Rediscovery of the Elements

Cronstedt and Nickel

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Axel Fredrik Cronstedt (1722–1765) (Figure 1) was born in Ströpsta, an estate 38 km southwest of Stockholm (Figure 2).[1] Cronstedt was the great-grandson of Erik Jönsson Dahlberg (1625–1703), a noted fortifications director during Sweden's military predominance of the 1600s. Dahlberg owned various estates about Stockholm, including Ströpsta, where descendants of his daughter Countess Dorothea Beata Dahlberg (1669–1712) settled. Axel Cronstedt's father was Gabriel Olderman Cronstedt (1670–1757), himself an engineer in the military. By 1758, Ströpsta had been sold and the estate was allowed to deteriorate. Today Ströpsta consists of a scatter of houses in a rural setting of canola fields and rye fields ("rapsfält och rågfält")—a popular setting for photographic essays—with no hint of the noble lineage who had once lived there.[2b,3]

Axel Cronstedt was encouraged by his father Gabriel to follow in his footsteps and to study engineering, surveying, and cartography.[1] However, Cronstedt did not choose the military profession; instead, in 1738, he entered the University of Uppsala where he was instructed by Johan Gottschalk Wallerius (1709–1785), the first professor of chemistry (1750–1767), and the astronomer Anders Celsius (1701–1744), the inventor of the eponymous thermometer. (The original chemistry building[4g] and observatory still[4c] stand and have been previously described in *The HEXAGON*). However, Cronstedt never received a degree because with the renewed threat of war in 1743, his father was recalled to his military duties as an inspector of military fortifications and required the amanuensis services of his son. During these travels Axel saw his first mines and he became fascinated with mining and mineralogy.[2b,3]

During these mining travels, Axel Cronstedt met many persons in mining who guided him during his career.[1] Two major influences were George Brandt (1694–1768), the discoverer of cobalt,[4a] and Sven Rinman (1720–1792), the "father of Swedish mining and metallurgy."[5b] Brandt (not to be confused with Hennig Brand, 1630–1710, the discoverer of phosphorus,[4f]) worked at the *Laboratorium Chemicum*, the royal mining laboratory in Stockholm (Figures 3, 4). Cronstedt joined Brandt[2a] in the *Laboratorium* during 1746–1748 where he learned chemical analysis and the chemistry of smelting. He also visited the historic copper mines of Brandt at Riddarhyttan (Figure 2) , the site of Brandt's 1735 cobalt discovery.[4a] Sven Rinman (1720–1792), a member of Royal Board of Mining and Metallurgy (Bergskollegium),[5b] was the discoverer of Rinman's green ($CoZnO_2$), a pigment produced by heating cobalt oxide and zinc oxide. Cronstedt met Rinman at Uppsala and the two were close friends throughout their lives. It was Rinman who got Cronstedt the post at the *Laboratorium* and who then appointed him Assistant Superintendent of Mines.[2b,3]

The critical role of the blowpipe. Cronstedt was the first person to use the blowpipe in systematic analysis of minerals.[6] This simple tool was originally used by the goldsmiths to heat and solder a pin-sized spot in jewelry, but was adapted to the identification of components of small ore samples. In this method, the operator used a brass tube to blow a concentrated stream of air through a flame (e.g., candle) to heat a localized region on a test specimen. By varying the position of the blowpipe in the flame, one could treat the sample with an oxidizing flame or a reducing flame (or, in pre-

Figure 1. Axel Fredrik Cronstedt medallion, located in the Gamla Jernkontoret ("big iron office"), Kungsträdgårdsgatan 6, Stockholm (N59° 19.85 E18° 04.37), located only 250 meters south of the famous Berzelius statue.[4d] The medallion was prepared in the 1870s by Johan Frithiof Kjellberg (1836–1885), after an earlier portrait. Kjellberg's best known work is the statue of Carl von Linné in the Humlegården (N59° 20.34 E18° 04.37). Courtesy, Jernkontoret.

Lavoisier parlance, the phlogiston-poor or phlogiston-rich region of the flame). One would note color changes (both of the sample and of the flame), melting, sublimation, decomposition, and behavior with fluxes (such as borax), to make remarkably rapid and accurate identifications. In addition, the portability of this compact kit of instruments and chemicals allowed one to perform analyses in the home, laboratory, or field. Cronstedt characterized all the minerals at his disposal; in 1756, he studied the aluminosiliciate which "boils" (because of entrapped water) by blowpipe analysis[7d] and named it: "zeolite" for Greek "boiling stone." Soon many were using this tool—Sir Humphry Davy (1778–1829)[4e] and Jöns Jakob Berzelius (1779–1848)[4d] always carried their blowpipe kits with them on their travels throughout Europe. Various mineralogists discovered eleven elements with the aid of a blowpipe[6]—and the first of these was nickel by Cronstedt (*vide infra*).

Figure 2. Sites associated with Cronstedt and nickel. Cronstedt was born at Ströpsta (N59° 10.88 E17° 27.05) and died at Nisshytte (N60° 16.99 E15° 43.56). Nickel was found in Los at the Koboltsgruva (cobalt mine) (N61° 44.52 E15° 09.40); the nickel monument is 250 meters southeast (N61° 44.48 E15° 09.66). An ingot of nickel was prepared at the Laboratorium Chymicum *in Stockholm (N59° 19.59 E18° 04.05). Cronstedt visited Brandt's cobalt mines at Riddarhyttan (N59° 49.64 E15° 33.00). Cronstedt discovered scheelite (tungsten source) at Bispberg Klack (N60° 21.44 E15° 48.92). From the Kuhschacht mine in Freiberg, Germany (N50° 54.81 E13° 20.82) a sample of nickeline was obtained from which Cronstedt procured nickel which he showed was identical with Swedish material.*

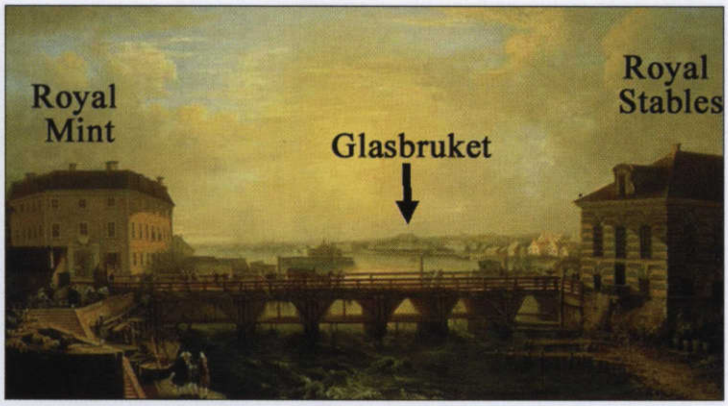

Figure 3. This 1761 painting by Johan Sevenbom (1721-1784) includes the best rendition of the Royal Mint (built 1696), where the Laboratorium Chymicum *with a hearty forge was established in 1727; here cobalt and nickel were first prepared by Brandt and Cronstedt, respectively (N59° 19.59 E18° 04.05). Title: "Utsikt från Lejonbacken över södra Norrström med gamla Norrbro, Kungliga Myntet och Kungliga Stallet" ("View from the Lejonbacken over the south North Stream with old North Bridge, Royal Mint, and Royal Stables.") "Glasbruket" (old glass factory) in the distance was one of the laboratories of Berzelius near the present City Hall (Radshuset), the site of the Nobel Banquets.* Courtesy, Stockholms Stadsmuseum.

Figure 4. Near the Sverige Riksdag (Swedish Parliament) is this Annex (government offices) on Mynttorget (Mint Square) (inset). This is the location of the previous Royal Mint, taken down in 1784.

Cronstedt's systematic identification of minerals.[1] Cronstedt, having studied at Uppsala, was very much aware of the work of Carl von Linné (Latinized "Carl Linnaeus," 1707–1778) who was professor of botany there. Linné created a comprehensive binomial nomenclature (*Genus, species*) for flora and fauna.[8] Linné depended on external characters such as color, texture, shape variations, etc. He was aware that his taxonomy was "artificial"—he once stated "Deus creavit, Linnaeus disposuit" (God created, Linnaeus organized)[8]—but fortuitously his method of "counting pistils and stamens" or "describing teeth and bones" actually reflected deeper relationships, *viz.*, eventually the sequence of evolution and even the DNA code itself. Moving from the Animal and Plant Kingdoms to the Mineral Kingdom,[9] Linné attempted this method, again using external characteristics such as form, color, or hardness, but here the system failed. For example, he used the same genus *Gemma* for ruby, zircon, and emerald (*G. rubinus, G. hyancinthus,* and *G. smaragdus*), when today we know the compositions are widely divergent, *viz.*, Al_2O_3, $ZrSiO_4$, and $(Be_3Al_2(SiO_3)_6)$; he assigned beryl its own species name, *Gemma beryllus*, when it actually was chemically identical to emerald. Cronstedt was the first to understand that in God's universe of the three Kingdoms, the third must be treated differently.

Cronstedt wrote a book on his ideas, titled *Försök till Mineralogiens eller mineral-Rikets upställing* ("An attempt at mineralogy or arrangement of the Mineral Kingdom").[10a] According to his "New Mineralogy," the composition, as determined by chemical analysis, should be the method of classification of minerals. He originally did not intend to publish, but when he showed his draft to Rinman and other friends in 1756, they strongly urged him to proceed. Anticipating the displeasure of Linné, Cronstedt published the book anonymously (Figure 5)—he apologized that "it was only an essay" and he "wanted to be at liberty to modify it...to be sheltered from too severe censures."[10b,g] According to Per Enghag, the Swedish expert on chemical elements (Figure 6), Cronstedt was also afraid of the fierce reaction it might invoke in the scientific community, particularly with Wallerius who was still

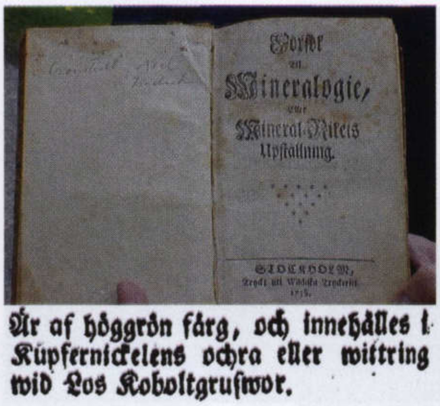

Figure 5. An original 1758 copy of Cronstedt's Försök till Mineralogiens eller mineral-Rikets upställing *("An attempt at mineralogy or arrangement of the Mineral Kingdom"), provided by our Swedish hosts.*[4a] *The author's name has been penciled in at the upper left because it was published anonymously. LOWER: the specific entry for nickel vitriol*[10c,i]*: "Is of a deep green color, and is contained in/Kupfernickel or in other erosion products/at the Los Cobalt mine."*

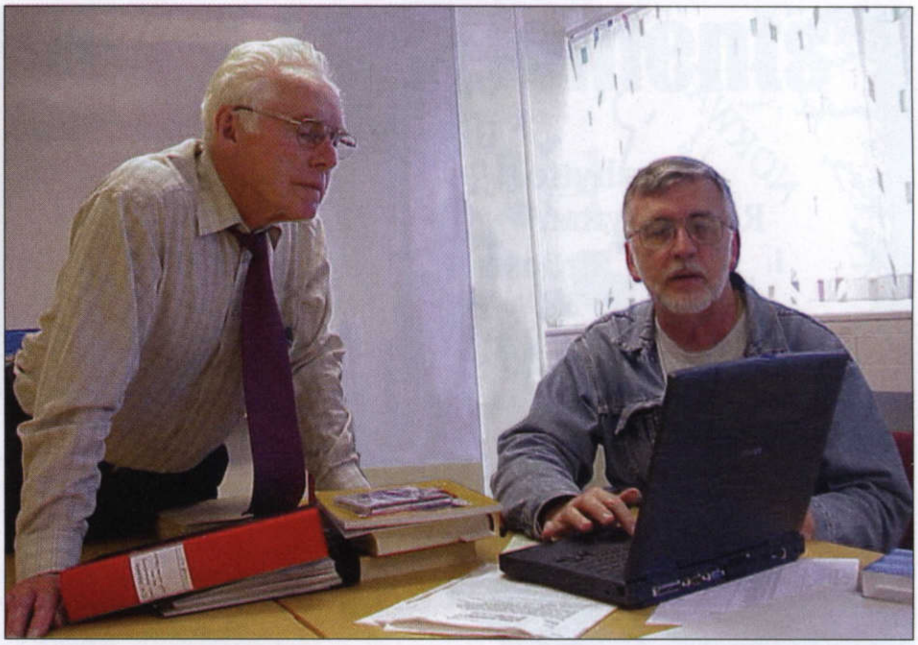

Figure 6. An expert on Swedish chemistry, Dr. Per Enghag (left), has written perhaps the most complete and objective account of the discovery of the elements.[5a] *He has been especially helpful in contributing much information for the "Rediscovery" project, including details of the lives of the Swedish scientists.*

Figure 7. Copper can oxidize to form a green patina, for example, as is seen with the Statue of Liberty. The mineral Kupfernickel (left) confounded the medieval miners; it appeared to be copper, because it can grow a green coating (right), but in the hands of the coppersmith it didn't behave. Obviously, it was cursed, hence its name "copper devil" (German). Actually, the mineral was nickeline (nickel arsenide, NiAs), which oxidizes to form apple-green annabergite (nickel arsenate, $Ni_3(AsO_4)_2 \bullet 8H_2O$). From the element collection of the authors.

Chair of Chemistry of Uppsala (the more progressive Torbern Bergman, 1735–1784, the mentor of Scheele,[4c] did not replace Wallerius until 1767). Wallerius had just written a treatise "Mineralogy"[11] which was rendered obsolete by Cronstedt's new mineralogy.[2b] For example, Wallerius maintained that heavy spar (barium sulfate) was a form of gypsum (calcium sulfate) when Cronstedt's blowpipe would immediately differentiate them (green and red flames, respectively). Far ahead of his time, Cronstedt reported in *Försok* an "unidentified earth" in a "rödlätt Tungsten" (red heavy stone)[10d,j] from the Bastnäs Mine in Riddarhyttan[4a] which 45 years later was isolated by Berzelius and Hisinger from that same mine and named "cerium"[4a]—the first element of the lanthanide series.

Cronstedt was not optimistic about the acceptance of his ideas; in the Foreword of *Försok,* he complained about those who were "so addicted to the surface of things, that they are shocked at the boldness of calling Marble a Limestone . . . ."[10b,h] (the two are chemically identical, $CaCO_3$). To his surprise, his ideas were rapidly accepted. By the time the English translation[10f] appeared, the author was well known and his name appeared with distinction on the cover page. Also in this English translation, a beautiful treatise appears of Cronstedt's methods of the blowpipe. The translator was Gustaf von Engeström (1738–1813), the successor to Brandt as manager of the *Laboratorium Chymicum*. Engeström, in his praise for the treatise, remarked that he had "never seen a book so rapidly become known."[1]

The discovery of nickel. Miners in Germany had often seen reddish stones which could be dissolved in nitric acid to produce greenish solutions, behaving like copper. However, it was impossible to obtain any metallic copper from these solutions. The undesirable stones were called "Kupfernickel" (copper-devil) (Figure 7) since they obviously were cursed.[5]

After Cronstedt had finished his sabbatical at Brandt's copper mines in 1748 at Riddarhyttan, he was well aware that cobalt was also available in quantity at Los, 210 km north (Figure 8). Thinking that Los might have more interesting minerals, Cronstedt visited the mine (Figure 9) and came away with several new specimens. One particular mineral dissolved in nitric acid to generate a green solution (just as in Germany). Electroless deposition was not understood in the mid-18th century, but it had been known since Paracelsus (and explained *ca.* 1700 by Lemery and Homberg on the "atomic theory" of "pointy acid particles"[12])

Figure 8. The welcoming sign to Los uses the old spelling "Loos." Sweden mandated a sweeping orthography reform in 1906 (e.g., "Upsala" to "Uppsala," "Loos" to "Los," etc.), but the old spelling persists for historical names, e.g., the name of the mine. The sign reads: "Welcome to Loos! Rooms and breakfast. Cafe." With only a few hundred inhabitants, Los is far north of the populated areas of Sweden, and is accessible only by automobile.

Figure 9. The Koboltsgruva ("Cobalt Mine") in Los is open to tourists and has numerous exhibits and offers a mine tour. This mine dates from the 1700s and has been worked for copper, bismuth, and cobalt. A cobalt glassworks was established at Sophiendal, about 8 km southeast; it was operational only 1763–1771 and today only scattered ruins remain. As the authors descended into the mine, their Geiger counter (which they always carried with them) showed an extremely radioactive layer about one meter thick. This was commonly observed on their travels through mines in Europe!

Figure 10. Cronstedt in his laboratory tries to precipitate metallic copper by adding iron filings to the green solution from the Los ore, but fails.[5b] *This experiment was the key piece of evidence that allowed Cronstedt to conclude that he had discovered a new component, which he named "nickel" from the* Kupfernickel *of German lore.*[5a] *He was elected to the Swedish Academy of Science in 1758.*

that iron "releases acid from copper" which can then fall out of solution. Thinking that he had found a copper mineral, he placed pieces of iron in the solution to plate out the copper—but nothing happened (Figure 10).

Cronstedt also noticed that these stones weathered to produce green spots (Figure 7). He scraped off this green powder and heated it with charcoal at the forge at the *Laboratorium Chymicum* (Figure 3) in Stockholm. He obtained a regulus (small ingot) which was white and magnetic.[5a]

He subsequently obtained Kupfernickel from Saxony, Germany (Figure 11) and found it also produced the same new metal. He presented his findings[7b,c] to the Swedish Academy of Sciences in 1751 and 1754 and called his new metal "nickel."[7c] (Note 1)

Figure 11. The Kuhschacht ("cow shaft") mine in Freiberg, Germany was once a prolific provider of silver and also furnished the Kupfernickel that Cronstedt studied. The mine was operational 1514–1834. This monument on Wernerplatz on Bahnhofstraße (Railroad street) marks the site of the original shaft (now filled in). The "Huthaus" (mining shack) dates from 1700 and is today used as a dentist's office; the peculiar attic window—"eye"—is a "Gaubenfenster" or "German eye." On the monument, Alexander von Humboldt is mentioned as a student of the Freiberg Mining Academy (1791–1792).

The acceptance of Cronstedt's discovery. In the pre-Lavoisier era, metals were considered to be the combination of a calx with the flammability principle (phlogiston). Whenever a new metal was isolated, such as the medieval bismuth, antimony, or arsenic, it was considered not so much a "discovery" as a novel calx-phlogiston combination produced for the first time, like a new baking recipe. With a backdrop of fire, earth, water, and air as the primary ele-

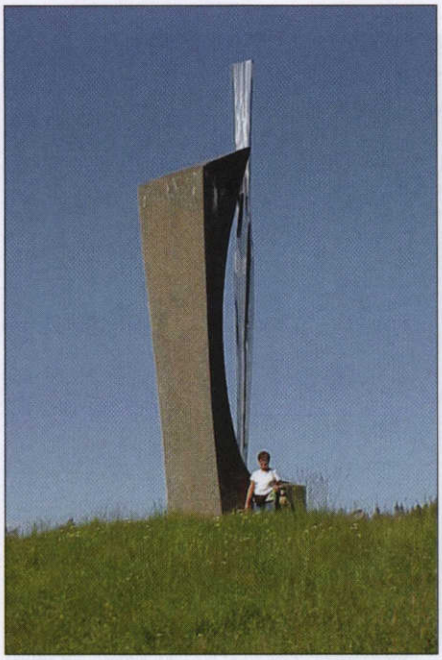

Figure 12. The nickel monument, "Form för Nickel" in Los, was erected in 1971 by Olof Bernhard Hellström (1923–), sponsored by the township of Los, International Nickel Limited, and the Royal Swedish Academy of Sciences. The 30-meter blade appears to be nickel, but it is actually stainless steel.

Figure 13. At the base of the nickel monument, beside the main road through town, is a memorial to Cronstedt, in both Swedish and English. The English portion reads: "For centuries cobolt [sic] ore was mined in the township of Los to be used in the colouring of glass and porcelain. In 1751 Axel Fredrik Cronstedt (1722–1765) discovered in the ore the new element nickel which was later to become of world-wide importance in high quality alloyed steel. Cronstedt, metallurgist and chemist, belongs to the great pioneers in the field of mineralogy. . . ."

ments, the differentiation between metals was obscure, and it was natural to suspect that any new "discoveries" were simply new blends of the old metals. Any experimentation would tend to "prove" this view, because a preparation was almost always contaminated with impurities.

Brandt was the first to attack the question of new metals.[2a] In 1733, when he announced the discovery of cobalt,[13] he listed six true metals (gold, silver, copper, iron, lead and tin) and the six "semi-metals" which were not so malleable (arsenic, zinc, bismuth, antimony, mercury, and cobalt), and he elaborated tests to differentiate them. To Cronstedt, nickel would have been the seventh semi-metal. However, many were not convinced; French scientists[14] said that Cronstedt had isolated a mixture of cobalt, iron, copper, and arsenic[14a] or had simply confused cobalt and nickel.[14b] Ten years after Cronstedt's death, Tobern Bergman at Uppsala confirmed Cronstedt's claim by isolating pure nickel,[15] pointing out that nickel stubbornly retains arsenic and cobalt and that this was the origin of the confusion. But it took decades for all scientists to become convinced that nickel (and cobalt) were not mixtures of previously known substances.

At the end of the 18th century, Lavoisier published his *Treatise*[16] where he abandoned

Figure 14. Bispberg Klack is a 314-meter mound where various iron mines have been worked during the past millennium. Somewhere down this slope in 1751 Cronstedt discovered the "heavy-stone" which was named "scheelite" in 1821.

Figure 15. Scheelite (discovered by Cronstedt) sometimes forms octahedral crystals, but it is more commonly amorphous like this specimen. This sample is displayed in the acclaimed Scheele museum in Köping, Sweden.[4c] Swedish miners and mineralogists call this form of scheelite "fruset snor" ("frozen snot") for obvious reasons.[4a] Night rock hunters search for this mineral with portable UV lamps, which cause scheelite to fluoresce a beautiful blue, very much like diamond's fluorescence.

the idea of phlogiston and defined the metals as elements; these included not only the six metals and seven semi-metals defined by Brandt and Cronstedt, but also newly discovered manganese, molybdenum, platinum, and tungsten (Lavoisier considered calcium, magnesium, barium, aluminum, and silicon as "earths").

Today, a nickel monument is located (Figures 12, 13) at the crossroads at Los memorializing the discovery of nickel by Cronstedt. (Note 2)

Later life of Cronstedt. In 1760 Axel Cronstedt married Gertrud Charlotta Soderhielm (1728–1769), and the following year he moved to Nisshytte, an estate 54 kilometers north of Riddarhyttan. Nisshytte was only 10 kilometers south of Bispberg Klack, (Figure 14) where Cronstedt in 1751 had found a "Tungstein" (heavy-stone),[7a] (Figure 15) from which Scheele discovered the element tungsten three decades later.[4c]

At Nisshytte Cronstedt purchased an iron foundry, but was now more interested in gardening—he grew flowers and introduced the potato to the region.[2a,3] He felt he had often been unfairly glossed over in promotions; he lamented that he "had avoided Linnaeus' plant kingdom and wanted to return," noting that "roses gave more reward than minerals, which were sorely lacking in monetary return."[2b] Nevertheless, he still devoted his energy and time to the mining profession when asked. After attending a meeting in Stockholm, he returned exhausted and faded rapidly, dying at the young age of 42.

His foundry became idle, and his mansion burned down in the 1800s; now only a stone foundation remains. Today, Nisshytte is an attractive rural settlement, with cottages for rent where summer vacationers can rest, hike in the forests, and swim and fish in the lakes.

Notes.

NOTE 1. There is some doubt as to exactly which was *the* Los mineral from which Cronstedt first isolated nickel.[5] Candidates are: (a) nickeline, *i.e.*, "Kupfernickel," NiAs, (b) annabergite, $NiAsO_4$, (Figure 7) or (c) gersdorffite, NiAsS, a silvery-gray mineral.[5a] Enghag (Figure 6) prefers (c) because Cronstedt's major entry from both Los and Saxony was described by him as *niccolum ferro et cobalto arsenicatis et sulphuratis* (nickel-iron arsenide sulphide).[10e,k] Other Swedish geologists, notably Erland Grip (1905–2007),[17] also favor the gersdorffite interpretation. Undoubtedly, Cronstedt worked ultimately with all three minerals.[5b]

NOTE 2. An alloy called "packfong" containing nickel was produced in China prior to Cronstedt's discovery. This alloy is today known as "German silver" and contains copper, zinc, and nickel. In their lecture tours, the authors have often been questioned whether or not the "discovery" of nickel (as well as a few other elements) should be credited to the Chinese, whose technology was superior before Europe's ascendency during the Age of Enlightenment (17th–18th centuries). "Rediscovery of the Elements" has necessarily been restricted to the modern scientific paradigm; other works[5a,18] present excellent discussions of advanced technologies.

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