmosphere and pump it into the sedimentary rock formations below. Pumped back where it was taken and where it had once been for a long time. Humans quickly dig up what was built up in geological time, and humans also try to quickly undo it. But is it a durable solution? (N) Picher, Oklahoma, 1917–1970. A boomtown of lead and zinc mining. By the time operations ceased in 1970, over 10 million tons of lead and zinc ore had been removed from the area. The companies left behind an environmental disaster that was declared, in 1983, to be one of the most toxic areas in the United States. This monumental waste site has been continually expanding through the motion of the wind, rivers, and aquifers. The term "chat" is applied to fragments of siliceous rock, limestone, and dolomite waste rejected in the lead-zinc milling operations in the first half of the 20th century. These chats, found as huge man-made mounds, look like psoriasis on the Earth's surface from above. Today, ~100 million tons of chat remain in the states of Oklahoma, Kansas, and Missouri. The U.S. federal government has spent 301 million dollars since 1983 chewing and digging away at the chat piles, and will spend an estimated 178 million in the next 20 years (EPA, 2019). Psoriasis of the earth, it itches. (O) Lucy R. Lippard. A contemporary American writer, art critic, activist, and curator. The weft of her writing (Lippard, 2014) is deeply entwined with land as place and identity, land as Mother Nature, and how land has been imagined, captured, and (ab)used. She has been a persistent advocate of excavating the truth about human's damage to the Earth's surface and how we have eroded the foundation of rock formations, damaged and weakened gradually and insidiously. In honor of a writer and activist who cared about all of this. (P) Pink Floyd. The lyrics of Pink Floyd's song "Breathe (In the Air)" from their 1973 album *The Dark Side of the Moon* by David Jon Gilmour, Richard Wright, and Roger Waters are an anthem to the appreciation of human life. Floyd's saying "breathe in the air" can be interpreted as an urge to work toward a healthier environment and stop digging holes one after the other (see the lyrics of "Breathe (In the Air) at https://www.azlyrics.com/lyrics/pinkfloyd/breathe.html, accessed 17 February 2022).

where the coal deposits lay, suffered Mongol invasions, civil war, floods, and plagues at that time, which hindered further development (Stokes-Brown, 2007).

The (Spanish) Price Revolution, with the discovery of gold and silver in the Americas, highlighted the transition of agricultural society to a monetary society in Europe. The next step in this development was triggered by the exploitation of coal. García-Moreno et al. (2019) stated that the industrial use of coal meant a radical change in the way of life in the Asturias region from a farming economy to a mainly industrial economy. The opening of coal mines brought regional cultural development, but at the same time, caused lots of environmental changes.

Coal and coal mining had a global influence on human history. Here, a closer look is taken at coal exploitation in England because of its direct connection to the Industrial Revolution. Britain had large deposits of coal. By the late 2nd century CE, the Romans were exploiting most of the major coalfields in Roman Britain. After the Romans left Britain in 410 CE, coal was hardly used there until the end of the 12th century. Instead, wood was used as a major source of energy. During the 13th century CE, the coal trading increased across Britain, and by the end of that century, most of the coalfields in England, Scotland, and Wales were being worked on a small scale. In the first half of the 14th century, coal began to be used for domestic heating in coal-producing areas of Britain, as improvements were made in the design of domestic fireplaces. The demand for coal steadily increased in Britain during the 15th century, but it was still mainly being used in mining districts and coastal towns, or being exported to continental Europe. However, by the middle of the 16th century, supplies of wood were beginning to fail in Britain. Stokes-Brown (2007) described that iron production began to slump because England ran out of forests to convert into charcoal. Burning regular coal for smelting iron did not work, since the impurities in coal made the iron brittle. In 1709, the Darby family in Shropshire discovered that when coal is first converted into cokes, smelting could be done successfully. In the 1770s, Scotsman James Watt improved the design of the steam engine (which had already been in use in China long before), and by 1800 Britain had ~2,000 steam engines (Stokes-Brown, 2007).

The first phase of the Industrial Revolution from ca. 1760–1840 was based on the availability of coal to power steam engines. This period was the transition to new manufacturing processes in England, Europe, and the United States, and included: moving from hand production methods to machine production, new chemical manufacturing and iron production processes, increasing use of steam and water power, the development of machine tools, and the rise of a mechanized factory system. As central and northern England contained abundant coal, many mines were situated in those areas, as well as in South Wales and Scotland. Small-scale techniques of mining were not suitable for the increasing demand, and mining moved away from surface extraction to deep shaft mining as the Industrial Revolution progressed. When coal-fed steam engines were built for the railways and steamships during the Victorian era (1873–1901), international trade expanded exponentially. As steamships traveled overseas from the industrialized countries of Europe, their need for coal served as a trigger for coal mining to start at various locations across the globe (Fig. 5K). The Industrial Revolution led to an unprecedented rise in the growth rate of global populations. Smill (2005) called the period from 1867 to 1914 the period of the big innovations on the basis of science.

6.2 Social and Economic Impacts of the Industrial Revolution

The Industrial Revolution marks a major turning point in human history in which almost every aspect of daily life was influenced in some way. Arnold Toynbee (1884) was one of the first to recognize the importance of this change: "The essence of the Industrial Revolution is the substitution of competition for the medieval regulations which had previously controlled the production and distribution of wealth." And he suggests, "Europe owes to it the growth of two great systems of thought—Economic Science, and its antithesis, Socialism" (Toynbee, 1884, Reader lecture no. 27, VIII, The Chief Features of the Revolution, p. 8). Mentioning Socialism, he refers, of course, to the ideas of Karl Marx (1867) in *Das Kapital* and his friend Friedrich Engels (1848) in *Die Lage der Arbeitenden Klasse in England*, who criticized the economic politics of the time. On the other hand, Clapham (1930, 1932) asserted that wages and standards of living for most of the English urban working class (save for handloom weavers) had risen significantly throughout the period. Clapham's optimistic interpretation kicked off a debate among economic historians that would continue until the 1960s (e.g., Hobsbawm, 1964; Thompson, 1963). They concluded that although the incomes of some were growing considerably, incomes for generations of others grew much less, which led to the development of a differentiated class society.

The Industrial Revolution caused many upheavals in western society, including urbanization, the rise in power of the common person, the decline of patriarchy, and democratization. Harari (2011) suggested that traditionally people lived in the bubbles of three levels of intimate groupings: the nuclear family, the extended family, and the local intimate community or your "tribe." The second phase of the Industrial Revolution diminished the importance of family and community by empowering the market, making transportation and communication easier, and giving governments the means to provide towns with teachers, policemen, and social workers. Also, Harari (2011, p. 394–395) stated that the Industrial Revolution created "artificial" time: "The Industrial Revolution turned the timetable and the assembly line into a template for almost all human activities." The market, (i.e., the world of producing, buying, selling, and advertising) and the state, he concluded, came to influence almost every aspect of our lives. People have become weaker as individuals than they were as a group: it is easier for the market to exploit us and for the state to persecute us (Harari, 2011).

The Industrial Revolution is not over yet (Fig. 6). Landes (1969) claimed that Europe and the world can only sustain themselves in the years ahead through continuous industrial revolutions. He stressed the importance of new technologies, like electricity and the oil industry in the second phase of the Industrial Revolution. Oil, of course, became after coal the next natural resource that greatly influenced human history. But also, the use of all kinds of chemicals became important, which gave mining new directions. Even agriculture was "industrialized" (Fig. 5L). The keywords of the third phase of the Industrial Revolution (Fig. 6) would be communication, information, globalization, and digitalization. For the first time in human history, it seems that the resources of Earth are not setting the stage for human history, but rather cultural conditions are doing so. However, the technologies required to realize all this communication, information, and digitalization do need many rare elements, and mining these rare elements is still a priority. And again, the distribution of these elements in the Earth's crust is a prime driver of economy and politics.

A fourth revolution of the "cyber-physical," based on algorithms that some foresee, (Fig. 6) goes one step further yet with the idea that input from humans is removed altogether and computers take over. But even then, humans and the earth must stay connected: environmental and climate problems make that clear.

6.3 Environmental Impact

Using the increasing amount of energy available since the beginning of the Industrial Revolution has a downside. The Industrial Revolution may have had numerous advantages, but as Spier (2015) claimed on the basis of the second law of thermodynamics, any local rise in complexity must be accompanied by an increase of disorder and waste (entropy). A national nonprofit organization of concerned scientists, founded more than 50 years ago at the Massachusetts Institute of Technology, postulates in a Reports & Multimedia (2017, updated 2019) study on coal mining, the following disadvantages:

1. When coal is burned, it releases a number of airborne toxins and pollutants. They include mercury, lead, sulfur dioxide, nitrogen oxides, particulates, and various other heavy metals, which cause several health impacts.
2. Burning coal produces coal ash, which can contaminate waterways and drinking water supplies.
3. Coal mining produces environmental pollution or landscape change.
4. Climate change is coal's most serious, long-term, global impact.

These are some of the negative evaluations of the social (health) and environmental impacts of the Industrial Revolutions. Many people understand these today, even as most people also understand the advantages of mining. Of course, people have different solutions for the problems that are mentioned. The final solution is not yet agreed upon (Fig. 5M).

7. DISCUSSIONS

Inspired by Alvarez (2017), the impact of five natural resources on human history are described through five sequential periods, with the intention of highlighting the importance of the occurrence patterns of these natural resources in channeling the path of human history. Of course, there is a lot more to tell from both geological and from human history perspectives. (e.g., Dartnell, 2019). For each of the natural resources and time periods in human history, we summarize some aspects and questions about

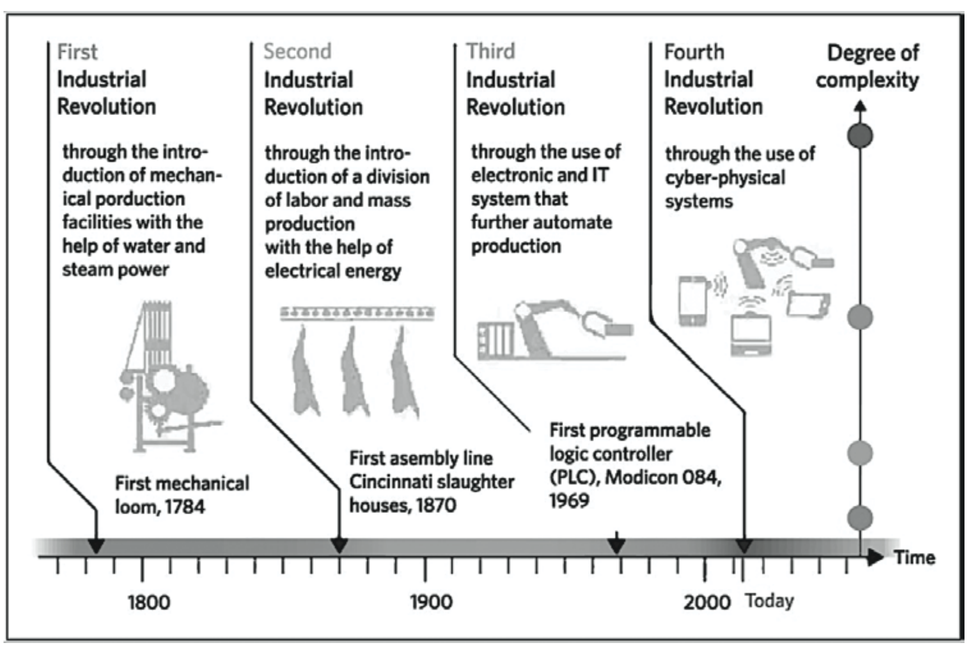

Figure 6. Industrial Revolution 1.0–4.0—A timeline and roadmap. Modified after:http://www.dfki.de/~wahlster/wp-content/uploads/Ten_Years_of_Industrie_4_0.pdf.

our findings. Finally, we discuss the value of interdisciplinary research, which is a central feature of "Big History."

During the Stone Age of humankind, which encompassed the archaeological time span from the onset of the Paleolithic period some 2.6 million years ago to some 3,000 years ago with the beginning of the Bronze Age, stone was the principal material for making tools. In the beginning, stones did not need to be quarried or mined but were simply picked up from the ground. Living near a river where all kinds of stone can be found was important. However, it wasn't long before obsidian started to be carried to certain sites in Eastern Africa, from distances as far away as 25–50 km. Was trade the cause? The obsidian trade in the Near East has been called the first trade in the world by Dixon et al. (1968). After groups of *Homo erectus* traveled north between 300,000 and 200,000 years ago, examples of chert quarries and mining were found in Egypt (Vermeersch and Paulissen, 1993), Israel (Verri et al., 2004), and the rest of the Near East (Delage, 2007) to use for making tools.

Goudsblom (1992) has seen fire as the start of civilization. He considered it as a one-way development toward the "domestication" of humankind, while stating that the more we controlled nature, the more we became dependent on it! When full control of fire was realized is still under debate. Gowlett and Wrangham (2013) studied the control and use of fire, including cooking, by early humans in Africa, and reconciled different viewpoints on the earliest use of fire in a more integrated approach. We have added a geological perspective to this approach. Indeed, it could be possible that the controlling and making of fire was developed by Stone Age man, working with chert cobbles ("firestones") to make tools, because chert sparks fire when struck with pieces of pyrite. It would, therefore, be necessary for resources like chert to be available. There is a small chance that some kind of chert was available in the Eastern African Rift, where the earliest tool-making hominids lived. But, it is more probable that basalt and quartzite, and later obsidian, were used to make tools there. Flint, on the other hand, would have been weathered from Cretaceous limestones in Egypt and the Near East. Pyrite is abundant in many places around the world, so geologically speaking the idea of making fire with flint and pyrite happening in Egypt or the Near East becomes plausible.

Another debate had been going on for some time about the origin of tin used in the Bronze Age in the Mediterranean and Eastern Europe. Hausten et al. (2010) suggested that by measuring the isotope ratios of tin ores, the origin of the tin could be discovered. Berger et al. (2019) applied this method and concluded that most of the tin came from Cornwall, England. Further research along these lines may solve similar questions in ancient history.

During the Bronze Age, a web of trade routes began in which tin—which is rather rare in the crust of the earth—at least partly played a role. These routes were part of a very early human network of communications between Western Europe and Eastern China. This suggestion is in line with how exchanges among cultures are described in the world history book *The Human Web* by McNeill and McNeill (2003). Tin may have played a role in these early networks, though that has not been recognized by most historians.

If tin trade from Britain stimulated the Bronze Age to spread throughout the Eastern Mediterranean and the Middle East, it could be that periods of unrest, such as during natural disasters (e.g., the mega-eruption of the Santorini volcano), large scale migrations of people (in Anatolia), and invasions of belligerent Sea Peoples throughout the Mediterranean Sea, obstructed this tin trade. We suggest that a shortage of tin in these countries during the so-called Bronze Age Catastrophe could have stimulated the start of iron metallurgy as an alternative for tin-bronze.

Iron smelting led to the manufacture of new tools for agriculture and new weapons for warfare, which were cheaper and more available, because iron was found in abundance and in more places than tin. And when early methods to make "carbon-steel" were invented, they were much stronger than copper or bronze tools. In practical terms, utilization of iron for weapons put arms in the hands of the masses for the first time; in other words, it stimulated the democratization of warfare (McNeill and McNeill, 2003).

Gold became important during the transition from a bartered agricultural society to a generalized monetary system until medieval times (even though we should not forget the role of silver, which needs further research). The rise of monetary inflation, which occurred across Western Europe following the discovery of the Americas, caused prices to rise on average roughly six fold over 150 years. Many economists and historians believe this high inflation was started by the Spanish treasure fleet's large influx of gold and silver from the New World, including Columbia, Mexico, Peru, and the rest of the Spanish Empire. It seems that this monetary interpretation of the price revolution was indeed one of the important reasons (e.g., Fisher, 1989). From then on, western societies quickly expanded to become competitive imperialist domains, where capitalism was the "buzzword" (i.e., more production brings more wealth, which leads to more consumption, which leads to more production). Looking for gold or any other kind of precious material can cause greed, and gold rushes in recent history are legendary. But mining often has a downside, like destroying the landscape and environment (Fig. 5N).

More production inevitably meant more energy needed to expand an ever-growing mechanized industry, and neither human nor animal muscle power was enough to provide the energy needed to fuel the imminent Industrial Revolution. That energy was eventually found in coal. Balancing the positive and negative impacts of coal mining and the Industrial Revolution is a central theme of this discussion among historians. Spier (2015) explains how he learned from Chaisson (2001) about the way energy is flowing through matter within certain boundary conditions that caused both the rise and demise of all forms of complexity. There are three kinds of complexity, which all change through energy: (1) complexity of cosmic inanimate matter, organized by the fundamental laws of physics; (2) complexity of life that maintains itself by harvesting matter and energy with the aid of special mechanisms; and (3) complexity of culture, processed and communicated as information, and stored in nerve and brain cells or in human records of various kinds. However, complex order has a tendency to create disorder as well. Following the second law of thermodynamics, any local rise in complexity is accompanied by a rise in disorder elsewhere. Actually it was the energy saved in coal that could be transformed into controlled circular movements for powering machines that led humans to the fundamental insights into the natural world that are now known as the science of thermodynamics (Spier, 2015). In a way, we can say thermodynamics taught us that entropy, waste, and negative impacts are part of any change to develop more complexity (Fig. 5O). The question is, at what point will the costs and negative impacts grow larger than the yields of creating a more complex order? Many believe that for coal mining, that point has been reached. But, more phases of the industrial revolution may follow (e.g., Mathas, 2013). What will the impacts be? (Fig. 5P).

Finally, we suggest that a focus on interdisciplinary study has its advantages, allowing us to look with fresh eyes and use new methodologies, which offer new opportunities for acquiring knowledge. But for interdisciplinary results, it is necessary to work in teams of specialists, for specialization has made it almost impossible to cover more than one discipline. In such teams, we must learn to speak a language that each can understand. Also, it is hard to find ways to publish in specialized scientific papers, when one is working on an interdisciplinary approach. Moreover, finding a way to include an artistic perspective, however enlightening it may be, offers its own challenges.

Alvarez (1990) noted that the most difficult problems within interdisciplinary research involve different cultures in different sciences, perceptions of a hierarchy or pecking order of sciences, judging the quality of scientific work, and the barrier of jargon and technical language. He stated: "Doing interdisciplinary science involves learning the languages of different fields," and he suggests that "perhaps the interdisciplinary style that is growing up in this field, may eventually be as important as the things we are learning about impacts and mass extinctions" (Alvarez, 1990, p. 93). We have tried to take another little step in that direction.

Leonardo Da Vinci (1452–1519) wrote:
"Man has been called a world in miniature,
as man has bones inside him
the supports and armature of flesh
so the world has the rocks,
As man has in him a lake of blood,
where the lungs rise and fall in breathing,
so the body of the earth has its ocean sea,
which rises and falls every six hours
as if the world breathed."
-from Cianchi (1998)

Alexander Von Humboldt (1769–1859), a polyedric scientist of the 19th century,
like Big History, he sought to unify diverse branches of scientific knowledge and culture
and motivated a holistic perception of the universe.
He wanted to understand the interconnections among diverse orders of reality,
and sought ways to transcend the antipathies between the sciences and the humanities.
His succinct graphic representations of landscapes and life-ways
are intended to illustrate the importance of aesthetics
in the journey toward understanding the quest for wiser ways of dwelling.

Figure 7. Flowering Mind. Image taken from a piece by Paula Metallo in a two-artist exhibition with Dona Jalufka, titled "Unmeasuring The World" (2009, Humboldt Museum, Berlin Dig History series; www.paulametallo.com: HOLES section, New Works, Shrinky Dink® plastic, mixed media, and chopsticks, 8 × 18 cm).

8. CONCLUSIONS

In conclusion, we suggest in this chapter that the distribution pattern of natural resources on Earth exploited by humankind, such as silica, copper, tin, iron, gold, and coal, indeed had a fundamental influence on human history. The possibilities for early humans to use flint and pyrite to make tools and fire in earliest times could depend partly on the geographic availability of these materials. Better knowledge of the geology and isotopic geochemistry of resources in different places has, like in the case of tin, solved old questions about the paths human history took. The fact that the occurrence pattern of iron is common and easily available in the world made it a logical alternative when tin trade was obstructed during the Bronze Age Catastrophe. Iron weaponry democratized warfare; trade, war, and conquest often went hand in hand. Gold, because it is usually found in small amounts and is also very durable, became, early in history, the basis of the global monetary system. When new sources of gold were found and put on the market, it lost its original value, causing a deepening gap between the rich and the poor. Coal fueled the energy needed to fire the Industrial Revolution, creating a global economic system in which some empires overpowered others for several ages. Even more than the natural resources studied above, the mining of new resources will influence the lives of people in the future. Big History has the possibility of integrating the knowledge of different scientific disciplines in order to understand the deep history of mankind and help make decisions for our ever-growing, more complex future. Geology, if only because of our need for natural resources and the consequences of mining, certainly plays a role in this approach (Fig. 7).

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