A History of Global Metal Pollution

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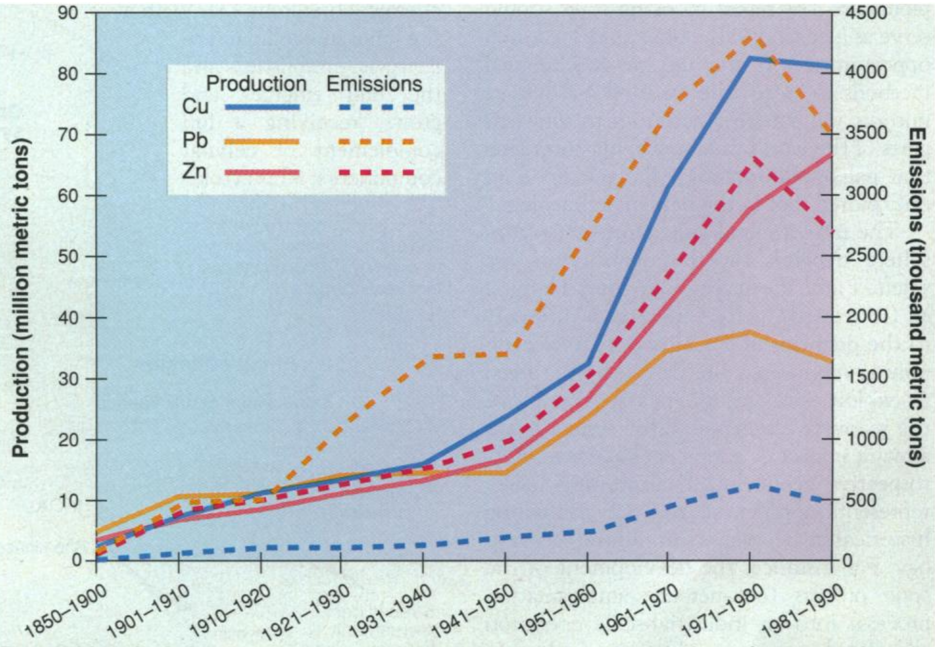
Ancient environmental impact. One source of air pollution by heavy metals. [Photograph: Alinari/Art Resource, New York]

Air pollution is often regarded as the product of modern technological development. In fact, environmental pollution caused by heavy metals began with the domestication of fire: The deposition of small amounts of trace metals released during the burning of firewood altered the metal levels in the cave environment. With the discovery of mining and metal-working techniques in ancient times, the close link between metals, metal pollution, and human history was formed. Mining and trade of mineral resources became a key feature of the early economy, and metal recovery techniques attained status as a barometer of technological advancement for ancient cultures. During the time of the Roman Empire, large quantities of heavy metals, especially Pb (80,000 to 100,000 metric tons per year), Cu (15,000 tons/year), Zn (10,000 tons/year), and Hg (>2 tons/year), as well as Sn and Zn, were required to sustain the high standard of living (*1–3*). Although the mines were operated on a small scale, uncontrolled smelting of large quantities of ores in open fires resulted in substantial emissions of trace metals to the atmosphere. Emissions of toxic metals were serious enough to draw the attention of a number of ancient authors and may have been responsible for the interdiction of mining operations in Italy and near some ancient cities (*4*). The influence of ancient mines and smelters on air quality on a global scale is now documented in the report by Hong *et al.* on page 246 of this issue (*2*).

Although many ancient mines in Central Europe were reopened beginning around the 11th century A.D., it was the development of large furnaces with tall stacks during the 16th century that drastically extended the sphere of influence of smelters and industrial installations (*5*). The Industrial Revolution brought about unprecedented demand for metals and an exponential increase in the intensity of metal emissions, both in absolute masses and in the number and type of toxic metal compounds released (see graph). The emissions may be compared with mine productions of Cd, Cu, Pb, Ni, and Zn; about 90% of the mine outputs were consumed in this century (see graph). These inventories show that the cumulative industrial releases of heavy metals into our environment are indeed massive and pervasive and have overwhelmed the natural biogeochemical cycles of the metals in many ecosystems (*5*, *6*).

Records of atmospheric metal pollution dating back to ancient times have been preserved in various types of natural deposits, especially polar ice caps, ombrogenic (nutrients derived exclusively from the atmosphere) bogs, and aquatic sediments (*7*). Because of the rapid rates of accumulation, ice deposits often provide the most detailed paleopollution records including short-term fluctuations. Their use in retrospective geochemical monitoring tends to be tempered by the thick pile of firn that must be drilled or excavated to reach preindustrial layers and by the very low concentrations of trace metals [often $<10^{-9}$ g of metal per gram of matter (g/g)], which necessitate meticulous procedures in the collection and analysis of samples. Peat bogs and aquatic sediments are deposited at much slower rates and hence provide compact records that can further be distorted by basin characteristics and postdepositional behavior of metals (*7*). In spite of differences in the accumulation efficiency and nature of the archives, the various deposits have yielded a coherent picture of long-term contamination of the atmosphere with heavy metals.

In their pioneering work, Murozumi *et al.* (*8*) used profiles of Pb levels in ice layers from northwest Greenland to deduce that extensive contamination of Arctic atmosphere with Pb began before the Industrial Revolution. Subsequent studies (*1*) found that the Pb contents of ice layers deposited in Greenland between 500 B.C. and A.D. 300 were about four times that of background, implying widespread pollution of the Northern Hemisphere by emissions from Roman mines and smelters. The Pb content returned to baseline levels (~0.5 pg/g) after the eclipse of the Roman Empire and then began a steady rise with the mining renaissance in Europe, reaching values of 10 pg/g in the 1770s and 50 pg/g in the mid-1990s (*1*). Since the 1970s, a sharp (approximately sevenfold) decrease in the Pb content of Arctic snow fields has been documented, which can be attributed to the phase-out of leaded gasoline in North America and Europe. Evidence for widespread atmospheric Pb pollution is not lim-



Recent historical changes in mine production and anthropogenic emissions of trace metals to the atmosphere [revised from (5)].

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ited to the Northern Hemisphere, however: Wolff and Suttie (9) have shown that the mean Pb content (2.5 pg/g) of Antarctic snow deposited in the 1920s was five times that of background (~0.5 pg/g); pollution records before this time remain to be ascertained. Lower Pb levels in Antarctic compared to Arctic regions are attributable to smaller emission intensity in the Southern Hemisphere.

Studies of other types of deposits have confirmed the global nature of Pb pollution dating back to ancient times. Analysis of lake sediments from various parts of Sweden found a peak in Pb deposition around 2000 years before present (B.P.) and steady increases that began from around 1000 years B.P., reached 10 to 30 times background levels by the beginning of the Industrial Revolution, accelerated during the 19th century, and usually peaked in the 1970s (*10*). Records in ombrogenic bog at Etang de la Gruyere, Switzerland, show rates of Pb deposition by 2000 years B.P. that were an order of magnitude above background as well as the usual highly elevated values in recent deposits (*11*). Similar records with peaks in Pb deposition during Roman times have also been reported in peat bogs in other parts of Europe, including northern Scotland, Gordano Valley near Bristol, and Featherbed Moss in Derbyshire (*7*).

Hemispheric-scale pollution in ancient times apparently was not limited to Pb. The latest paper by Hong *et al.* (*2*) provides evidence for widespread atmospheric contamination with Cu from Roman mines and smelters. Ombrogenic bogs, aquatic sediments, and snow fields are distributed widely throughout the globe. These deposits can potentially be used to trace the broad temporal and spatial differences in mineral resource exploitation. The report by Hong *et al.* should serve as a beacon to the unexplored research opportunities in the use of geochemical methods to "read" the exciting archives of mining and smelting activities in different parts of the world. It is somewhat surprising that paleopollution study has remained an unexplored tool in the field of archaeology.

The rate of metal emission to the atmosphere depends on the quantity of ore smelted and the technology used. Hong *et al.* (*2*) related the ice core records primarily to the quantity of Cu mined. Advances in mining technology are driven by the need to exploit new ore minerals or to improve the recovery efficiency. Either impetus has a major impact on metal emission rate. Retrospective geochemical monitoring hence represents a potential tool for evaluating historical developments in mining technology. For instance, the development of the *patio* process (or mercury amalgamation process) into an industrial-scale operation stimulated massive production of silver in South and Central America and left behind an unparalleled legacy of Hg pollution in the area. Between A.D. 1580 and 1900, annual loss of Hg in the silver mines averaged 612 tons/year (in a range of 292 to 1085 tons/year) and totaled about 196,000 tons (*12*). So far, little attempt has been made to "read" the geochemically archived records to determine the pattern of dispersion and deposition of such massive quantities of Hg at the local, regional, or global scale. The archives, one suspects, will likely show that the current problem of Hg pollution associated with the gold rush in Brazilian Amazon is only a faint reenactment of a major old tragedy.

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Cell Shape Determination: A Pivotal Role for Rho

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Morphogenesis, the complex process that shapes cells to their myriad forms, has long fascinated biologists. Two reports in this issue (*1*, *2*) move us closer to an understanding of why one particular cell—a yeast cell—has its characteristic shape.

Cells of the yeast *Saccharomyces cerevisiae* bud to form daughters in their own image. Once a mother cell commits to undergo a new mitotic cycle, a bud site is chosen through an elaborately regulated biochemical hierarchy (*3*). With a site chosen, cellular polarity is established and the bud emerges and grows, receiving a full complement of cellular components; after cytokinesis, the bud forms a daughter cell. It is during bud construction that the distinctive yeast cell shape is established by the architecture of cell wall glucan deposition. Construction of the bud begins at the bud tip, and many components need to be marshalled at this site to ensure their ordered elaboration: The actin cytoskeleton polarizes the secretory apparatus to the bud tip to provide the necessary building materials for cell wall assembly.

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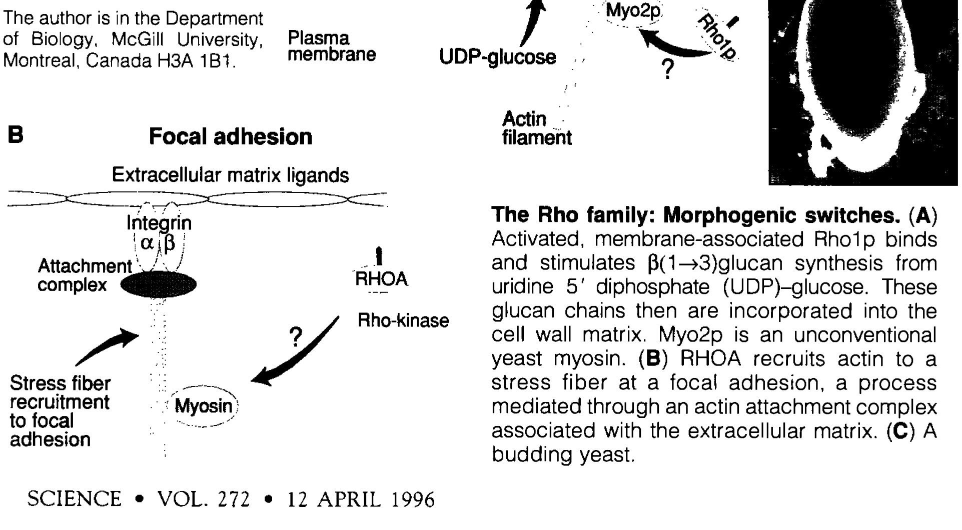

The Rho family: Morphogenic switches. (**A**) Activated, membrane-associated Rho1p binds and stimulates $\beta(1\rightarrow3)$glucan synthesis from uridine 5′ diphosphate (UDP)–glucose. These glucan chains then are incorporated into the cell wall matrix. Myo2p is an unconventional yeast myosin. (**B**) RHOA recruits actin to a stress fiber at a focal adhesion, a process mediated through an actin attachment complex associated with the extracellular matrix. (**C**) A budding yeast.