# **A Little Big History of Iberian Gold**: How Earth processes concentrated the precious metal that played a critical role in the history of Spain and Portugal

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**ABSTRACT**
We present a "little big history" of the gold that either was mined in the Iberian Peninsula, or was brought there from deposits located elsewhere, by trade or by conquest. During Roman times, gold was extracted from the Peninsula itself. In the Middle Ages, gold was brought across the Sahara from very rich near-surface occurrences in West Africa. After the discovery of the New World, Colombia was the most important source of gold entering the Peninsula. Each of these gold-bearing regions has had a different geological history, and in each one, gold was concentrated by a variety of geological processes. The West African gold dates back to fairly early in Earth history, about 2 billion years ago, and resulted from closure of an ancient ocean basin. The Iberian gold is related to the continental collision that produced the Appalachians and their Variscan continuation in Europe, while assembling the Pangea supercontinent. The Colombian gold is associated with the subduction under South America of the Pacific Ocean crust that has produced the Andes. For each of the three regions we present a database of historical and active gold mining areas, and we summarize this information in maps. The ways in which Earth concentrates gold are the subject of much geological research, and we give a brief introduction to this remarkable topic, hoping that big historians will go beyond Carl Sagan's statement that "We're made of star-stuff," and will recognize that "We're made of star-stuff, concentrated by Earth."

## I. INTRODUCTION

One approach to the study of big history is to take some feature of the human situation and trace the history, from the beginning of the Cosmos, which has led to this aspect of the world we live in. Esther Quaedackers pioneered this approach, and she calls such a study a "little Big History."

Of the four regimes of big history — Cosmos, Earth, Life, and Humanity — different ones are of differing importance in different little big histories. Most little big histories will begin with fairly similar cosmic histories, because everything in big history has obeyed the same laws of physics, set up early in the Big Bang, and the chemical elements of which our physical world is constructed were fashioned by the same stellar processes (with differences however for light and heavy elements).

Little big histories begin to turn complicated in the regime of Earth history, because the long and complex history of our planet has constructed very different geological conditions in different parts of the Earth. The very young basalt volcanic rocks of Iceland, for example, which erupted where brand-new oceanic crust is forming, bear no resemblance whatsoever to the very ancient and complicated, cycled and recycled, geology of Australia. With our backgrounds in geology and geophysics, this is the part of big history that is most familiar to us. Little big histories become seriously complicated in the regime of Life history, and overwhelmingly so in that of Human history.

In this paper we present a "little big history" of gold in the context of Iberia. This large peninsula, now shared by Spain and Portugal, has had access to copious amounts of gold for most of its history, from pre-Roman and Roman times until the independence of the former Iberian colonies in the New World about two centuries ago. This has had a major influence, for good or ill, on the economic, social, and political history of Iberia, and contrasts with other regions lacking this resource, such as the Low Countries or Italy.

### We're made of star-stuff, concentrated by Earth

In addition to our specific focus on the gold that was discovered in or brought to Iberia, we have a much broader point to make in this paper, one which is important for big historians to understand. Most big historians now recognize that all the chemical elements heavier than hydrogen, helium and lithium were produced in stars and scattered through the galaxy as the result of supernova explosions. This essential piece of understanding is encapsulated in Carl Sagan's statement, "W*e're made of star-stuff.*"

But for geologists like us, that statement, although true, is incomplete. The scattered atoms and the dust grains made of silicate minerals and iron in interstellar space are too dispersed to be of any use to humans. The elements we are made of or that we use have been concentrated in a large variety of processes that go on either inside or at the surface of the Earth (Alvarez, 2016, Ch. 3). So we would amend Carl Sagan's concept to a form that big historians should embrace, and stress that:

*"We're made of star-stuff, concentrated by Earth."*

In this paper we will show that the gold that affected Iberian history was concentrated in a variety of different geological ways, and these are just a sampling of Earth's remarkable virtuosity in forming rich gold deposits of many kinds. This kind of little big history could be written for any of the other chemical elements, or for rocks like limestones or granites, or for petroleum and other fossil fuels. This means that the range of Earth processes that have benefitted humanity is too great to be understood in full depth and breadth by anyone, including individual geologists, but we hope our study of Iberian gold will help big historians appreciate the critical role that Earth has played in setting up the human situation.

## II. GOLD IN THE HUMAN HISTORY OF IBERIA

To provide a focus for the very large, complicated, and controversial topic of gold geology (Goldfarb, 2001a, b; Goldfarb *et al.*, 2010), we present our little big history of gold in the context of Iberia. During the past two millennia, the gold of Iberia has come primarily from three sources — Iberia itself, the West African Sahel, and Colombia. To keep this treatment manageable, we will not consider gold that might have entered Iberia from other sources available to the Roman Empire, such as Dacia (modern Romania), the Egyptian-Arabian-Nubian region, or Wales. The gold from the three regions above was delivered to Iberia in four different ways during four historical episodes:

### Gold from Iberia

Some of the earliest known gold artifacts from Spain come from Asturias in the northwest of the Peninsula, dating from the early Chalcolithic (Blas Cortina, 1994), and are currently under study. We also have the Pre-Roman Treasure of Arrabalde, found near the later Roman mining site of Las Médulas (Perea and Rovira, 1995). Pre-Roman gold is also known from the realm of the Phoenicians and the contemporary native Kingdom of Tartessos, in the south of Spain. In Extremadura, in south- central Spain, as the site where at least some of this gold was originally collected is now known, the chemical details of natural nuggets match those of the Tartessian Treasure of Aliseda (García-Guinea *et al*., 2005).

Abundant gold paleoplacers —or ancient alluvial ore deposits— in northwest Iberia were probably exploited by artisanal mining in pre-Roman times. This area subsequently became a major source of gold for the Roman Empire. Las Médulas, where Roman engineers and miners recovered gold from old, consolidated sedimentary deposits, must have been an environmental disaster at the time, but today is a landscape of colorful beauty that has been designated a UNESCO World Heritage Site (Fig. 1). The Roman mining system used at Las Médulas, aptly named *Ruina Montium*, was described by Pliny the Elder (transl., 1952). A

Figure 1. Las Médulas (León, NW Spain). This UNESCO World Heritage landscape is an ancient gold mine from Roman times. Photo courtesy of Bernardo López Santamaría.

newly discovered site of large-scale Roman extraction of gold from river gravels is in the Valdería, near Castrocontrigo (Justel-Cadierno *et al*., 2014; Fernández-Lozano *et al.*, 2015). Both of these sites are within 100 km of the city of León, a name deriving not from "lion," but from "legion," for this was the headquarters of the Roman legion charged with protecting these critical sources of gold. Production evidently tapered off or ceased after the Roman decline and the Germanic invasions eliminated the technical expertise and infrastructure necessary for intense gold mining. We also briefly consider the gold-bearing region in southwestern Iberia, whose geological origin is quite different from that of northwestern Iberia.

### Gold from West Africa

After a few centuries in the Early Middle Ages in which gold was less important in Iberian history, the Islamic conquest of the 8th century

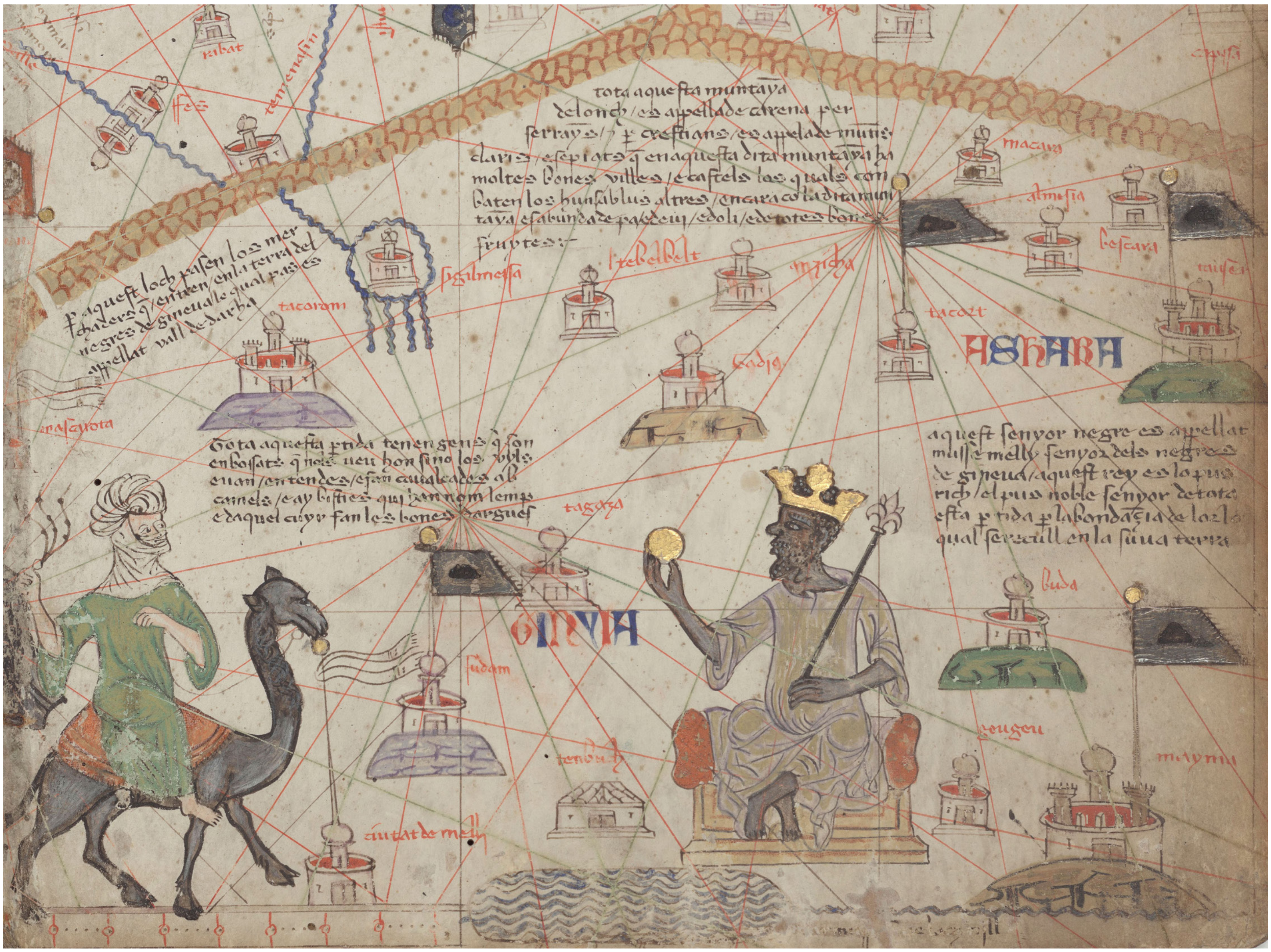

Figure 2. Mansa Musa. Catalan atlas about 1525 ACE, with the image of the King of Mali, Mansa Musa, shown with the gold that made his kingdom so wealthy (attributed to Abraham Cresques, about 1375, https://upload.wikimedia.org/wikipedia/commons/7/7a/Catalan_Atlas_BNF_Sheet_6_Western_Sahara.jpg)

brought contacts with Morocco. This eventually led to an influx of gold into Iberia via the trans-Saharan caravan trade from abundant sources in sub-Saharan West Africa. In this long-enduring caravan trade, Arab merchants exchanged salt, extracted from 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). Much of the gold eventually reached Islamic Iberia, in exchange for its sophisticated manufactures.

As the strong Islamic control of Iberia, centered at Córdoba, faltered after the 11th century, much of the African gold reaching the Islamic parts of the peninsula was extracted by militarily strong Christian kings, as the tribute called *parias*, from the weaker kings of the Islamic successor, *taifa* kingdoms. Christian kings like Fernando I (1037-1065) and his son Alfonso VI (1065-1109) of León-Castile gave huge gifts of gold to the French Benedictines, and these riches largely funded the cultural and artistic flowering of Cluny (although Fernando's gifts have recently been questioned: Pick, 2013).

By the 14th century it was well known that the kingdoms of the Sahel were enormously rich in gold, because of the pilgrimage (1324-1325) of the King (or Mansa) of Mali, Musa I (c. 1280-c. 1337), to Mecca, in which he distributed huge amounts of gold in Cairo (Fig. 2). The search for a way to outflank the Arab-controlled trans-Saharan gold caravan may have been one of the motivations for Prince Henrique of Portugal ("Prince Henry the Navigator") to begin the Portuguese exploration along the west coast of Africa in the early 15th century (Russell, 2000). As a result, by the 15th century the Portuguese had reached the African gold region by sea, founding the trading center of Elmina in 1482, on the coast of modern Ghana, within 100 km of rich gold-producing regions (Leitão and Alvarez, 2011).

**Gold from Colombia**

After the capture by Castile, in 1492, of Granada, the last Islamic kingdom in Iberia, African gold could no longer reach Spain in large quantities by the trans-Saharan route. However, in that same year, the discoveries of Columbus brought two whole new continents to the attention of

Figure 3. Pre-Columbian boat sculpture as an example of Muisca art in Colombia; the gold probably came from placer deposits in riverbeds. (Votive figure. Cordillera Oriental – Muisca. 600 CE – 1600 CE. 10.2 x 10.1 x 19.5 cm. Museo del Oro Collection – Banco de la República. Colombia. Photography by: Clark M. Rodríguez.)

the Spanish, who rapidly undertook exploration, one major goal of which was to find resources of precious metals. Truly enormous quantities of silver were discovered at Potosí in Bolivia (1545) and at Zacatecas in Mexico (1546), while the most abundant gold resources were found in Nueva Granada, now Colombia, which seems to have been the most 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. The wonderful gold ornaments in the Museo del Oro in Bogotá (Fig. 3) give us an idea of the artistry of the goldsmiths of the Muisca (Chibcha-speaking) and related peoples.

The rich streams of New World silver and gold were funneled into Spain in early colonial times, funding the Habsburg wars against the Protestants in Europe, and causing waves of inflation that spread from Seville all over Europe — the so-called "Spanish Price Revolution." This last source of gold and silver entering Iberia dried up after the Latin American Wars of Independence in the early 19th century, ending perhaps 3,000 years of Iberian gold. But it is interesting to note that the Spanish and then the Mexicans controlled the coastal belt of present-day California until 1846, unaware of the vast gold resources that would be discovered in the Sierra Foothills, just to the east, in 1848.

## III. HOW DO GOLD DEPOSITS FORM?

Almost any little big history that involves a physical aspect of the human situation — from a water glass, to a human being, to a city — must ask about the origin of the chemical elements of which it is made. This is well understood by many big historians, but what is less appreciated is that we must also ask about how each element was concentrated and made useful.

In most cases it is the Earth that has done the concentrating, through a wide variety of processes that have acted slowly over long periods of time (Brimhall, 1987, 1991). The production of natural deposits of each element thus has a history and is a vital part of big history. In this section of our paper we aim to make the origin and history of gold deposits understandable.

We have found it most effective to do this in the form of a narrative, presented as a sequence of questions. Some of the questions have answers, but others can only be answered partially, or in the form of other questions, for these are topics of active geological research. Except for the first three, our sequence of questions moves from the familiar surface of the Earth downward into the inaccessible interior of the planet.

### Question 1: What is the ultimate source of gold in the Cosmos?

**Q:** Cosmologists now understand that at the end of the Big Bang, during the Dark Age, before the first stars began to shine, the Cosmos was made of hydrogen, helium, and traces of lithium (ignoring dark matter). How did the other 90 or so elements come into being?

**A:** Many big historians are familiar with the recognition that the other elements were made in stars, as by-products of the nuclear reactions that make the stars shine or, for many elements heavier than iron, during the stellar collapse that produces a supernova explosion. Gold is one of these r- (rapid-) process elements (Cowan and Thielemann, 2004), both formed and dispersed by supernovas. This understanding of nucleosynthesis has become part of the canon of big history, identified as Threshold 3, "The Creation of New Chemical Elements," in the textbook of Christian, Brown, and Benjamin (2014). In a broader sense, it is now recognized that matter has evolved during the unfolding of big history (Garzón-Ruipérez, 1994; Tolstikhin and Kramers, 2008).

**Question 2: What is the ultimate source of gold in the Earth?**

**Q:** Carl Sagan's "star-stuff," the product of many supernovas preceding the formation of the Earth, was dispersed through interstellar space and was a mixture of many different elements. How did Earth acquire its gold?

**A:** A detailed answer to this question would take us far from our subject. For a brief review, see Alvarez (2016, Ch. 2). But a critical point for understanding gold is that Earth is dominantly composed of four elements — magnesium, silicon, iron, and oxygen (Mg, Si, Fe, O) — which are concentrated in Earth first because they were relatively abundant in the solar nebula, and second because they make solid mineral grains, too heavy to have been blown out of the inner Solar System by the strong solar wind of the young Sun.

As Earth accreted, the growing planet must often have been largely or partly molten because of the heat of large impacts, and dense iron sank to the center to make Earth's iron core, probably carrying along most of Earth's gold, which is a "siderophile" element, easily absorbed by hot or molten iron. The other major elements — magnesium, silicon, and oxygen — went into making the Earth's rocky mantle, which we can think of as composed of minerals like olivine ($Mg_2SiO_4$).

A second critical point is that when Earth was almost completely accreted from solid grains and gas in the solar nebula, its growth was interrupted by a giant impact of a body probably about the size of Mars. This off-center impact tore away a substantial fraction of the Earth's mantle, which ended up as the Moon, orbiting the Earth. But the accretion of smaller objects onto the Earth continued, and they added what is called the late veneer.

Our current understanding is thus that Earth differentiated early and quickly into an iron core, surrounded by a rocky mantle that makes up about 90% of the Earth by volume. The other first-order component of Earth is its crust, richer in silicon and oxygen, and poorer in magnesium, than the mantle. In contrast to core formation, the crust has come into being slowly and gradually through the whole of Earth history. It is of two kinds: Oceanic crust forms by sea-floor spreading at mid-ocean ridges, lasts perhaps a couple of hundred million years, and then sinks back into the mantle at subduction zones; oceanic crust is ephemeral. Continental crust on the other hand, being more buoyant, generally does not subduct, but continues to float on top of the mantle, although it is subjected to repeated cycles of mountain building, becoming more and more complicated through time. To our knowledge, most of the gold that has been successfully mined is in the continental crust, although there are also very important gold deposits that formed on oceanic crust but are now found on the continents after accretion.

**Question 3: How can we understand how gold has been concentrated?**

**Q:** Over its 4.5 billion years of history, Earth has operated like a giant chemical processing plant, taking chemical elements that were all mixed up and dispersed, and gradually concentrating and refining them. Gold, for example, has been concentrated and refined by Earth in a variety of ways, which involve geology, chemistry, and physics. How can scholars and scientists who are not geologists acquire a broad, clear understanding of this important but complicated aspect of Big History?

**A:** By restricting ourselves to the three regions that supplied gold to Iberia in historical times, we make the topic more manageable. The three regions are geologically completely different, so we get a sense of the variety of processes at work. It might have been logical to begin our study of gold in the Earth's core and to follow it upward, ending with economic gold deposits in the crust. However, we have chosen to start at the more familiar surface and work downward.

**Question 4: The easiest gold to find and mine is in placer deposits. How do placers form?**

**Q:** 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 at the bottom of the river sediment. These secondary, or "placer" deposits are relatively easy to mine, and were the first to be exploited in all three of our regions — in ancient times in Iberia, in mediaeval times in West Africa, and in pre-Columbian and Spanish-colonial times in Colombia. How does gold come to be concentrated in placers?

**A:** Sedimentary grains of gold are first eroded from some older rock, commonly from gold-bearing quartz veins, then transported — in this case by running water, and finally deposited as sediment. Gold has a much higher density than common quartz grains (density of 19.3 vs. 2.65 $g/cm^3$), so it gets sorted from quartz grains by density, accumulating at the bottom of sand bodies. The first California gold was discovered in excavations of river gravels for the foundations for a saw mill, and eventually many of these detrital grains were traced to upstream vein sources.

Sand grains in a flowing river hit against each other. In the case of quartz sand, this breaks them into smaller and smaller fragments. But gold behaves differently. Gold grains may get reduced in size, but as a malleable metal, they can also stick together as nuggets (Fig. 4a, b). Some studies (e.g., Johnson *et al.*, 2013) indicate that some bacteria excrete nanoscale gold particles and are able to concentrate gold in this way as part of their metabolism. Both of these mechanisms can build up nuggets of gold, which in rare cases can reach several pounds in weight.

**Question 5: How did the gold get in veins, deposited by water, when gold is insoluble?**

**Q:** The secondary gold in placers commonly comes from erosion of "primary" gold in bedrock, commonly gold hosted as tiny blebs of metal in quartz veins (Fig. 4c). Silica and gold have been transported in solution by hot fluid ascending from depth, often following fractures or faults, and precipitate as crystals of quartz, sometimes together with much smaller amounts of gold. The fluid carrying the gold and silica can either be relatively pure water or a mixture of water and carbon dioxide.

Gold is valued as jewelry partly because of its attractive color, but also because it does not tarnish, as silver does. The gold in a wedding ring may very gradually wear away over the decades, but it does not dissolve or react chemically. If gold is insoluble and chemically inert, then how can it be carried along in fluid rising through fractures or faults to be deposited chemically at shallower depths?

**A:** The answer to this puzzle is that in hot, deep fluids, gold *is* soluble, and is carried up in solution from depth — from deeper in the continental or oceanic crust. In addition to its *siderophile*, or iron-loving character, gold is also a *chalcophile* element, with an affinity for sulfur, as copper also has (Barnes and Ripley, 2016). Sulfur, among other chemical elements, will help the solubility of gold in these deep fluids. One can recognize this difference in chemical behavior under different conditions also in the fact that the gold-bearing veins are mainly composed of quartz, for quartz, like gold, is also extremely insoluble and unreactive under surface conditions (Alvarez, 2016, Ch. 3).

Like placer gold, primary gold in quartz veins and disseminated in certain rocks is of great economic importance and is mined by underground workings and in open pits in many places around the world (Fig. 4c, d). However, this "lode" mining is more difficult than placer mining because the gold is dispersed in hard rock that must be broken up into small fragments, and commonly also treated chemically, before the gold can be extracted. This was difficult in pre-industrial times, but is common today, and each of our three regions is now the focus of modern-day exploration for lode gold (see the maps in Fig. 6-8).

**Question 6: What crustal environments can host gold deposits?**

**Q:** The primary gold near the Earth's surface is transported upwards in various ways from deeper in the Earth's crust. In what kinds of geologic environments can gold-concentrating processes occur?

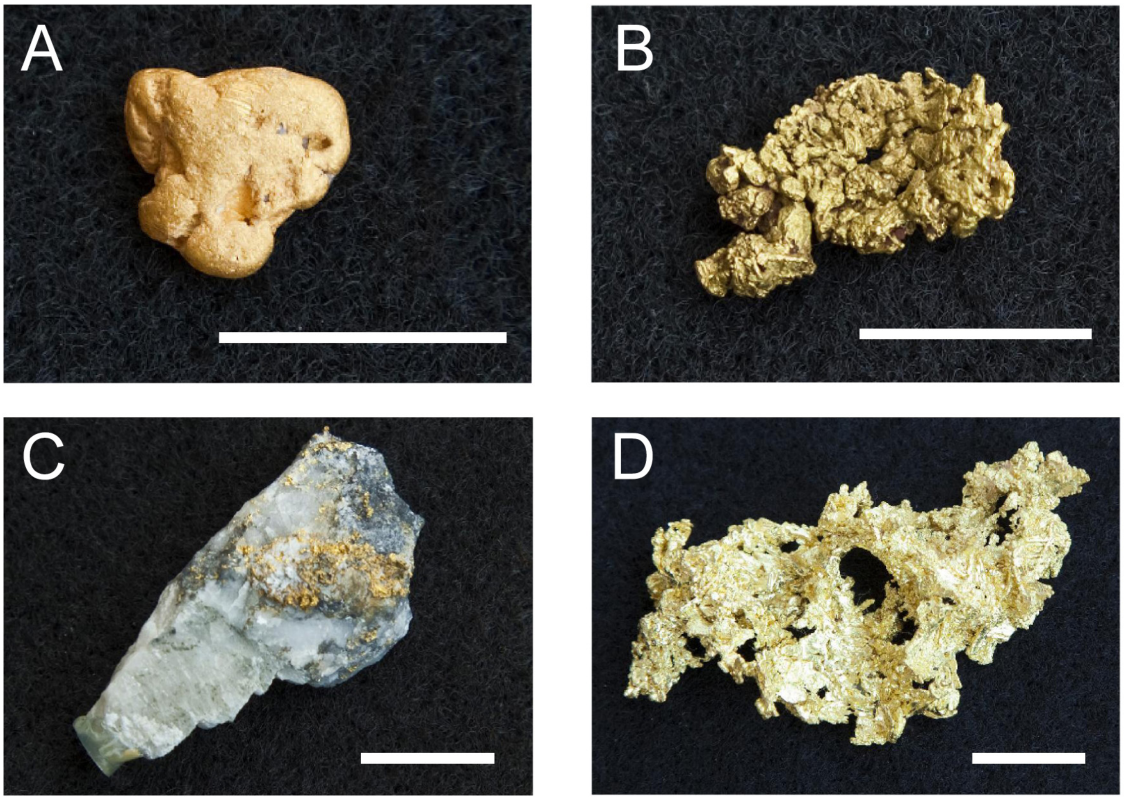


Figure 4. Natural gold samples. Horizontal scale bar is 1 cm.
a. Gold nugget from Howard River, Nelson, South Island, New Zealand.
b. Gold nugget from Galice District, Josephine Co., Klamath Mountains, Oregon, USA.
c. Quartz vein with gold from Western Lode, Level 12, Obuasi mine, Ashanti gold belt, Ghana, West Africa.
d. Nicely crystallized gold from Eagle's Nest Mine (Mystery Wind Mine), Placer Co., Sierra Foothills, California, USA.

**A:** We have now reached the point where the geology of gold becomes very complicated, controversial, and uncertain, so we will give only a brief synopsis of what appear to be some of the important gold-producing crustal environments:

(1) At mid-ocean ridges, two plates are moving apart, so that mantle rises and partially melts, solidifying to form new oceanic crust. Here there is a dramatic process that produces metal deposits that may contain gold. Sea water, driven

down by pressure into cracks in the new crust as it is pulled apart, is heated by contact with hot rock, expands, and rises to gush forth on the sea floor in spectacular hydrothermal vents. This hot circulating water leaches metals and sulfur out of the surrounding rocks and then deposits them in chimneys called black smokers, which may contain gold. There are spectacular images of black smokers on the web. These deposits are called volcanic massive sulfides (VMS), and some of the gold in southwest Iberia and western Colombia appears to be of this origin.

(2) At subducting plate boundaries, like the west margin of South America, thousands of kilometers of old oceanic crust may sink, dipping below the continent, and thus under continental crust, and descend into the mantle. Through these subduction processes, magmas are formed by melting of the mantle or lower crust and they rise to shallower levels in the crust. They may cool at mid-crustal or upper crustal depths to form great bodies of granitic rock, or erupt at the surface from volcanoes like those of the Andes. Gold deposits may form in this environment, such as in parts of the Colombian Andes and the Iberian Peninsula, from fluids either released from the crystallizing magmas or from surface fluids convecting around the cooling granites. Gold resources formed in these environments are typically classified as porphyry, skarn, and epithermal deposits, and many are also associated with economic concentrations of silver, copper, molybdenum, tungsten, lead, and/or zinc.

(3) Another major gold environment occurs where old ocean crust has been partly subducted and partly scraped off, or "accreted," to the edge of a continent — something like a huge car wreck in slow motion. The accreted rocks get intensely deformed and metamorphosed, magmas are produced and cool to form granites, a mountain range is driven upward, and then the continents may rebound slightly, pulling the mountain range apart in extension. Gold may accumulate in this environment, in what are called "orogenic" gold deposits (Goldfarb *et al*., 2001b, Goldfarb and Groves, 2015), using a geologic term where "oro" refers to mountains, not to gold. The gold-transporting fluid, a combination of water and carbon-dioxide, was released from different minerals as they were heated and metamorphosed during the accretion. The fluids were then focused upward along major faults during earthquake activity. Many of the Iberian gold deposits are of this type, and were generated during the Variscan Orogeny, about 300 million years ago, when Gondwana collided with the northern continents to assemble the supercontinent of Pangaea, forming the Appalachian Mountains and their former Variscan continuation through Iberia and central Europe. In addition, almost all the gold deposits in West Africa were formed this way 2 billion years ago and many of the gold deposits in Colombia were formed this way about 90 million years ago.

All three of these environments are related to plate tectonics, but two other possibilities may not be. So we treat them separately in the two following sections.

### Question 7: How (and when) did gold get from the mantle into the crust?

**Q:** Evidently the gold in the crust must have come from the mantle, and we can ask, How did gold get into the continental crust from the underlying mantle? There seems to be no clear answer to that question because of the inaccessibility of the deep crust, but there may be an answer to a related question: *When* did gold get into the continental crust from the underlying mantle?

**A:** In a detailed review paper, Goldfarb *et al.* (2001b) showed that very large amounts of orogenic gold were emplaced in the latter part of the Archean (~2.8-2.5 Ga) and the early Proterozoic (2.1-1.8 Ga). This was followed by a gap in the ages of orogenic gold during the Mesoproterozoic and Neoproterozoic (1.6-0.6 Ga) before widespread orogenic gold deposits recognized in the Phanerozoic (0.6 Ga to now). Of our three regions of interest, West African gold was emplaced before the Mesoproterozoic-Neoproterozoic gap, and Iberian and Colombian gold after it. Goldfarb suggested that this episodic character of orogenic gold deposition may be related to changing heat regimes during Earth history — a topic of much interest and little agreement — as well as differences in preservation of certain crustal levels that relates to the changing regimes. One possibility is that early Earth was much hotter and lost heat by general overturn of the mantle, rather than by the organized patterns of plate tectonics.

**Question 8: How did gold get into the mantle?**

**Q:** As a siderophile element, most of the Earth's gold must be in the iron core. We also know that there is gold in the crust, where it is mined. We know less about gold in the mantle, because of its inaccessibility, but it seems likely that the mantle also contains gold, some of which has migrated into the crust. Are there ways in which the mantle could have acquired gold?

**A:** Broadly speaking, there are three ways the mantle could have retained or acquired gold:

(1) Some amount of gold may have remained in the mantle because of incomplete partitioning into the core during core-mantle separation (Brenan and McDonough, 2009).

(2) Some extra-terrestrial gold may have been brought to Earth by impacting objects as a "late veneer," late in the accretion process, after the core and the mantle had separated and the Moon had formed (Willbold *et al*., 2011).

(3) A small amount of gold may be carried up from the core in plumes — in slowly rising columns of hot, buoyant mantle material that continue to be active today, with the most familiar examples located at Hawaii and Iceland. It has been suggested that mantle plumes were the source of gold for at least some major gold provinces (Oppliger *et al*., 1997; Bierlein and Pisarevsky, 2008), and magma that comes not from the normal mantle, but instead from the Iceland mantle plume has been shown to contain slightly higher amounts of gold than normal mantle (Webber *et al*., 2013).

Plumes are thought to originate at the base of the mantle, where it is in contact with the hot core, and these hotter, buoyant plumes migrate upward over millions of years in a shape that resembles a mushroom (Fig. 5a). Eventually the plume 'head' reaches the surface and generates enormous amounts of volcanism (Richards *et al*., 1989) (Fig. 5b). After this burst of intense volcanism caused by the plume head, which can last for a million years or more, the plume tail forms a long-lived 'hotspot' that remains fixed in the same place for tens of millions of years, generally characterized by an active volcano or volcanic field (Fig. 5c). Tectonic plates move over this fixed plume 'tail,' and when an active volcano moves too far away from the hotspot, a new volcano is formed over the hotspot. The hotspot thus creates a chain of extinct volcanoes, leading away from the active volcano in the direction of the motion of the tectonic plate, in a way that might resemble fabric passing through a sewing machine (Fig. 5d). The Hawaiian Island chain is a perfect example, with the currently active volcano at the Big Island, and progressively older extinct volcanoes on the islands and seamounts stretching toward the northwest.

Burke *et al*., 2008 have suggested that mantle plumes originate not just anywhere on the boundary between the mantle and the core, but from anomalous regions identified through seismic studies. These regions are so deep and so small that exactly what they are remains a topic of lively debate. One appealing explanation is that these regions are the result of some material being pushed out of the core and into the mantle (Buffett *et al*., 2011). If this is the case, mantle plumes could provide a conduit to transport gold from the core directly to the crust, with very little interaction with the mantle (Fig. 5); this is a topic of active research, and there is not a general agreement among geologists.

## IV. THE THREE REGIONS THAT SUPPLIED IBERIA WITH GOLD

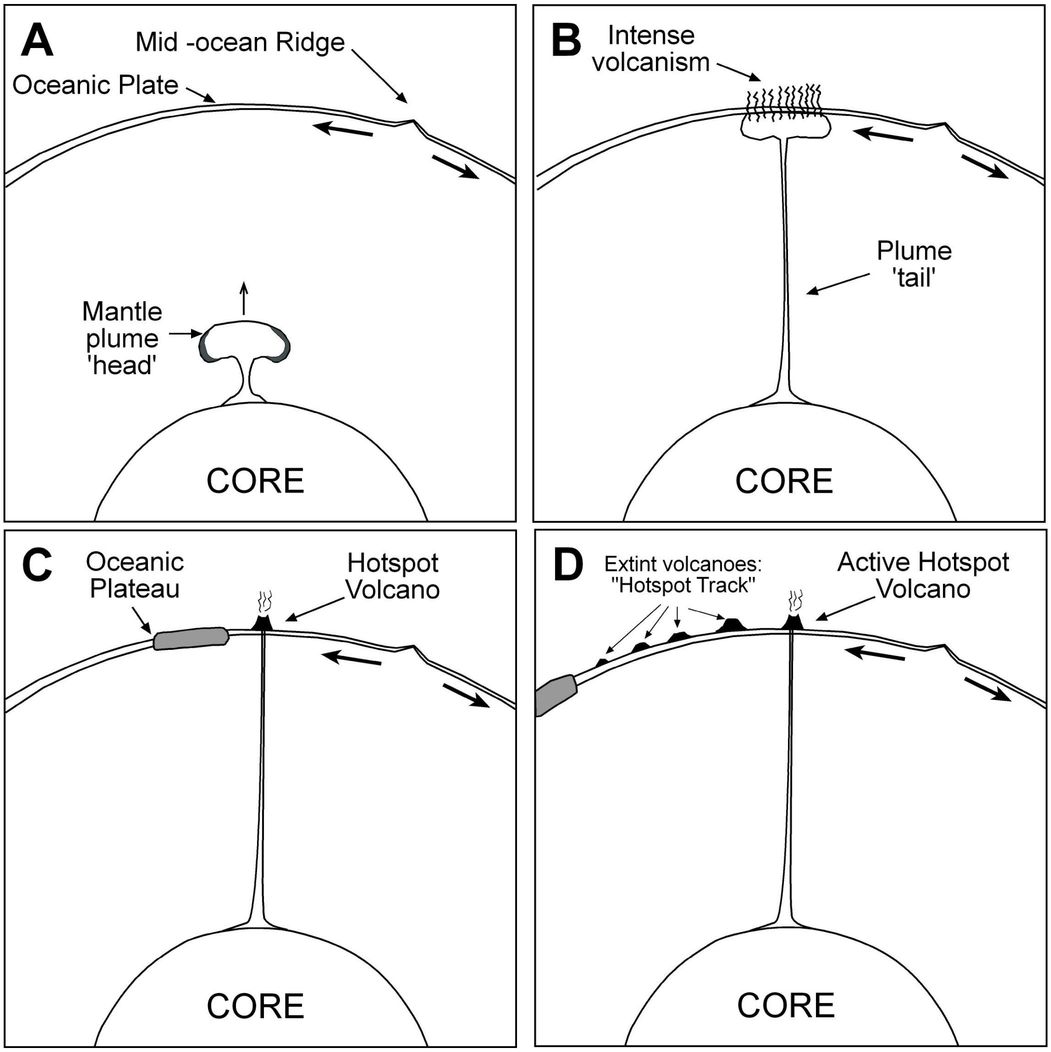


Figure 5. The evolution of a mantle plume. The base of the plume is rooted at the core–mantle boundary. Two tectonic plates separate from a mid-ocean ridge.
a. The plume rises from the core–mantle boundary in the shape of a mushroom.
b. The plume head reaches the bottom of a tectonic plate, and generates a large amount of magmatism and volcanism at the surface.
c. The plume head has entirely been erupted out or solidified on the underside of the tectonic plate, creating an oceanic plateau. The tail of the plume creates a volcano as the oceanic plateau moves away from the hotspot.
d. Each volcano at the hotspot is subsequently moved by the tectonic plate far enough away that the hotspot can no longer supply magma. That volcano goes extinct, and a new one is formed over the plume tail.

We have compiled databases for the three regions that supplied gold to Iberia, giving information about historical mining areas, where available, and about presently active gold mines and prospects. The information comes from the published literature, and from reports available on the web about modern mines and prospects in various stages of development. In many cases it has been possible to identify active mines and prospects on Bing Maps and Google Earth. We provide the databases in the Appendix, and here we summarize the distribution of gold deposits in each of the three areas in maps.

### West African gold

West Africa is the largest of the three regions, and also the oldest geologically, with continental crust that was produced by

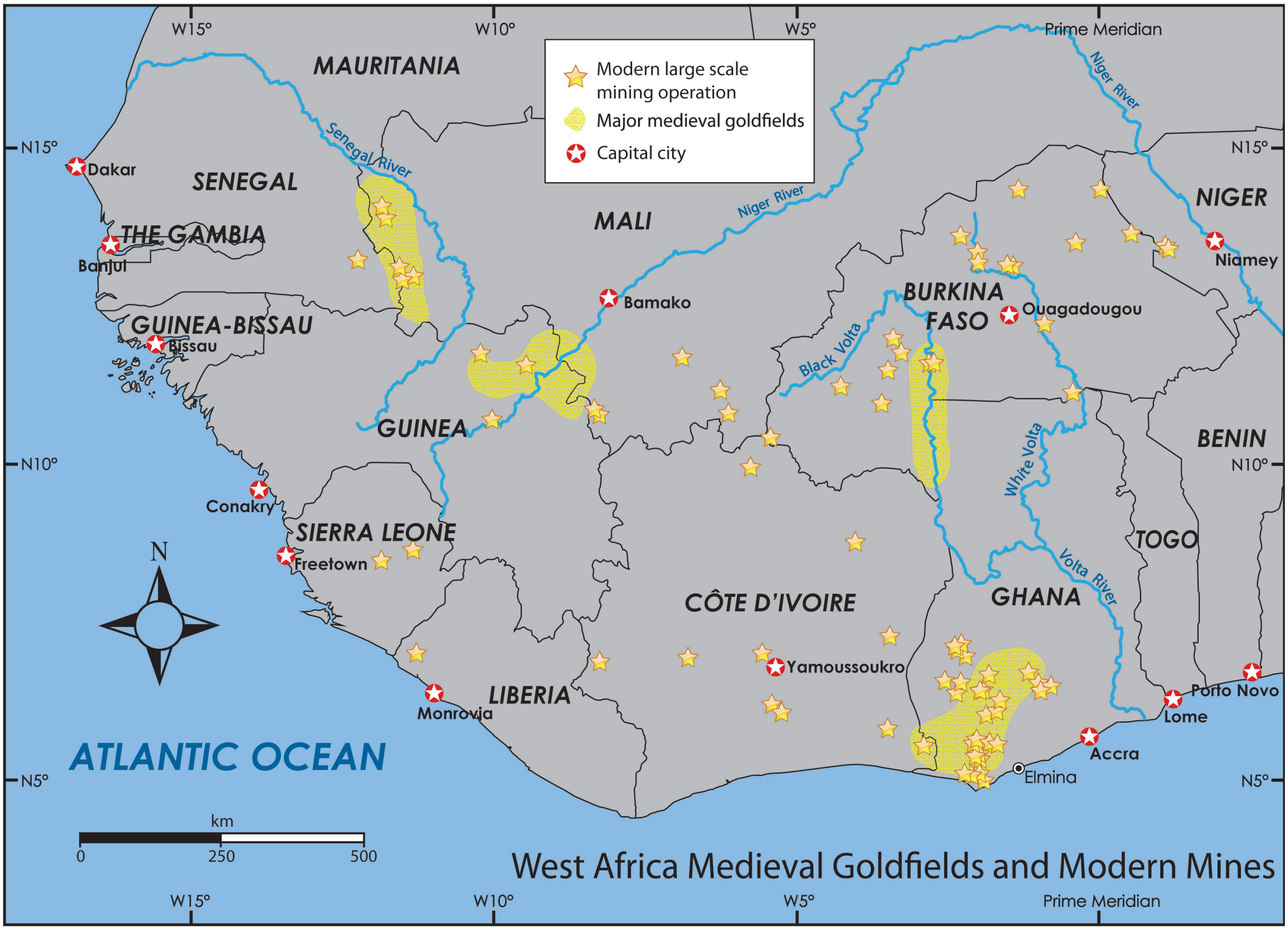


Figure 6. Gold deposits in West Africa showing historical and current mining activity. Elmina was the Portuguese trading center.

tectonic events about 2,200-2,100 Ma, in the Paleoproterozoic, around the time when our planet was beginning to acquire an oxygen-rich atmosphere and the first eukaryote cells emerged (Alvarez 2016, Ch. 7). We have compiled a database of medieval and modern gold mining areas in this region (Appendix 1), summarized on a map (Fig. 6).

Gold here is found mostly in the "Birimian" sequence, made originally of volcanic and sedimentary rocks (Smith *et al.*, 2016). Metamorphism — textural and chemical change in rocks due to heat and pressure — has changed the color of these rocks to shades of green. These "greenstone" metamorphic belts are separated by granitic bodies, and this kind of granite-greenstone belt is characteristic of Archean and Paleoproterozoic regions (de Wit and Ashwal, 1997). Granite-greenstone geology is not known to be forming today, and may be the result of processes that were only active on a hotter, young Earth.

Gold in West African deposits is commonly related to faults and shear zones and is mainly found in quartz veins and disseminated in surrounding rocks of all types that may host these veins.

Erosion of those veins has led to concentrations of gold flakes and nuggets in paleoplacer deposits, which have been exploited in both medieval and modern times. It was these rich and easily exploited gold placers that made the medieval West African empires — Ghana (4th to 12th centuries A.D.), Mali (13th to 16th centuries A.D.), and Songhai (15th to 16th centuries A.D.) — so wealthy and powerful.

## Iberian gold

The Iberian Peninsula (Appendix 2) is the smallest of our three regions, but gold exploitation has come from two geologically different regions (Fig. 7). Both are parts of the Variscan belt, a collisional mountain belt that crossed central Europe and, before the opening of the Atlantic Ocean, continued into the Appalachians.

One part of the Variscan belt in the southwest part of Iberia is the Iberian Pyrite Belt, an area where gold and other noble metals come from volcanic massive sulfide (VSM) deposits formed on the ocean floor by hydrothermal vents in what was a volcanically active spreading plate boundary. As discussed above, modern hydrothermal vents are the deep-sea "black smokers," some of which host abundant life despite the extreme conditions (www.youtube.com/watch?v=huTJlHMR_LE). The deposits in the Iberian Pyrite Belt are found in oceanic volcanic and sedimentary rocks of Devonian to Carboniferous age (ca. 383-323 Ma) (Gibbons and Moreno, 2002, p. 478), a time when the first seed plants, land vertebrates and primitive reptiles appeared in the fossil record.

Pre-Roman metal and gold working has been recognized in southwest Iberia dating back to Chalcolithic and Bronze Age times (O'Brien, 2015; Blanco and Rothemberg, 1981), but it was not until Roman times that substantial mining operations took place. Gold and silver were mined in the region, but they were not as important as other metals, such as copper, tin, iron, lead (O'Brien, 2015), with the addition of sulfur after the development of large open pits in the 20th

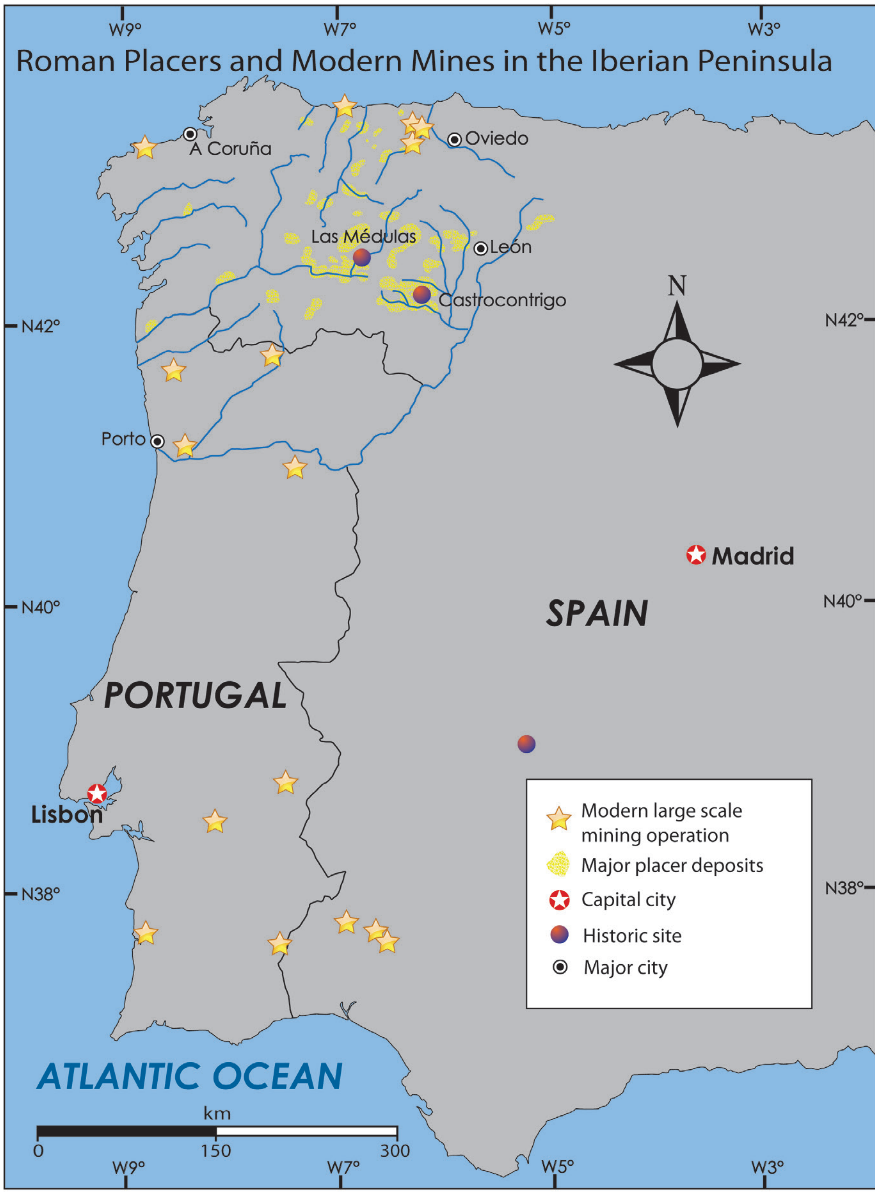


Figure 7. Gold deposits in the west Iberian Peninsula showing historical mining areas in the northwest, and current mining activity.

century (Gibbons and Moreno, 2002).

Northwest Iberia is also part of the Variscan belt. This belt was formed by the continental collision that brought together the northern continental mass (Laurentia) and the southern continental mass (Gondwana), thus assembling the most recent supercontinent, Pangea. The Variscan-Appalachian orogenic belt is geologically much younger (ca. 300 Ma) than West Africa, and most of its features are well explained by plate tectonic processes. These processes and the resulting geology are complicated, however, involving the suturing together of ribbon continents and the twisting of the mountain belt in Iberia into a doubly-curving "orocline," or bent mountain system (Gutiérrez-Alonso *et al.*, 2004; Johnston *et al.*, 2013). The northwest Iberian gold deposits are of the orogenic gold type reviewed by Goldfarb *et al*. (2001b).

**Colombian gold**

Colombian gold is found in the Andes, a long chain of deformed rocks with volcanoes formed above a subduction zone that is carrying oceanic crust of the eastern Pacific down to the east, beneath the South American continent. The Colombian gold belt is the youngest of our three regions; it began to form during the age of the dinosaurs (Mesozoic) and the subsequent proliferation of mammals (Cenozoic), but deformation and volcanism continue to play an active role in today's Andes.

The Colombian Andes (Nie *et al*., 2010) comprise three parallel ranges, separated by the valleys of the Magdalena and Cauca Rivers (Fig. 8). The Eastern Cordillera is continental in origin, while the Western Cordillera is made of oceanic rocks. Including the complex Central

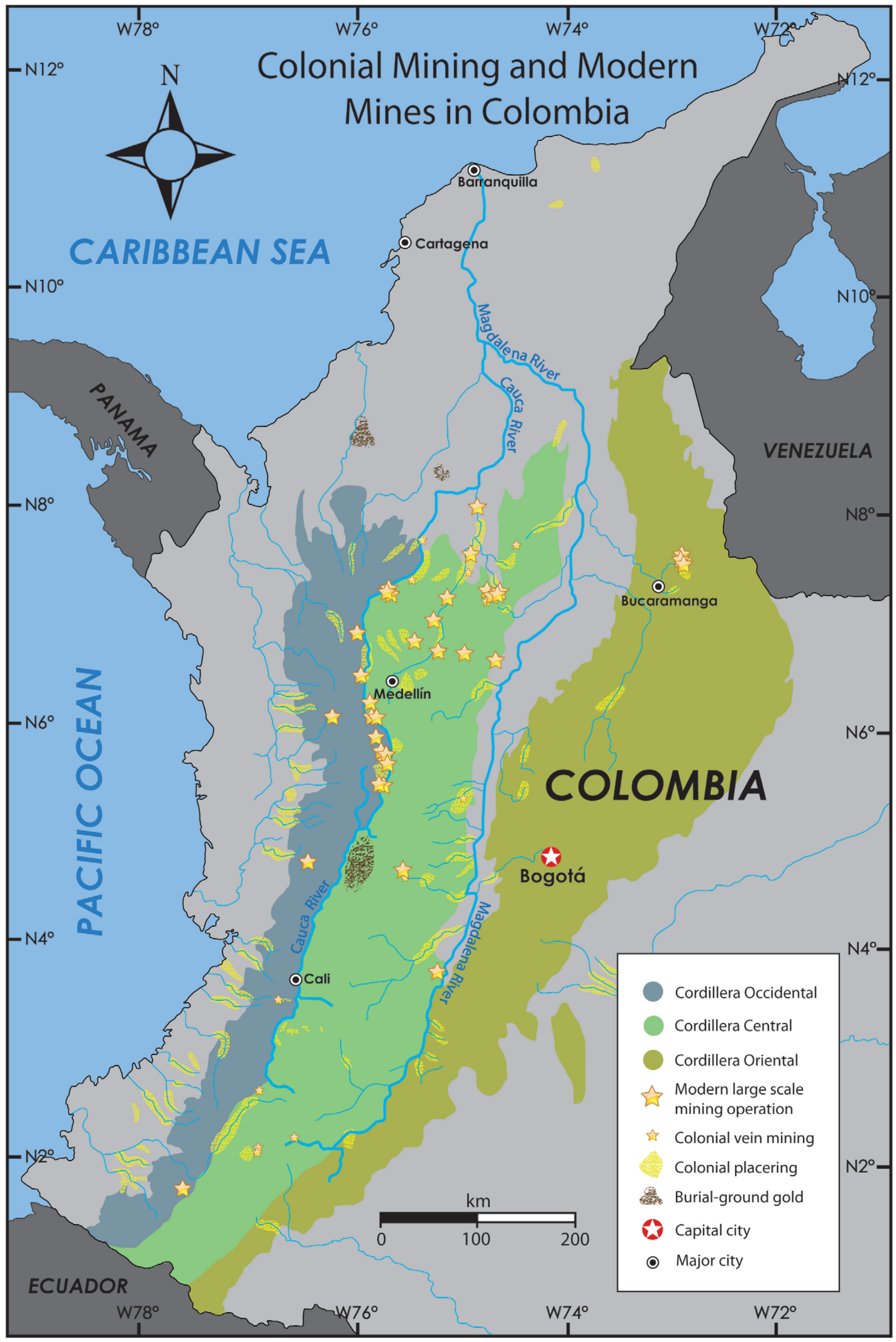


Figure 8. Gold deposits in Colombia showing historical and current mining activity.

Cordillera, surmounted by active volcanoes sourced by the descending subducting slab, the Colombian Andes record a long history of collisional accretion of continental and oceanic terranes and their lateral displacement. It is in this complicated geological environment that the Colombia gold deposits have been emplaced.

Our map and database (Appendix 3) show that Colombian gold is found in all three cordilleras, which seems surprising, considering their very different geological character. The most accessible exploitable gold in Pre-Columbian and colonial times was in placer deposits found along beds of the major rivers and their tributaries coming from the high rugged cordilleras, and in small and medium scale vein mining. Early on in the Spanish period, gold was also taken from Pre-Colombian burial grounds (West, 1952). A few mining operations of considerable scale (Fig. 8), along with smaller and illegal gold mining, are active in present-day Colombia.

## V. SUMMARY AND CONCLUSIONS

Gold is an uncommon metal in the Earth and plays little or no role in biology, but humans have chosen to value it highly, perhaps because of its attractive color, its resistance to corrosion and tarnishing, and its rarity. Because of this rather arbitrary valuation, people go to great extremes to find and extract gold, to accumulate it, and to take it away from other people. Because of its accepted value, gold can be exchanged for other things that have real, intrinsic value, like food, material goods, land, and the services of other people, like workers and soldiers.

For many centuries, the countries of Iberia, for contingent historical reasons, had easy access to large supplies of gold, which was not always used for the benefit of the Iberians. Gold from the peninsula itself was the basis for the coinage of the Romans, supporting the legions that expanded and maintained the Roman world. Gold from Sub-Saharan West Africa, extracted from the petty Muslim kings after the fall of Córdoba by the stronger Christian kings, helped bring about the Christian Reconquest, and paid for much of the Cluniac artistic flowering in France. Gold from the New World, and the even more abundant silver, helped the Catholic Habsburg kings of Spain make war on the Protestants of Northern Europe.

Gold was originally derived from supernova explosions and then dispersed and diluted in the early Earth. Over the 4.5 billion-year history of our planet, many different geological processes have concentrated gold into economic deposits of many kinds. Some of these are reasonably well understood, others are enigmatic and are the subject of continuing geological research.

The ways in which Earth concentrates gold, and all the other elements we humans use, can be understood at many different levels, from the very general to the complex and subtle. We hope that big historians will recognize the need for at least a basic understanding of Earth's virtuosic ability to concentrate and make useful all the chemical elements that originally were dilute, dispersed, and quite useless.

We thus hope that Carl Sagan's memorable aphorism, that "*We're made of star-stuff*," will be supplemented or replaced by a statement that contains a deeper understanding of Big History:

"*We're made of star-stuff, concentrated by Earth.*"

## VI. APPENDICES

Appendix 1: Database of historic and modern gold sources in West Africa.

Appendix 2: Database of historic and modern gold sources in Iberia.

Appendix 3: Database of historic and modern gold sources in Colombia.

## VII. ACKNOWLEDGMENTS

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