Historical Trends in U.S. Mineral Statistics for Selected Non-Ferrous Metals

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ABSTRACT

Production figures for selected nonferrous metals—aluminum (including bauxite and alumina), copper, lead, tin, titanium, and zinc—by the United States, as well as other statistics for these commodities, show strong volatility during 20th century. Major shifts were driven by the Great Depression and the two World Wars, but other major temporal changes are also noted that are not directly related to such global crises. For example, the price of tin exhibited a strong maximum in the 1980's, which is unrelated to world production, but rather to failed efforts of the International Tin Council to control price. In the case of copper, U.S. exports have varied throughout the second half of the century, by more than a factor of 5. Such volatility might be explained in part by global economic conditions, at least throughout recent decades. Supporting the interpretation of the importance of foreign pressure on the domestic commodities market is a close correlation between domestic consumption of antimony and its elevated price in the mid 1980's,possibly pushed up mostly by the world dominance in production of this commodity by China. However, only very superficial explanations can be advanced for such relations before we have examined, in concert, information for a much larger suite of commodities.

INTRODUCTION

This report represents the second in a series of reports (Piper et al., 1999) on mineral commodities in the U.S. The statistics for antimony, bauxite, alumina, and aluminum, copper, lead, zinc, tin, and titanium for the United States are presented here. The major sources of information for the report are the annual commodities reports, published in previous years by the U.S. Bureau of Mines and, since 1996, by the U.S. Geological Survey (Minerals Yearbook, 1887-1997), the Minerals Statistical Compendium published in 1991, covering the years 1970 through 1990 and now on the web (minerals.usgs.gov), and the U.S. Geological Survey web site publication (minerals.usgs.gov; OF-01-006) covering all years for which the Yearbook has been published, but currently including only a limited number of commodities. These reports represent an enormous effort throughout this century by individual commodity specialists, each monitoring and compiling information about several metal and non-metal commodities, in some cases ranging from mine production, to industrial consumption, to exports, to imports, to price. However, as with any report of such size, compiled by many different authors, and covering so many years and dating back to 1882, the data are, not infrequently, difficult to access. For the years 1970 to 1990, the data can be accessed on the Internet (Statistical Compendium, 1991), but in a format that requires considerable editing if one tries to import them into one of the more commonly used computer plotting programs or other statistical packages. Also, data for the different commodities in the Compendium are not uniformly presented; some commodities are treated quite thoroughly, whereas others are treated only superficially. The Compendium also is available as a hard copy. Although that publication uses metric units throughout, as do the annual reports printed since 1988, annual reports prior to 1988 use as many as three different units in a single table of data, for example, short tons, long tons, and metric tons. Also, table formats, as well as the data reported are not consistent through the years, even for a single commodity. The lack of uniformity reflects a change in focus, or effort, as end use of a particular commodity might have changed through time, or as its importance, source, or overall availability might have changed. Nonetheless, it somewhat complicates easy access and use of the data. These problems with the two earlier reports are now being addressed by publication of the information on the web (Kelly and others, 2001).

None of these comments are intended as criticism of the older reports, but are rather intended to point up some of the problems of the older reports and the need to present this information in a single format, making it easily accessible and in a ready-to-use table format that currently available computer plotting and statistical programs will accept without significant editing. The use of a single format will allow simple editing, further allows newly collected information of future years to be easily entered into the tables, and permits information of past years to be updated as more reliable information is gained through literature searches. For example, early production figures for the rare earth elements, listed in terms of monazite, can be converted to rare-earth oxide equivalent, the current reporting procedure, by a simple arithmetic step.

The data are presented in this report in paper copy and are available on floppy disc upon request. Inquiries can be directed to the authors, but should perhaps first be sent to the senior author. Upon completion of the series of reports, the data will be made available on CD Rom and the Internet. The latter will eventually carry all additions and updates.

The examination of the separate data files reveals several interesting temporal trends that are clearly related to major global events. However, relations between statistics for an individual commodity, or between the statistics of different commodities show possible causes of more subtle, albeit significant, trends.

PURPOSE

The purpose of this report is to make available statistics on a selected group of non-ferrous metals (Sb, Al, Cu, Pb, Sn, Ti, and Zn) for the 20th century, in a single format that can be easily accessed by computer without the need for major editing. Subsequent reports will present statistics on (1) iron and the ferroalloy metals and (2) chemical industrial and agricultural minerals. Our aim is to document historical trends in domestic production, overall availability, consumption and use, to highlight possible forces that drive those trends. For example, the major driving force for production must be demand, but short-term trends of a year to several years can be dominated by politics and economics. These are extremely important, but here we focus more on long-term trends by presenting annual averages of commodity statistics that extend over several decades, rather than monthly, quarterly, or seasonal statistics. Geology, technology, and of course, demand are perhaps more important determinants of decadal trends than politics or short-term economic swings, although economics and politics will surely still be important, even for long-term trends. The major determinant in every case for all commodities in every country is eventually economics.

Considering all commodities, each presents a somewhat different domestic scenario (Table 1). As examples, for gold, we are currently a major exporter; for barite we are a net importer, but at the same time being a major producer; and for lead, we have produced in the past few decades approximately the same amount as we have consumed. In the case of lead, this situation and its availability will likely remain much the same through the next two or three decades as it is today (see below). In the case of the copper, domestic availability is increasingly failing to meet an ever expanding demand and could very possibly change more so in the next few years. For other important commodities, for example, phosphate (listed as P in Table 1), the current market will very definitely change in the coming years. How will a change from domestic to foreign sources influence availability, that is, as the less costly recoverable ores of domestic mines are gradually exhausted, and/or environmental concerns about mining come to outweigh the benefits of domestic production? Of course, we depend totally on imports for several commodities, e.g., antimony, tin, and now bauxite, and that number will increase with time. Examining these commodities will possibly assist in ascertaining how, for example, the phosphate market will behave in the future as we turn to foreign sources.

We can see the pressure from being a major producer to becoming a major importer by examining trends in the statistics for bauxite throughout the 20th century (Fig. 1). The historical trend in mine production of bauxite, and its ever growing import, follow the classical curve (Fig. 2) of eventually all commodities (Craig et al., 1996). The examination of past and current trends for all commodities may allow the United States to predict future trends and assist in planning what its needs might be and what countries will likely meet those needs, i.e., be the major suppliers, in the 21st century.

PROBLEMS

In many of the older reports, and in current reports as well, consumption has been presented as domestic industrial consumption of raw material. In the case of antimony, as recently as 1995, as much as 40 percent of U.S. consumption was reported as derived from secondary recovery. However, this value may have been miscalculated for much of this century (Table 2). Lead presents another type of problem. Domestic production, currently, approximately equals the amount that is consumed by industry. That is, the consumption of lead is reported on the basis of domestic industrial requirements. Lead is used almost totally in the manufacture of lead-acid batteries. Consider if U.S. customs began requiring foreign auto makers to install batteries made in this country with all autos imported into the U.S., admittedly, an unlikely scenario. Consumption by domestic industry, as statistics on consumption are now compiled for all commodities, would increase proportional to the number of autos imported, a significant amount. This increase would occur without any change in the purchasing habits of the American public or any increase in the number of autos using our highways. Industry, and the country at large, would still be consuming the same amount of lead. The lead being used would simply be an end-use product of domestic production. Thus, should we report only industrial consumption or total end-use consumption of finished goods? In the case of lead, it would be quite easy to adjust consumption figures to reflect total consumption, as it largely has a single end-use. That would not be the case, however, for those commodities that have multiple uses, for example, silver, aluminum, and, indeed, most other commodities (Table 1).

For this report we will maintain the procedures of the annual reports of the U.S. Bureau of Mines and U.S. Geological Survey for reporting consumption. The alternative requires that we go back and examine data of imports of finished goods for all previous years, no small task, in addition to consumption by domestic industry, perhaps a worthy task. In the case of lead, we could probably compute the current total consumption as lead has essentially a single end-use, but for past years, when lead had a more complicated end-use and for most other commodities, the task would prove to be much more difficult. Perhaps, it is more important for this report that we maintain, throughout any reporting period, a consistency in the definition of what we report. Consumption by the U.S. public, however, is surely a statistic needed for planning a long-term strategy of metal availability and consumption. Collection of information about total consumption should be one goal of reports that follow this initial report.

We have refrained from reporting the resource of a commodity, either domestic or global. For most commodities, if not all commodities, this figure has grown throughout the period of exploitation (Hodges, 1995), this for a number of reasons, such that the current resources of many commodities are at all time highs, even though, as we shall see, consumption too is at an all time high. It is becoming clear, however, that the environmental problems created by an unchecked consumption of some commodities may be as great or greater than the economic problems created by shortages of a commodity.

In several cases, we have taken the liberty of rounding off data to fewer significant figures than reported in the original publications. This might have imposed a difference with values reported in the Compendium, but in essentially every case of less than 2 to 3 percent.

COMMODITY STATISTICS

Throughout much of the time of publication of the Yearbooks by the Bureau of Mines and U.S. Geological Survey, statistics for the most recent 5-year period have been published in each Yearbook. This has allowed for the revision of information in subsequent Yearbooks, information that was published as estimates the first year, in many cases. Such revisions were based on additional in-formation gained in years following the initial publication. In many cases revisions were made throughout the five years that a set of data was published. We have attempted to present here updated, i.e., revised, figures by examining the Yearbooks on a 4- (or fewer) year basis. However, the last-published set of data for a commodity may differ slightly from that presented in this report. A random examination by us suggests that the differences are less than about 5 percent.

Antimony

All antimony deposits are hydrothermal in origin and the antimony is initially present as a sulfide mineral. It most often is present as a secondary mineral in lead, zinc, and silver and/or copper ores, for example, in the Coeur d'Alene district in Idaho, and in tin-tungsten veins and tungsten skarn deposits. Thus, it is recovered as a by-product of these other metals. However, it is the primary product of the Murchison mine in South Africa.

Only for the few years during and immediately following WWII , for example, extending into the Korean War, did the U.S. produce a significant amount of this commodity (Table 2), as a by-product of other metals. Even then production was far less than domestic industrial demand (Fig. 3a and b). Demand, or consumption, has varied throughout this century, exhibiting strong minima during the depression of the 1930's and the recession of the early 1980's and maxima during the war years. Consumption (Fig. 3b) in the 1990's has been at an all time high of approximately 50,000 metric tons (mt).

U.S. imports (Fig. 3c) account for roughly 60 percent of U.S. demand (Fig. 4), which in turn accounts for about 30 percent of world production (Fig. 3d). Major foreign suppliers to the United States are China (60 %), Bolivia (15 %), and Mexico (10 %). It is imported (60 % of consumption) as ore, concentrate, the trioxide, and metal. The remaining 40 percent consumed has been derived from old scrap, principally antimonial lead, i.e., lead-acid batteries. However, the contribution from batteries has recently been revised downward (Fig. 5), owing largely to possible errors in its calculation in the past. Also, a change in the technology of manufacturing of batteries has decreased the demand for antimony.

Exports (Table 2), mostly to Canada and Mexico, are small, but not insignificant.

China dominates the world antimony market, accounting for almost 80 percent of the world's production. Even so, it has not been able to dictate nor stabilize the world price (Fig. 3a). One reason has been the ability of other countries to find alternative metals to antimony, as China has attempted to set the price independently of demand. Much of this reduction in usage has come in the production of lead acid batteries.

Dominant use of antimony during the first half of this century was in lead-acid batteries. Although approximately 20 percent of domestic consumption still goes into this application, use as a flame retardant, mostly in plastics, now dominates its use, accounting for almost 50 percent of domestic consumption. If China attempts to dictate the price in the future, it seems likely that alternatives will be found for this use as well. Bromine is long established in flame-retardant use and tin is entering this market. It is possible that will happen even without attempts to artificially fix price, owing to the highly toxic character of Sb.

Bauxite/Alumina/Aluminum

The most common aluminum ores are laterite deposits of bauxite, which typically are a heterogeneous mix of several oxihydrides of aluminum minerals, iron oxide, and aluminum silicate. The most abundant minerals of the oxihydrides are gibbsite, boehmite, and diaspore, and of the silicates is kaolinite. Bauxite deposits represent a residuum of weathering that forms under conditions of high rainfall, high mean temperature, good drainage, but modest relief. These conditions, which are met in tropical areas of the world, result in the removal (leaching) of the more soluble rock components—Na, K, Ca, and Mg—but not removal of the deposit by erosion. Under slightly acid conditions, achieved possibly by the presence of decaying organic matter, silica and iron are also removed to varying degrees, thus leaving a concentrate of aluminum oxihydrides. An original aluminum rich bedrock would seem to enhance formation, but this is not required. Deposits in Jamaica and Hispaniola have formed on bedrock consisting mostly of carbonate rocks.

In a few areas, principally Russia, aluminum-enriched bedrock itself is mined, for example, syenite. Still, world primary production comes dominantly from bauxite deposits.

The youngest laterite deposits, which formed over the past 25 my, are located in tropical latitudes; deposits found at higher latitudes, in the southern United States and southern Europe, are older, having formed when these now temperate areas experienced a more tropical climate.

Bauxite was mined in the U.S. throughout this century (Table 3), reaching a maximum in 1943, but with its total value achieving a maximum of approximately $30,000,000 in 1970 (Fig.

6a). However, production failed to meet consumption following WWII, owing to a tremendous increase in demand. Production dropped sharply in the early 1980's as high-grade ores were exhausted and/or production costs became non-competitive with foreign producers. The year, 1983, marked the first year since bauxite production commenced in the U.S. in 1889 that

last decade of the 20th century, domestic production from Georgia and Alabama represented less than 1 per cent of world production and none of that was used in the production of aluminum metal.

Aluminum needs for the U.S. have been met by increased imports of alumina (Al_2O_3) (Fig. 6b), mostly from Australia; aluminum (Al), mostly from Canada, Russia, and Venezuela; and bauxite ($Al_2O_3{\cdot}6H_2O$), mostly from Guinea, Jamaica, Brazil, and Guyana.

Bauxite represents essentially the sole primary source for aluminum in this country and the major primary source world wide. Thus, production, consumption etc. statistics for alumina and aluminum are not totally independent of the production, consumption, etc. of bauxite and their statistics may involve counting twice the same material.

Secondary recovery of aluminum, from scrap, has increased over the second half of this century both in absolute terms and in relative terms of total production and consumption (Fig. 6c). Aluminum from scrap currently roughly equals aluminum from primary production. This might be expected to grow in coming years, possibly significantly. For example, the recovery of aluminum from old scrap (scrap once used and discarded), as opposed to recovery from new scrap (that from manufacturing plants), stands at only about 20 per cent of apparent consumption. Thus, expanded recycling programs could quite easily return a greater percentage of old scrap aluminum to processing plants.

World production of bauxite (Fig. 6a), although showing tremendous growth throughout this century of approximately 5-orders of magnitude, has also been quite volatile. It was high during both world wars and dropped to lows during periods of economic downturn, for example, during the depression of the 1930's, but also in the early 1980's and early 1990's. The U.S. consumes about 10 percent of world bauxite production, but this is somewhat misleading. The U.S. produces about 25 percent of the world's aluminum from imports of bauxite and alumina, and consumes somewhat more of the world's production of aluminum, or about 30 percent.

The world's leading producers of bauxite during much of the 1990's have been Australia, Guinea, Jamaica, Brazil, Venezuela, and China, with approximate percentages of 40 percent, 13 percent, 10 percent, 8 percent, 5 percent, and 5 percent, respectively. Of these countries, Guinea and Jamaica provide over half of the U.S. imports. World reserves of 25,000,000 mt seem adequate to maintain the current level of production for the foreseeable future.

The world's leading aluminum producers are the U.S. (Fig. 6c), Russia, Canada, China, Australia, and Brazil, accounting for approximately 65 percent of world production; U.S. production is 17 percent. An extremely high energy demand required for the production of aluminum from bauxite, makes world trade in bauxite extremely robust. The U.S., Canada, and Norway produce little or no bauxite, but combined, they produce roughly 30 percent of the world's aluminum. This picture could change in the near future as China, Brazil, and Venezuela, for example, expand their production of aluminum from domestic ores. All three have considerable energy sources themselves. Also, expanded production of alumina by other bauxite-producing countries
could increase trade of this product between such countries and metal-producing countries.

U.S. and world consumption of both bauxite and its major end product, aluminum, have increased enormously during the second half of this century, but it has not been a smooth ride (Fig. 6e). Aluminum consumption has increased by about 10-fold during this time. During the most recent 25 years, however, the consumption of aluminum has varied from a low in 1975 of 3.5 x 10^6 mt to a maximum in 1993 of 6.9 x 10^6 mt. It seems to have stabilized somewhat over the past 5 year, remaining above 6 x 10^6 mt. This stability has been achieved largely because of a relatively healthy domestic economy. This same economy might be expected to drive an increase in production into the 21st century (Fig. 6f).

Aluminum exports (Fig. 6d), largely to Canada, Japan, and Mexico, account for about 13 percent of U.S. production. The figure is somewhat misleading, however, as the U.S. imports significant quantities of metal ingot, which are made into semi-fabricated products that are then exported and appear in the total export data. All exports do not then come from domestically produced ingot.

Aluminum has an extremely varied use, which will surely continue the increase in demand for this metal in the future, at least for the long term. For the last half of the 1990's, packaging and transportation each accounts for approximately 25 percent of domestic consumption, followed by packaging (20 %), building and construction (15 %), and electrical uses, consumer durable goods, and machinery and equipment (each about 7 %).

Copper

The largest copper deposits in the world, yielding the greatest amount of copper, are porphyry-type deposits. They represent low-grade deposits, which are mined on an exceedingly large scale. They are most common along the western continental margins of North and South America. Volcanogenic massive sulfide deposits (VMS), which are of two types, represent a second class. The Cyprus-type deposit formed at divergent margins of the earth's crust; whereas the Kuroko-type deposit formed at convergent crustal margins. Their names are derived from the areas where they were first identified. Stratiform deposits, hosted by clastic sediments, represent a third class of deposits. Most geologists consider the source of the copper, and other associated metals, nonetheless, to have been derived from hydrothermal solutions that reacted with the organic fraction of the hosting sedimentary rocks. These deposits can extend over thousands of square kilometers. Examples include the Kupferschiefer deposits of northern Europe and deposits of the copper belt in western Africa. Skarn deposits, formed through the interaction of hydrothermal solutions and carbonate wall rock of an intruding granitic magma, constitute another class of copper deposits. Supergene alteration has produced ores largely of copper oxide and/or carbonate minerals that can cap an underlying, otherwise, sulfide ore. Deposits of this type have yielded extremely high-grade ores and resulted in the discovery of an underlying and larger sulfide ore body. They have been mined in the past, but no such deposits are currently in production.

The U.S. production of copper (Table 4) ranks second in the world, accounting for approximately 12 percent of world production (Fig. 7a-b). Production increased in the 1990's to an all-time high, before decreasing toward the end of the decade. Of the ten current leading producing mines in the U.S., seven are located in Arizona. Several domestic producers have opened or expanded foreign operations, mostly in South America, during the last decade. In contrast, secondary production (Fig. 7a), production from old scrap, has increased only slightly over the past 40 years, varying between approximately 300,000 and 600,000 mt per year, or roughly 25 percent of primary production currently. Total production from scrap has shown a similar trend. In the mid 1990's the scrap market was relatively weak, despite a strong growth in the demand for refined copper. Nonetheless, production from scrap shows a strong correlation with price (Fig. 8a).

Imports of copper have increased sharply in the last several years, from a low in the early part of the 1990's (Fig. 7d). The trend in exports for this period has been the opposite. Although mine production has increased substantially during this same period (Fig. 7a), it has not been able to keep pace with consumption, which has increased almost 30 percent during this same period (Fig. 7f). Price (Fig. 7b, c and 8c) seems to influence little trade, but it does reflect the level of consumption (Fig. 8b). Certainly there exists a rough, temporal, parallel trend between price and consumption throughout the second half of the 20th century. Price has been extremely volatile, with substantial down turns having been recorded in almost every decade.

World production (Fig. 7b), similar to mine production in this country (Fig. 9), has increased over the past 50 years, but with slight down turns in the late 1960's and early 1980's. As an example of the increase in world production, mine production in Chile, which accounts for roughly 25 percent of the world's copper, has increased 2-fold in the last decade alone.

Use of copper in building construction and in the electrical and electronic products industry are the two leading sectors of copper consumption, representing approximately 40 and 25 percent of domestic consumption, respectively. Another 15 to 20 percent is used by the industrial machinery and equipment sector and approximately 10 percent in transportation equipment. Electrical application in all sectors accounts for almost 80 percent of consumption. How the development and expanded use of fiber-optic cable will influence the consumption by this sector remains to be established, but it could be substantial

Lead and Zinc

These two metals are grouped together because they have similar origins; that is, they are frequently found and mined together. Their uses and history of consumption are, however, quite different. The two dominant minerals are both sulfides, galena in the case of lead and sphalerite in the case of zinc. They precipitate from hydrothermal fluids, but under several different environmental conditions. Mississippi Valley-type deposits, named for their wide occurrence in this area, formed from brine solutions of 15 percent or more salinity that were expelled from proximal sedimentary basins. Precipitation occurred within limestones from solutions that followed extensive cave or fracture systems within the host rock. Sedimentary exhalative (sedex) deposits occur within clastic sediments; they represent stratiform hydrothermal sulfide deposits that formed from submarine hot springs that may or may not have debauched onto the sea floor. Association with nearby volcanism is problematic. Volcanogenic massive sulfide (VMS) deposits are largely of the Kuroko type, mentioned above as a source of copper. Vein deposits represent a fourth type, for which strongly saline solutions were injected into the host rock from associated magmas at temperatures of 350 °C or higher. Precipitation may have occurred in carbonate rocks to form skarns, in some cases, with relatively abundant silver co-precipitating.

Primary lead production in the U.S. has had an uneven history (Table 5, Fig. 10a). It reached a maximum in the 1920's, but declined sharply during the depression, and has never fully achieved the same levels since. However, production was high throughout the 1970's. It has been at a slightly lower level and somewhat more volatile throughout the 1980's and 1990's.

Secondary production (Fig. 10a), although showing a decline in the early 1980's, has been less volatile. It currently is at an all time high and now represents more than two thirds of total domestic production. Secondary recovery has been largely from lead-acid batteries. This can be seen in the relation between secondary recoveries of lead and antimony (Fig. 11), despite the recent adjustment of secondary antimony. The changes in this relation in 1940 and again in the early 1970's likely represent, in part, changes in technology of lead-acid batteries production, but also expanded use of antimony in other applications. For example, in the late 1960's, 35 percent of antimony went into the production of antimonial lead and 15 percent into flame proofing of chemicals and compounds. In 1997, the ratios were 9 percent and 58 percent, respectively.

Export of lead (Fig. 10b) has not been a significant part of U.S. production for the past century. Imports, however, represented approximately 30 percent of U.S. consumption from 1940 to about 1965. In the late 1960's, both primary and secondary production increased rather sharply, such that imports since that time have accounted for only about 15 percent of apparent consumption.

World mine production (Fig. 10c) is headed by Australia, with the U.S., China, and Peru (in that order) the next leading producers, and together accounting for slightly over 50 percent of total primary production. As shown by smelter production, world production has responded to some of the same pressure as has domestic production. The long-term outlook for both would not seem to be encouraging.

Domestic consumption of lead (Fig. 10a) has exhibited major temporal changes, but is currently at an all time maximum. Sharp decreases in consumption seem to have reflected the economic climate (Fig. 12a) rather than any of the major shifts in the use of lead that have occurred in this century. For example, two major decreases in consumption occurred in this century, one during the 1930's Depression and the other during the recession of the early 1980's. Even so, con- sumption has been curtailed in several sectors, in no small part, due to government legislation that recognized the strongly toxic nature of lead and that attempted to control its impact on the environment by limiting its use. Secondary production seems to have responded similarly (Fig. 12 c).

Uses of lead have changed through the years, perhaps more so than any other commodity, owing to its strongly toxic behavior. For example, in 1955, 15 percent of lead was used as an additive in gasoline, 10 percent in pigments, 2.5 per cent in pipes etc, and 30 percent in storage batteries. In 1997, storage batteries accounted for 87 percent, pipes less than 0.5 percent and the other two former uses are not now listed. These changes have been made possible by the development of substitutes for lead, but enforced by government legislation. For example, in 1967, the EPA set standards for automobile emissions of lead. In 1974, gradual reductions began; the European Community did not follow this course until 1984. Plastics have reduced further the use of lead in building construction, electrical cable covering, and containers. Tin has replaced lead as a solder in potable water systems. Its use in storage batteries may also be reduced in the future, with the development of alternative types of batteries now being experimentally tested. Such a development would surely deal the lead mining industry an even more severe blow than curtailment of its use in its other former applications.

Production of zinc (Table 6, Fig. 13a) comes from several States, but most zinc now comes from a single mine, the Red Dog Mine in northwestern Alaska, which produced 2.12 x 10^6 mt of ore, with an average grade of 18.8 percent zinc in 1994. This represents slightly over 50 percent of Zn production. Mines in other states (for example, Missouri) may actually produce more ore, but considerably less Zn.

The import of zinc, as slab, has risen sharply in the last 15 years (Fig. 13b) to meet a growing demand, despite a sharp increase in mine production beginning in 1989 with the start up of the Red Dog Mine (Fig. 13a). Canada represents the major supplier. Exports of ore and concentrate have also increased, largely as a result of production at the Red Dog Mine (13c). It is perhaps not an exaggeration to say that this one mine dominates the zinc market in the U.S. The U.S. production of slab zinc from scrap (Fig. 13d) and from ore (Fig. 13e) has remained relatively constant over the past 15 to 20 years. As a result, the increase in production from the Red Dog Mine has led to the sharp increase in export of concentrate (Fig. 13c).

Approximately 55 percent of zinc is used in hot-dip and electro-galvanizing. Perhaps the fastest growing use of this material is galvanized steel framing in the residential construction sector. Another 20 percent is used in zinc-base, die-cast alloys, followed by 10 to 15 percent in brass alloys. Smaller, but significant, percentages are used in paint, solder, fungicides, and pharmaceuticals. U.S. consumption of zinc is expected to grow (Fig. 13a), maintaining the U.S. as the largest consumer country in the world. Increased production in several countries (Fig. 13f) indicates that world capacity will be adequate to meet any increase in demand.

Recently, the price of zinc has exhibited strong variation (Fig. 13f), somewhat similar to that of copper. The maximum in 1989 of 82 cents/lb represented a doubling in price from 1987. It again dropped to almost half that value in four years, before climbing back to its present level.

Tin

The occurrence of tin, like that of several other commodities, is largely restricted to a few countries. Approximately 80 percent of world production comes from as few as five countries. The U.S. currently has no primary production (Table 7).

The majority of world production (Fig. 14a) comes from placer deposits, but most of the major deposits can be traced directly to lode deposits. Most are associated with granite intrusions, e.g., pegmatites, quartz veins, stockworks, and disseminated, clustered around protrusions known as cupolas at the top of an intrusion. Tin can occur with a number of other mineral commodities, with tungsten-vein and stockwork deposits, porphyry molybdenum deposits, and as a sulfide replacement (with other metals) in limestone. However, the dominant ore mineral is cassiterite, the highly stable tin oxide that can survive weathering and erosion, to be eventually concentrated as a placer deposit.

In earlier years, the U.S. produced small amounts for domestic consumption, sometimes as a byproduct of other metal mining activities, but the data were withheld for most years as they were considered proprietary, there being only one or two domestic producers in any given year. Currently, domestic production comes solely from secondary recovery of tin (Fig. 14b), which has held a rather constant share of U.S. consumption (approximately 29 %) for many years (Fig. 15). The balance of U.S. consumption has come from the import (Fig. 14c) mostly of unwrought metal, and less from U.S Government stockpile disposals. Major suppliers have been, in order of amount, Brazil, Bolivia, Indonesia, and China. All four are among the major ore producing countries of the world: China (approximately 27 %), Indonesia (20 %), Brazil (15 %), Bolivia (10 %), and Peru (8 %). Malaysia and Thailand, long major producers, now account for as little as 5 percent, down from 20 percent as recently as 1990.

Tin is rather unique among the non-ferrous metals, in that it is perhaps the only metal that is experiencing a long-term decline in consumption (Fig. 14c). This is due in large part to the increasing use of aluminum (and plastics) during the past 35 years in the beverage can sector. The decline in tin consumption is very strongly related to the increase in aluminum consumption (Fig. 16). However, tin-plate-steel cans still account for about 25 percent of the can industry, where they are used mostly in the packaging of food stuffs. Other important uses are in solder, bronze and brass, terne plate (a lead-tin alloy of 3 or 4 to 1, plated on steel), and chemicals. Its early importance as an alloy with copper to form bronze and with lead to form pewter are well chronicled (Kesler, 1994; Craig et al., 1996). Both alloys are widely used even today.

The price of tin (Fig. 14a) dropped following the collapse in late 1985 of the International Tin Council. It has since remained in the range of $2.50 per pound. Since 1956 the Council had attempted to control the tin price. As tin production and price show little relationship (Fig. 14a, 17), it will clearly be necessary for the major tin producing countries to limit production if the low tin prices are to improve, on a long term basis. They are attempting to do just that. For example, in 1994, the Association of Tin Producing Countries agreed to export quotas: China 20,000 mt, Indonesia 30,000 mt, Bolivia 16,600 mt, Malaysia 8,200 mt. In 1995, reported production figures were the following: China 52,000, Indonesia 30,000, Bolivia14,400, Malaysia 6,400. Brazil, the world's third leading producer country, was not a party to the agreement, having joined the Association that year. In 1994, it reported mine production at 27,000 mt, in 1995 at 16,800 mt.

Titanium

Titanium occurs in minor amount in virtually all rocks, at levels of approximately 0.5 to 1 percent. The dominant economic minerals are ilmenite, rutile, and leucoxene, the latter being an alteration product of ilmenite from which iron has been leached. The minerals tend to be widely dispersed in their host rock but, in a very few cases, the former two are enriched in mafic rocks. The major rutile deposits are placers, made possible by its to weathering and relatively high specific gravity. Ilmenite too is recovered from placer deposits, but approximately 40 percent comes from hard rock (igneous) deposits. The relatively high crustal abundance of titanium and a high demand would seem to offer future technology a challenge to develop improved and more sophisticated processing methods. Such development could expand this market many fold.

Major metal producing countries are Australia (currently about 50 percent of world titanium metal production), Norway, Sierra Leone, India, Canada, Republic of South Africa, and Ukraine (Table 8). The United States produces a significant amount from placer deposits, possibly about 25 to 30 percent of domestic demand, but the data are proprietary. As with statistics for other commodities, world production seems to be cyclical (Fig. 18a). Nonetheless, it has somewhat leveled in the past several years. It is possible that offshore deposits will be exploited in the future to replace modern and ancient, on-land, beach deposits that are now heavily exploited. Import/export figures also are quite cyclical (18b).

Titanium has a single major application (18c). Approximately 95 percent is used as TiO_2 (Table 8), which is a white pigment. A second minor, albeit important, use is as the metal, where high strength, high temperature tolerance, and low weight are desirable. A major use of the metal is in the aircraft industry. The relatively high cost of metal production, even greater than for aluminum, has likely contributed to titanium use not having expanded into other markets, despite its high strength, tolerance to high temperatures, and light weight.

DISCUSSION

The inter-dependence of one metal on another is well exemplified by several of the non fer-rous alloys. The decline in the consumption of tin (Fig. 14c) has resulted largely from a growth in the use of aluminum (Fig. 16) in beverage cans. Antimony and lead show the opposite trend (Fig. 19); they show a positive correlation owing to the major consumption of antimony throughout the early part of the 20th century in lead-acid batteries and its continued use in this application, albeit less so in the latter half of the century. The continued growth in the consumption of antimony and greater scatter in its relation with lead toward the end of the last century has been driven largely by its growing use as a flame retardant in plastics. An alternative use for tin may likewise rejuvenate use of this commodity, if current research in this field is successful.

Other factors, however, also contribute to the rise or fall in production and consumption of commodities, although in the long term it will be profitability. These other factors include governments' legislation; political crises; efforts of cartels, companies, and countries to set prices; and even the weather. Clearly, it will be very difficult to factor such variables into a single equation that will allow an agency to predict the demand, availability, and price of a commodity in the future. Without the data in some format similar to this compilation, it will be impossible.

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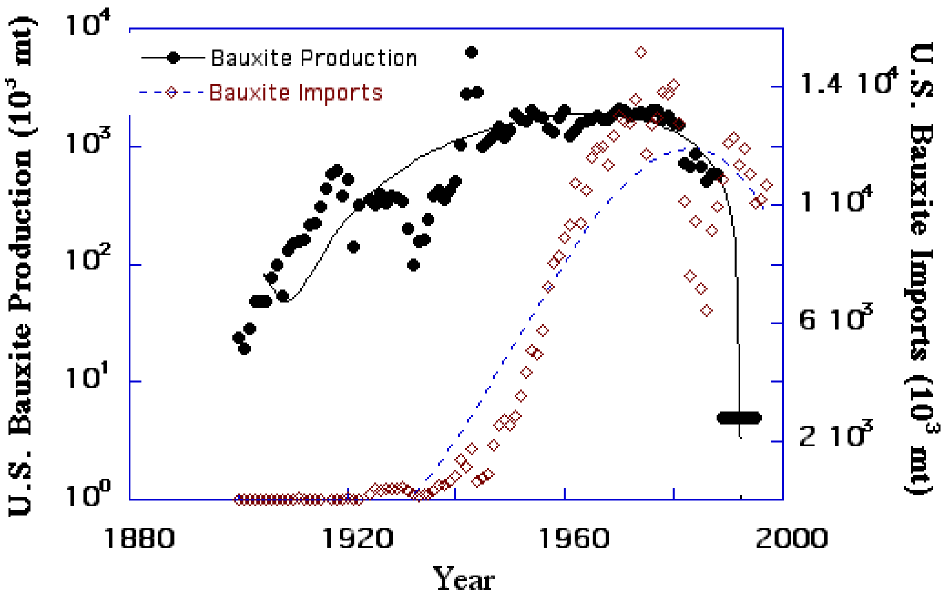


Figure 1. Bauxite production and imports for the U.S. throughout the 20th century. The two curves represent a third-order polynomial. Imports for the 1990's may represent a temporary down turn that can be expected to again increase into the 21st century.

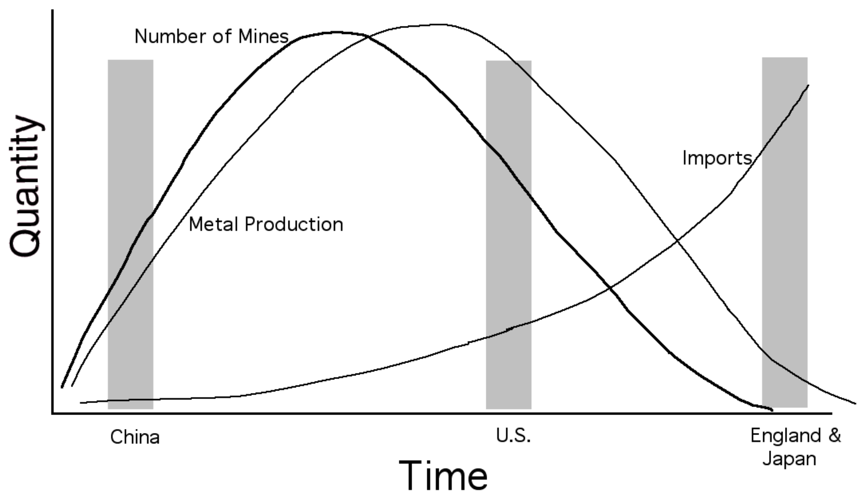


Figure 2. A theoretical representation of mine development, production, and imports of an industrial country through time. For example, the U.S. is a major producer of many commodities, but is on the decreasing part of the curve representing future production and the increasing part of the curve for imports, i.e., in the future. The figure is adapted from Craig et al. (1996).

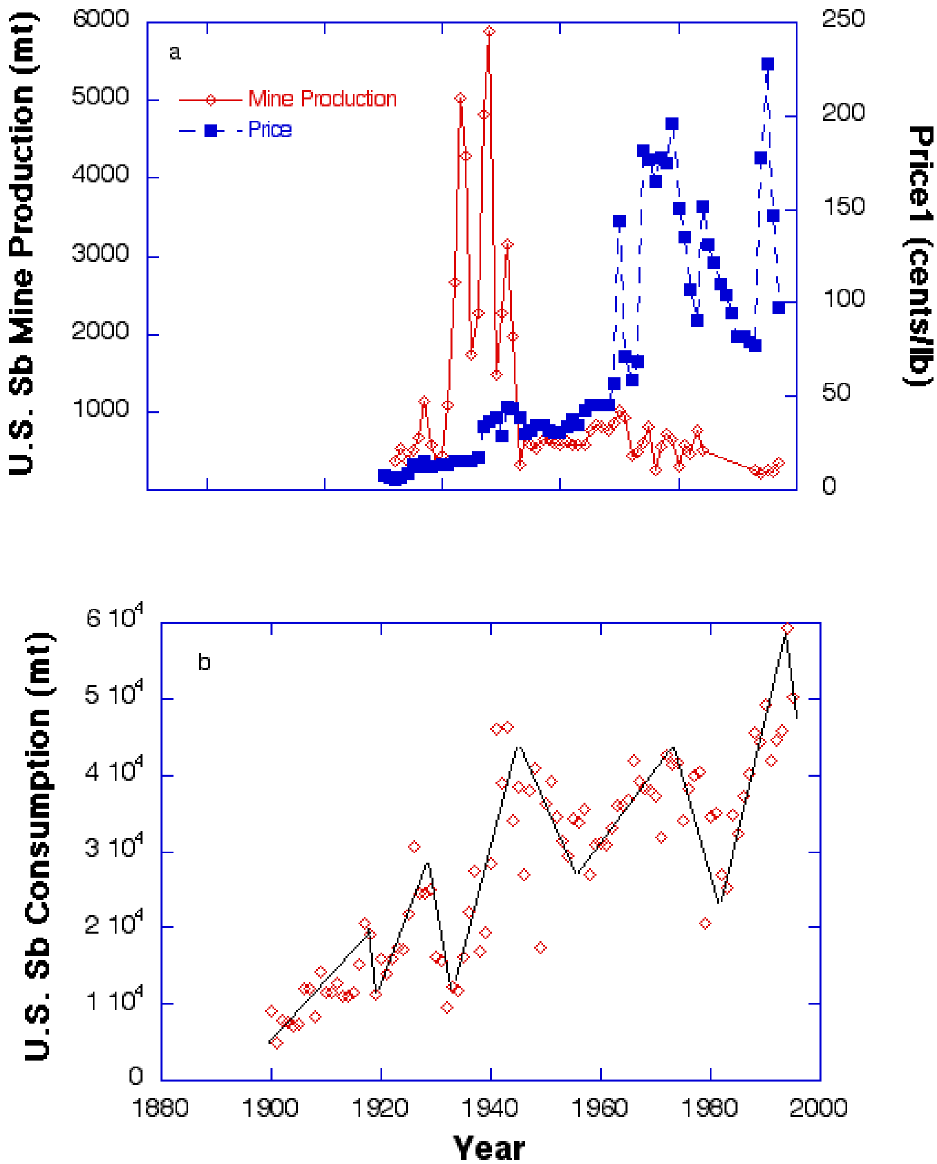
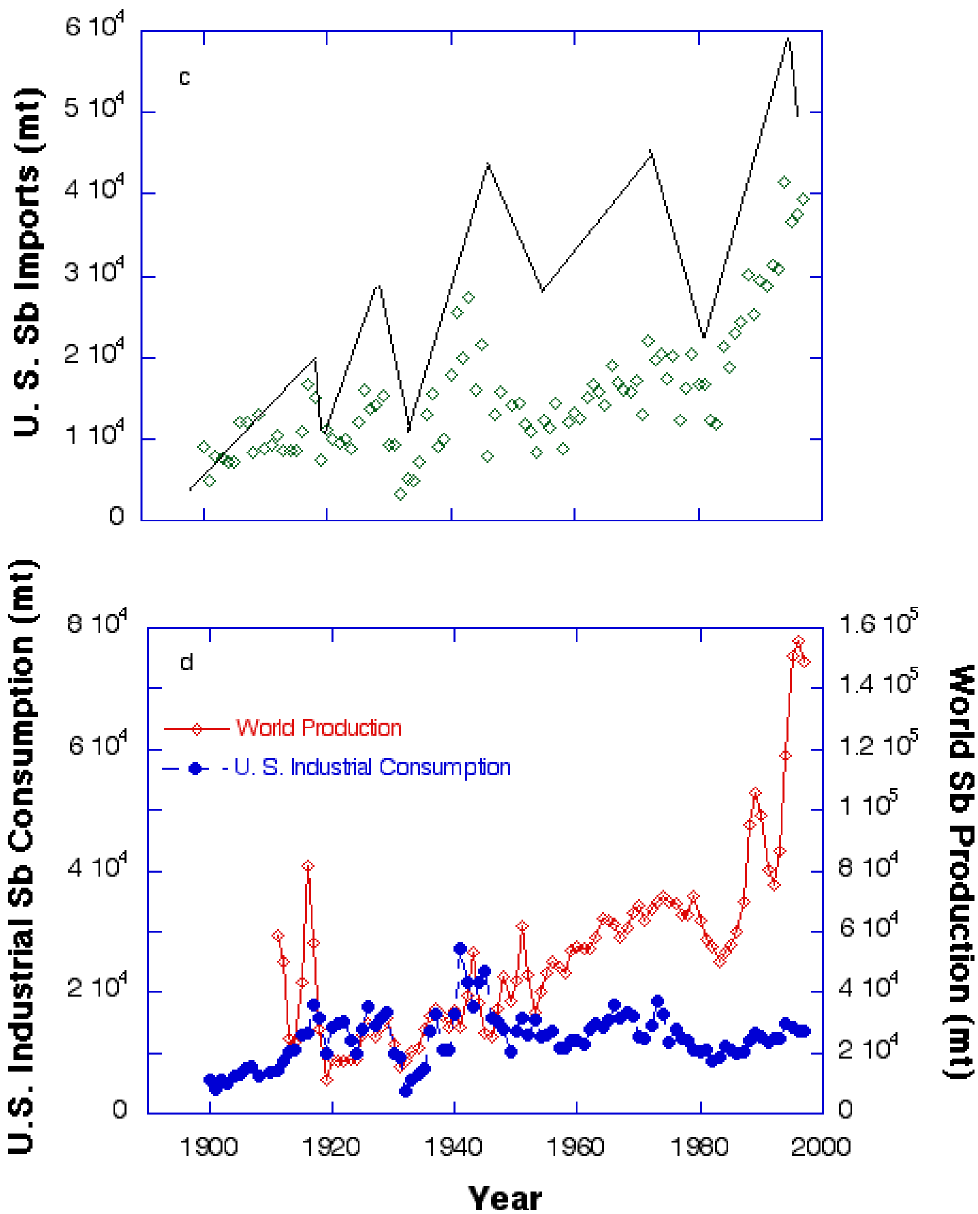


Figure 3. Statistics for Sb for the 20th Century, giving price and U.S. mine production (a), U.S. consumption (b), imports (c), and U.S. industrial consumption and world production (d). The curves in (b) and (c) are each intended to represent the U.S. Sb consumption.



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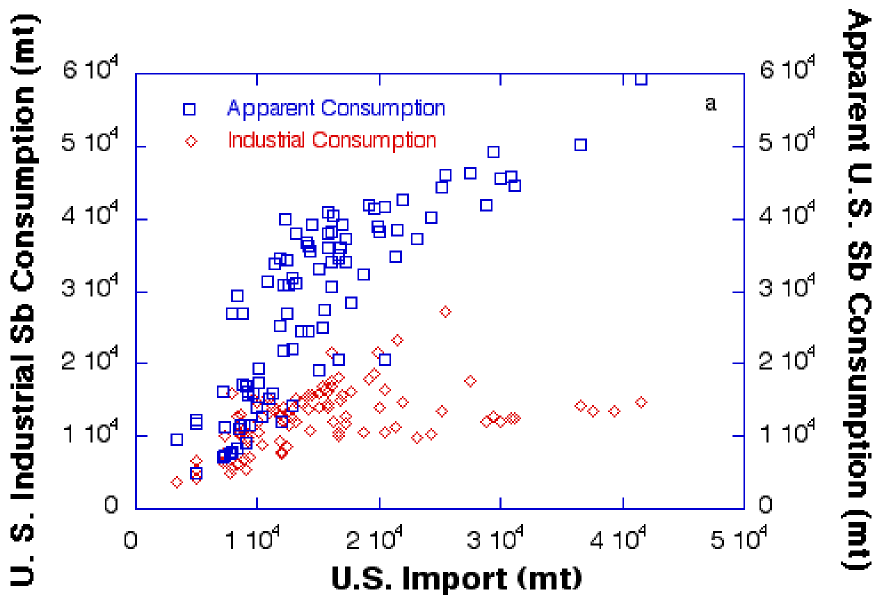


Figure 4. Relation between imports of Sb (x axis), the major supply of primary Sb to the U.S., and U.S. consumption.

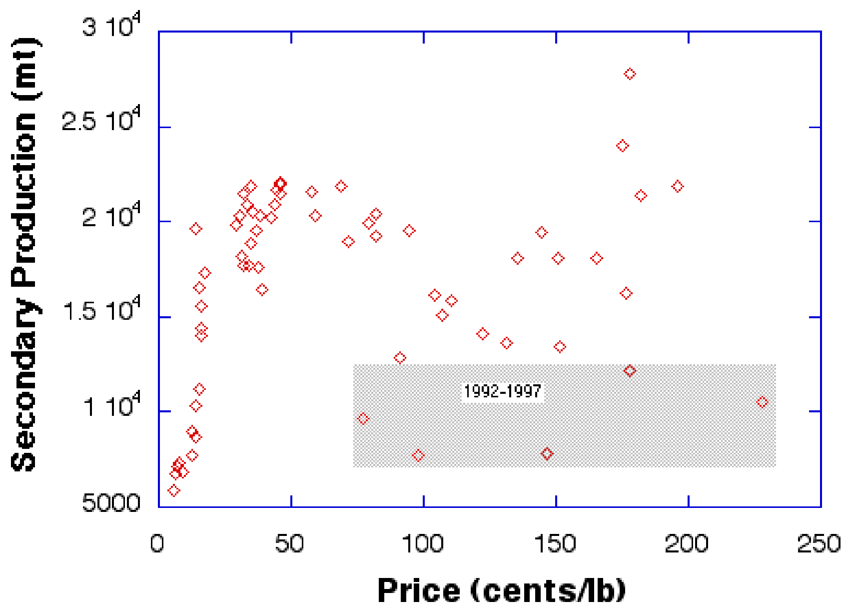


Figure 5. Relation between U.S. secondary production of Sb and price. The shaded area shows the field of most recent, apparently correct, secondary production figures.

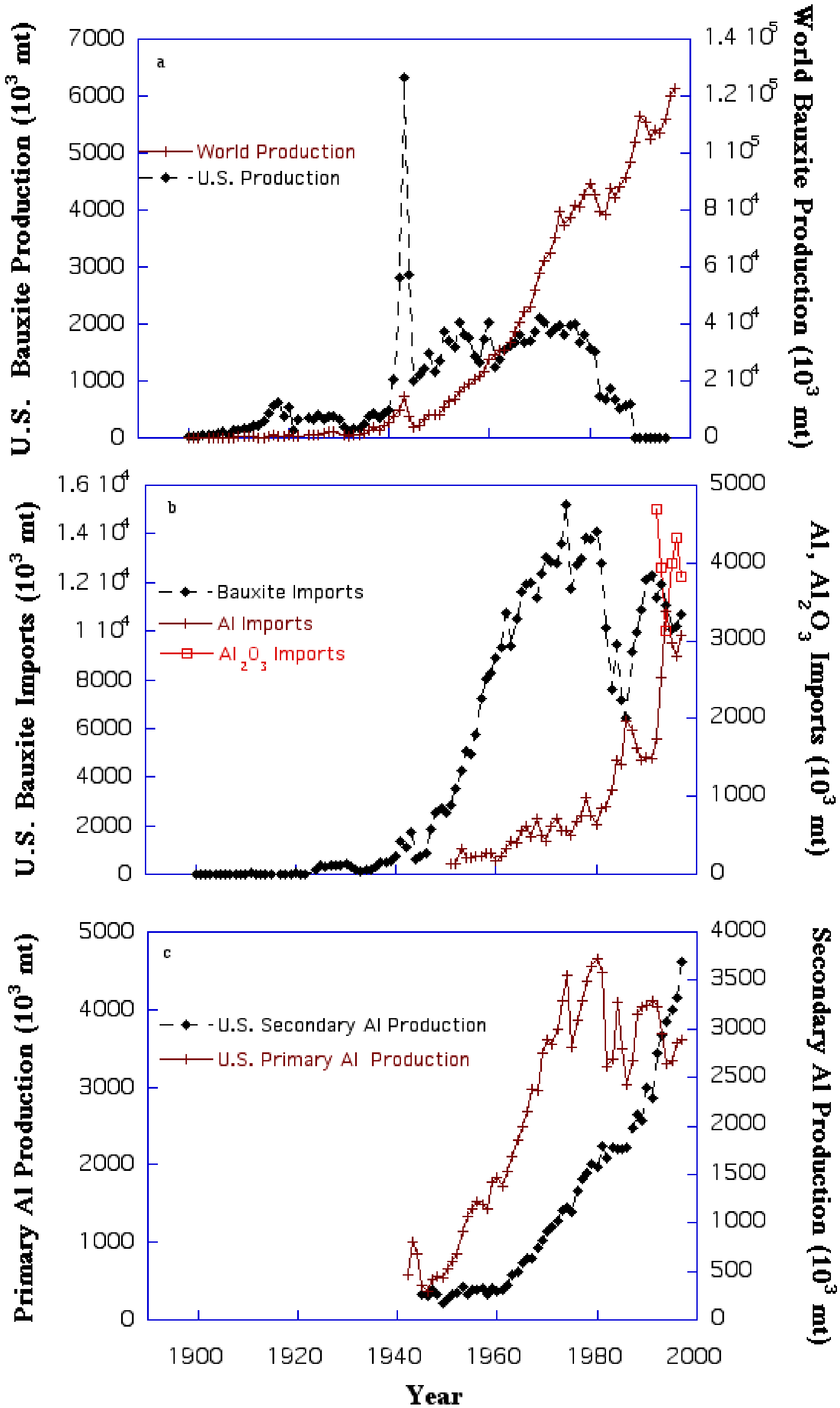
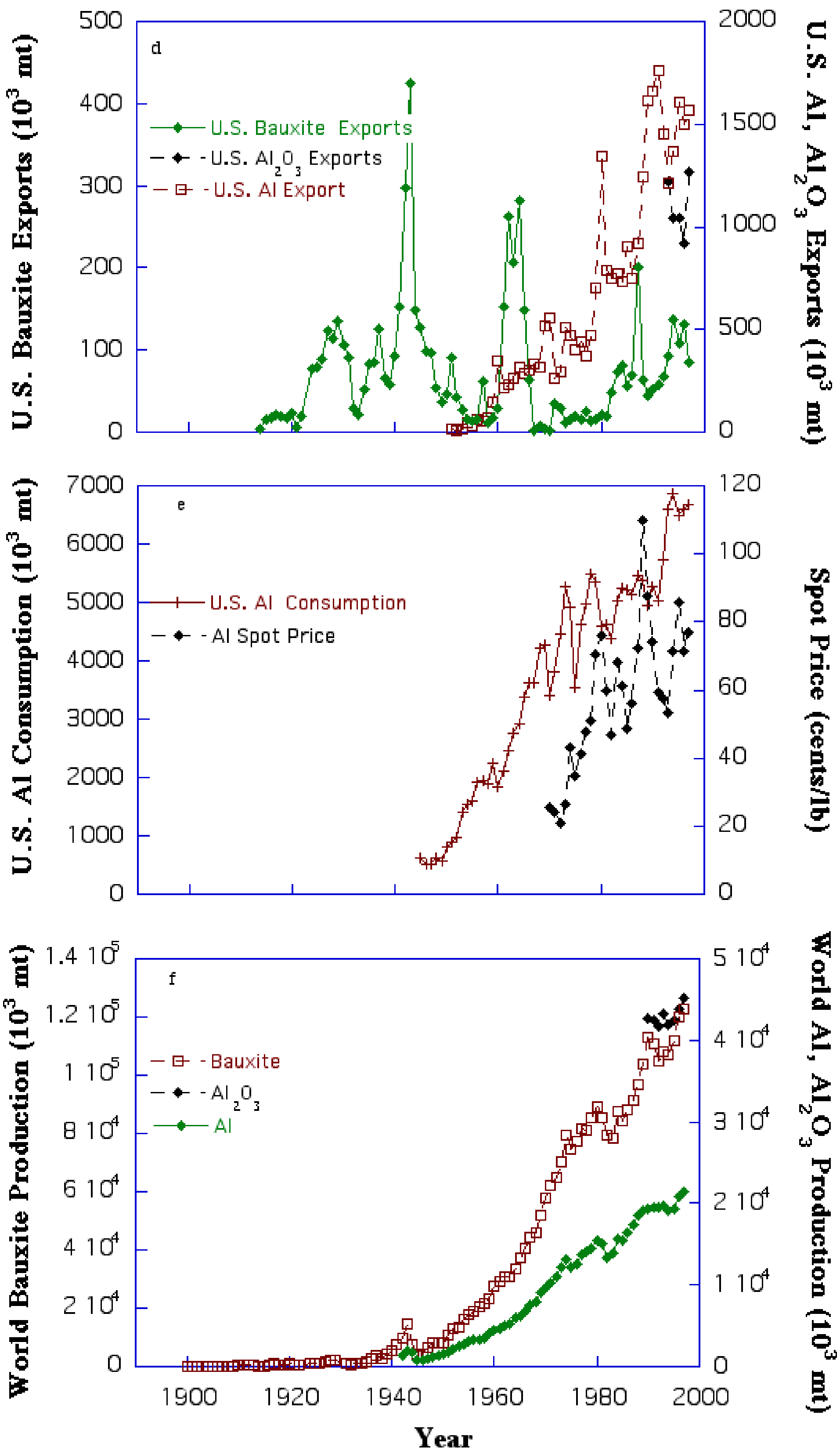


Figure 6. Statistics for bauxite, aluminum, and alumina for the 20th century. In a few cases, data are not available for the first part of the century. As a rough approximation aluminum (Al) = 1/2 alumina (Al_2O_3) and = 1/4 bauxite, by weight.



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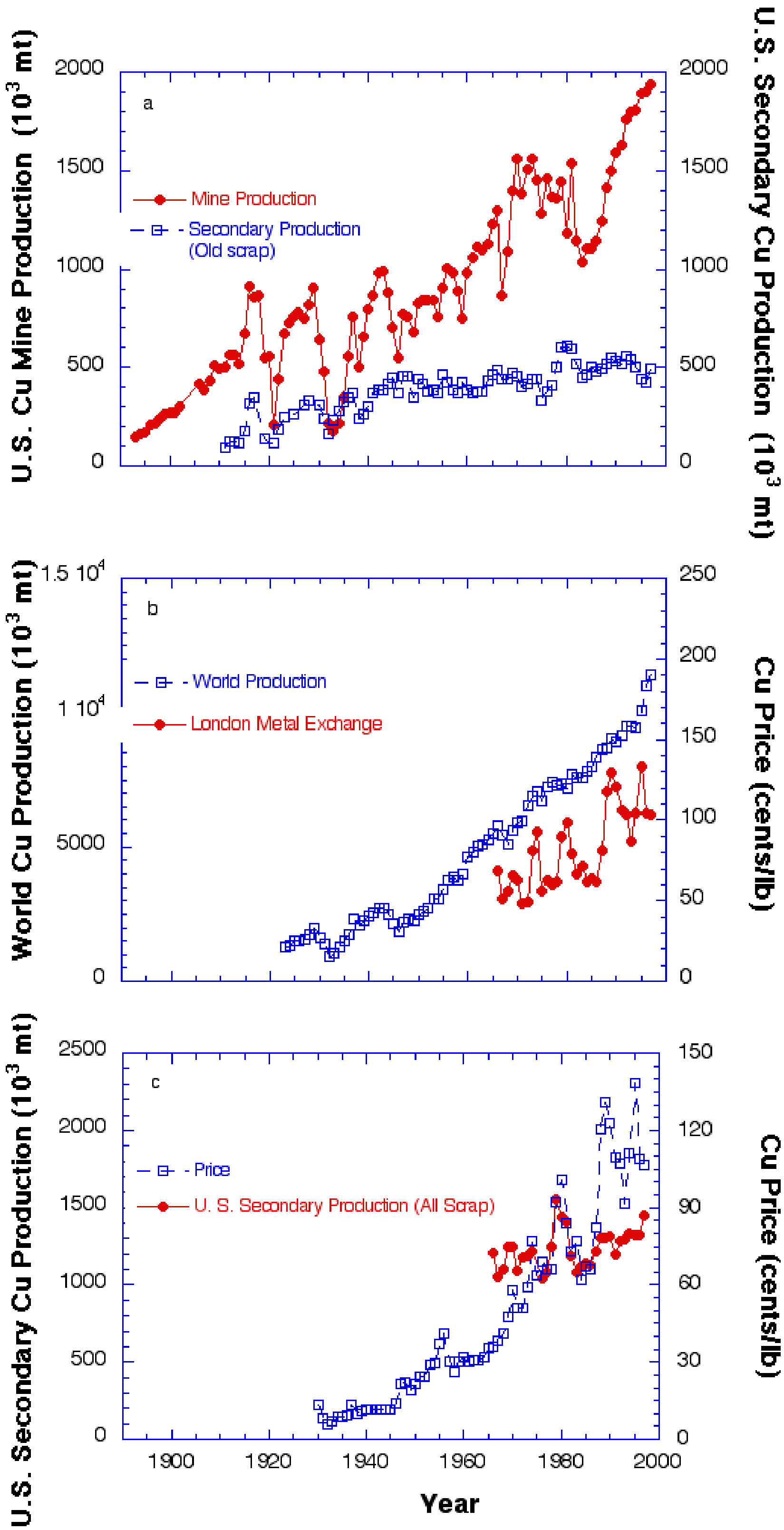
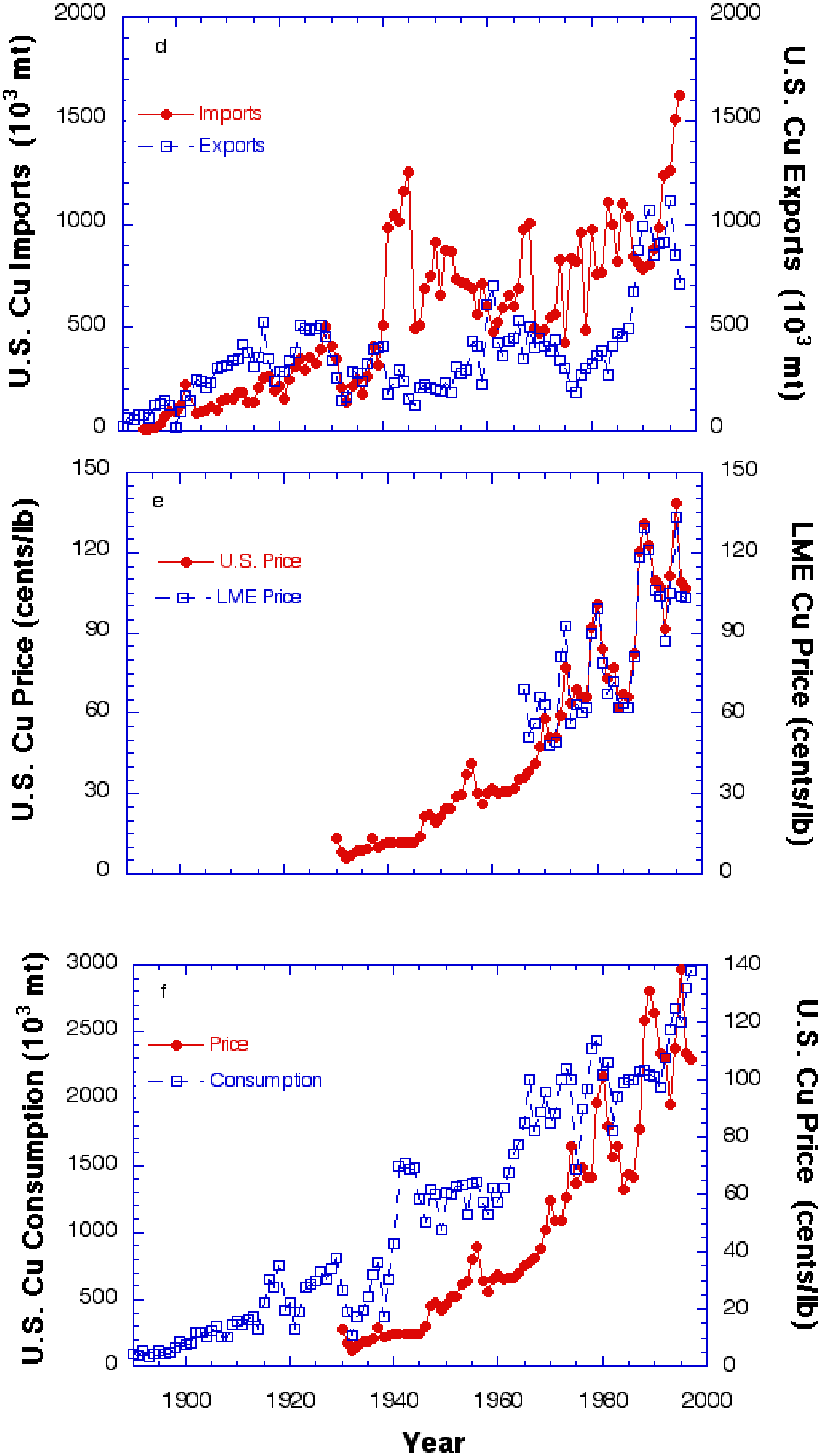


Figure 7. Statistics for copper for the 20th century, showing U.S. mine and secondary production of old scrap (a), world mine production and price (b), U.S. secondary production of all scrap and price (c), U.S. imports and exports (d), US. and London Metal Exchange price (e), and U.S. consumption and price (f), all for the 20th century.



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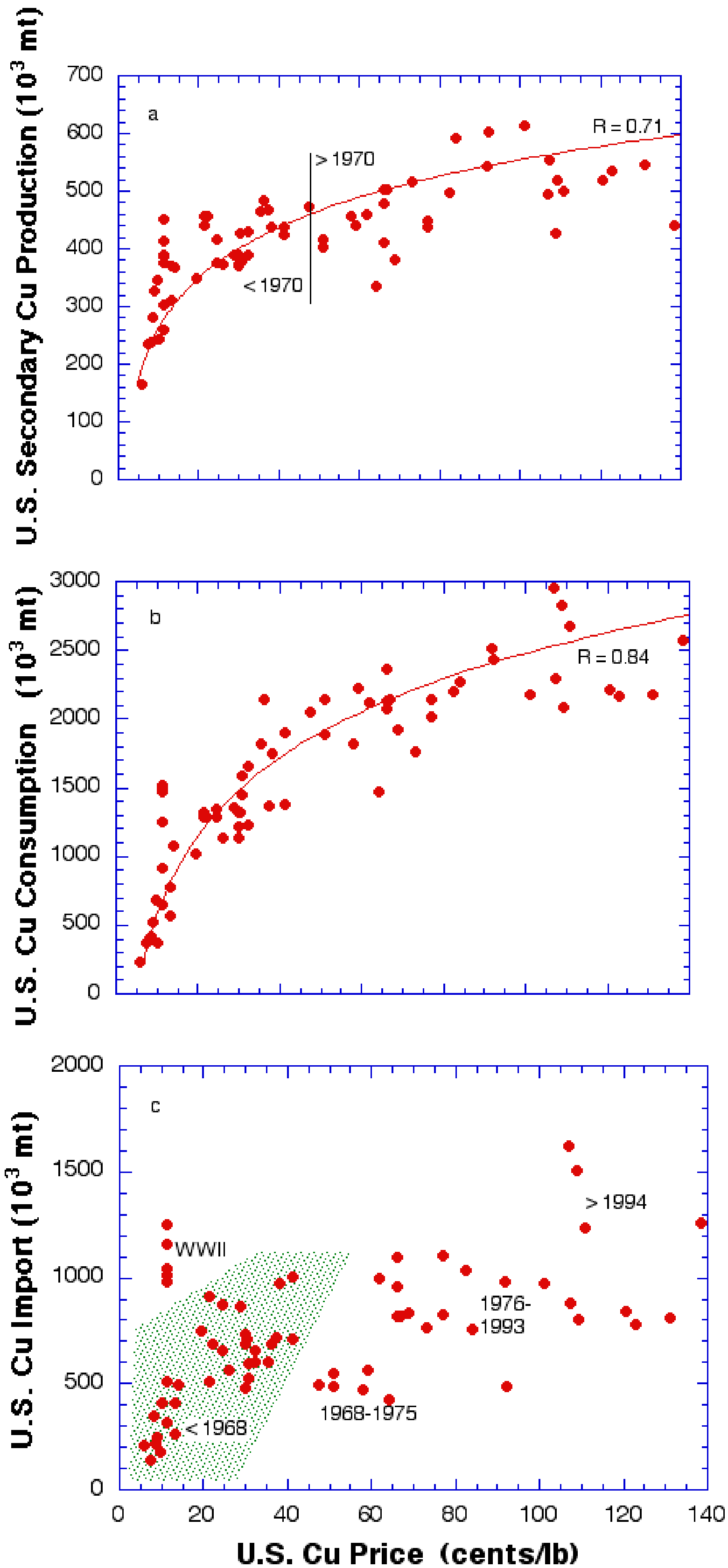


Figure 8. Relation between U.S. copper price and secondary production (a), consumption (b), and imports (c). Labeled areas in (c) show different temporal relations.

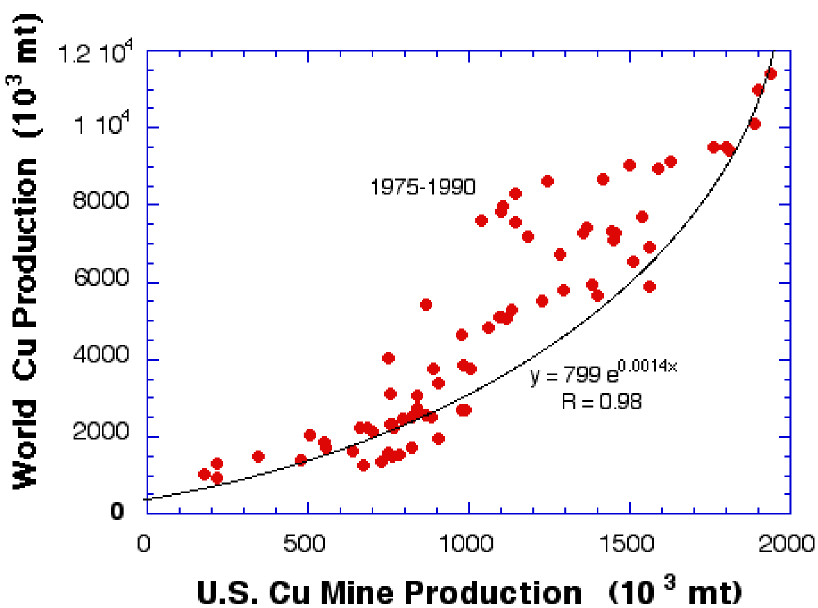


Figure 9. Relation between U.S. production of Cu and world production of Cu for the 20th century. World production for the period 1975 to 1990 exceeded the smooth exponential trend of the data for the rest of the century. All data still show a strong correlation of 0.98.

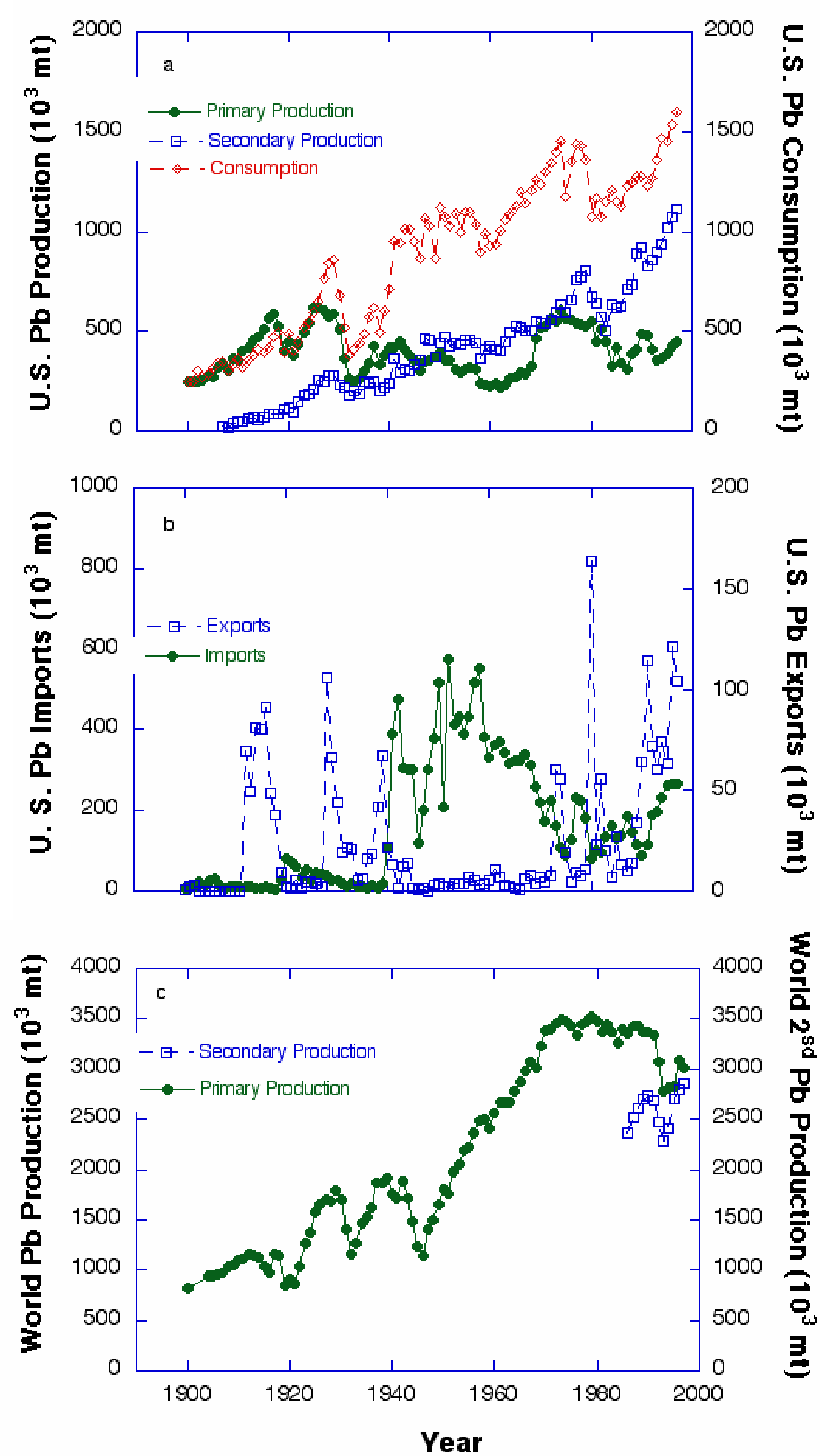


Figure 10. U.S. lead consumption and primary and secondary production (a), imports and exports (b), and world primary and secondary production (c), all for the 20th century.

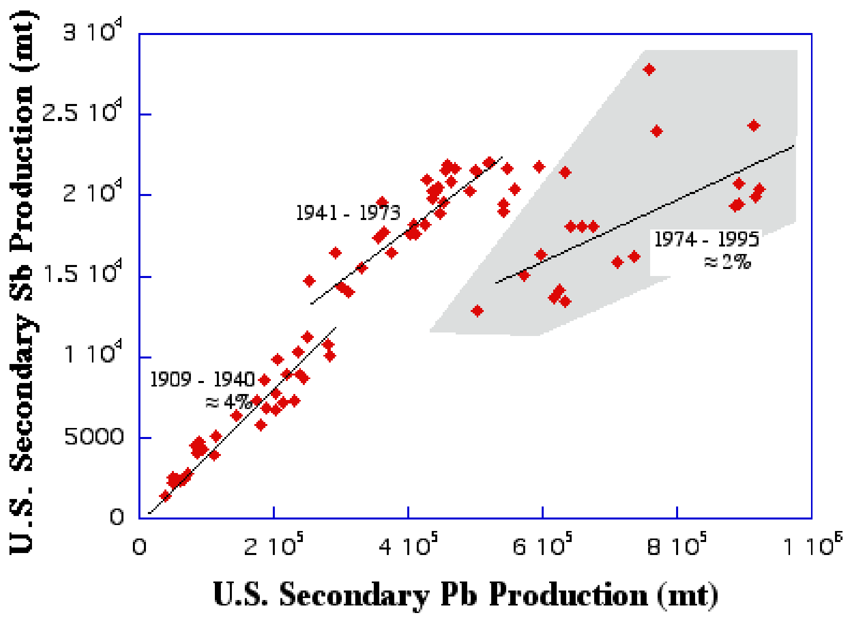


Figure 11. Relation between secondary Pb production and secondary Sb production for the U.S. Percentages for Sb production to Pb production are based on averages of the data, not the curves which represent linear regressions. A percentage is not reported of the years 1941 through 1973, although the average of the data gives a value close to 4 percent.

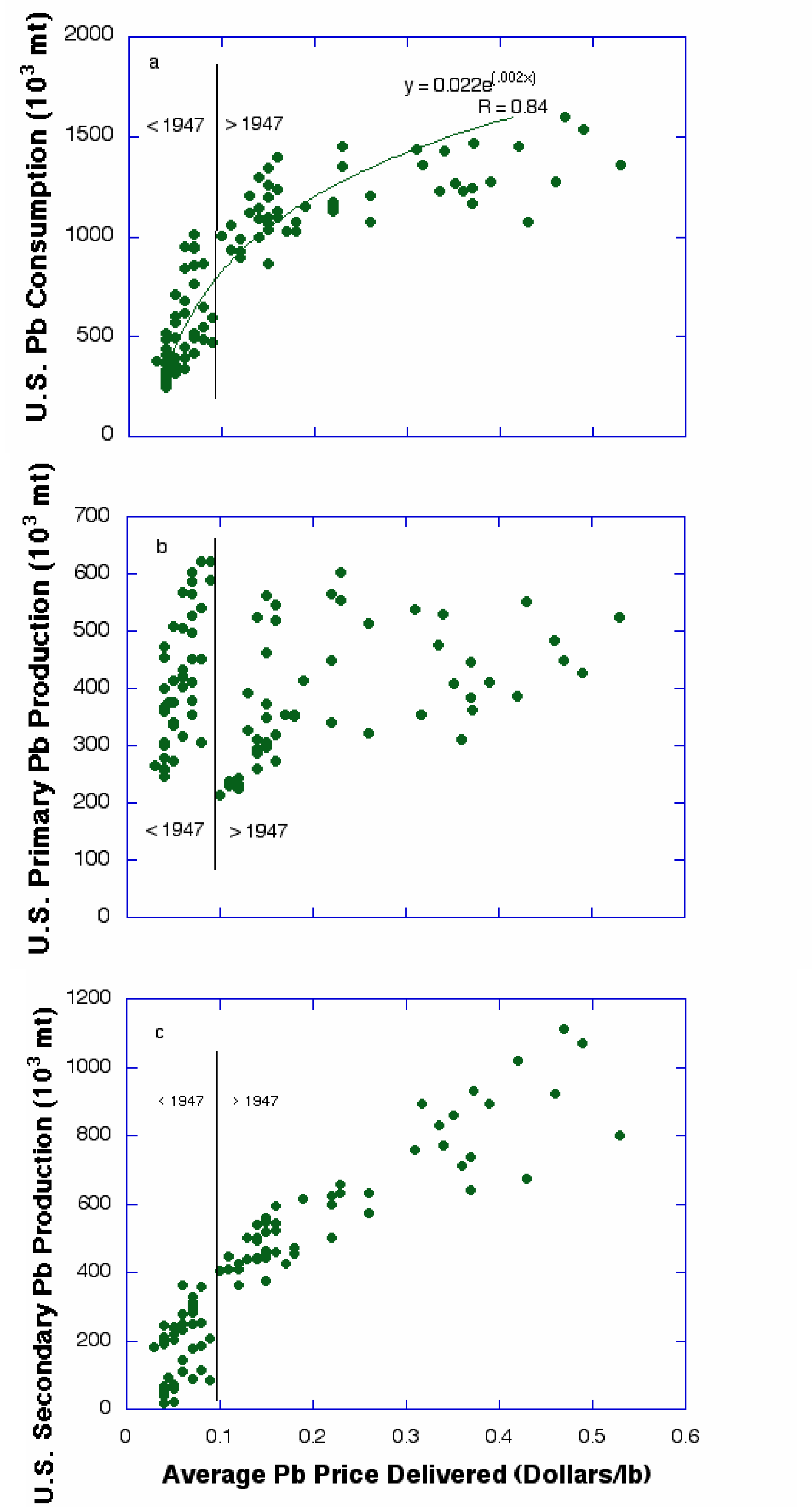


Figure 12. Relation between price and U.S. Pb consumption (a), primary production (b), and secondary production (c). Secondary production is tied most closely to price.

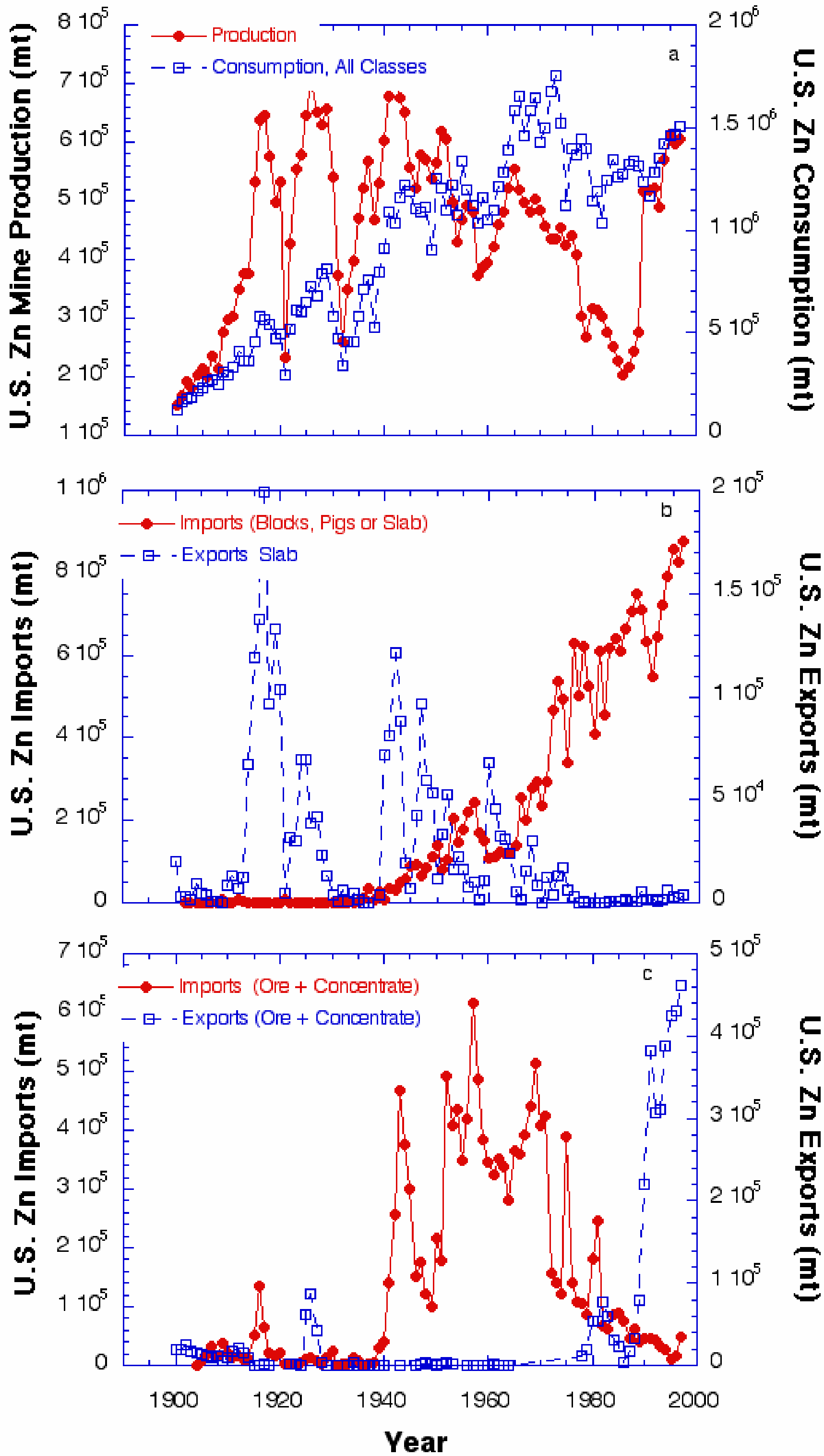
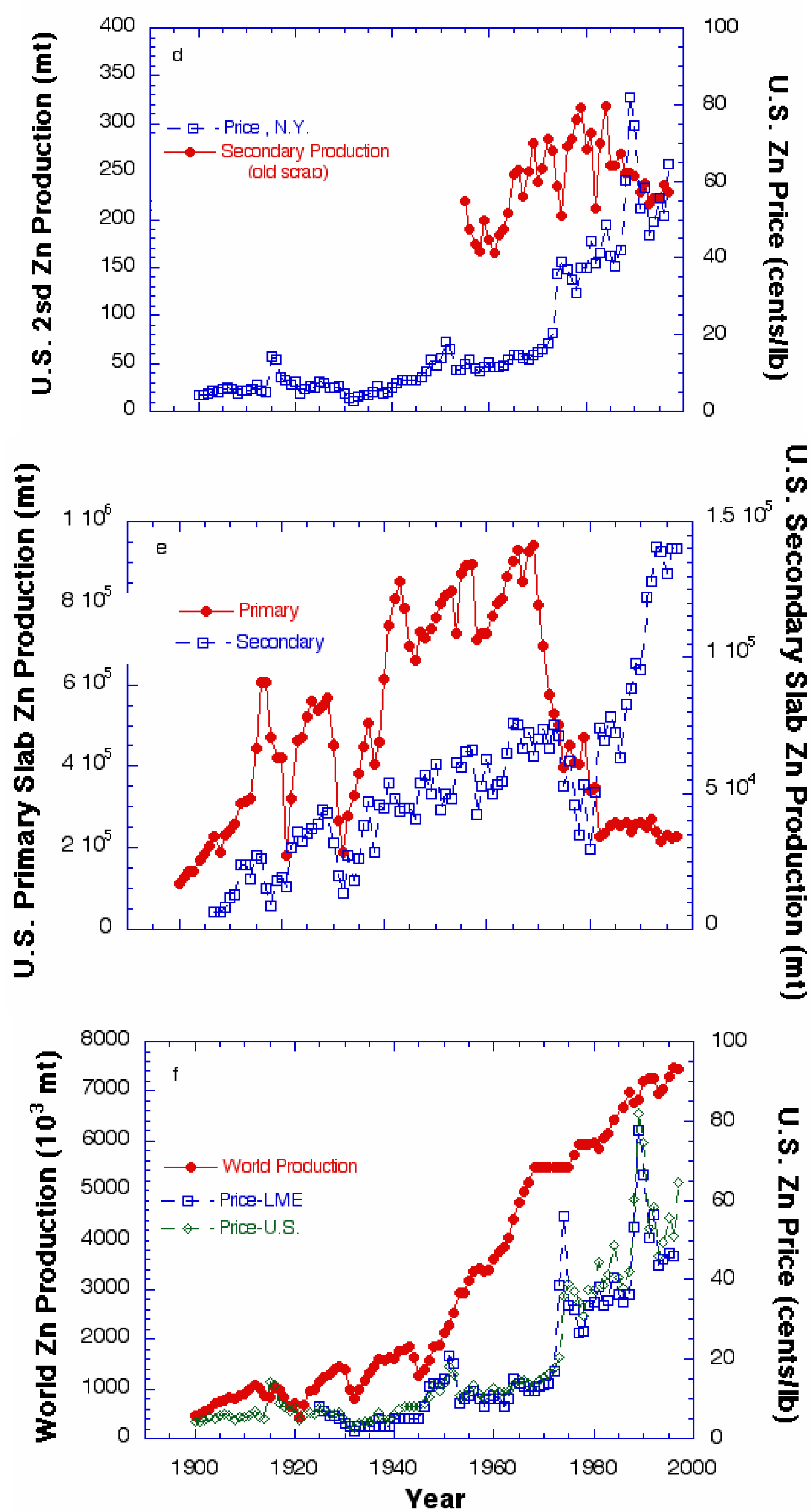


Figure 13. For the U.S., Zn mine production and consumption (a), imports of blocks, pigs, and slabs and exports of slab (b), imports and exports of ore and concentrate (c), secondary production and price (d), primary and secondry slab production (e), and world production and price (f), all for the 20th century.



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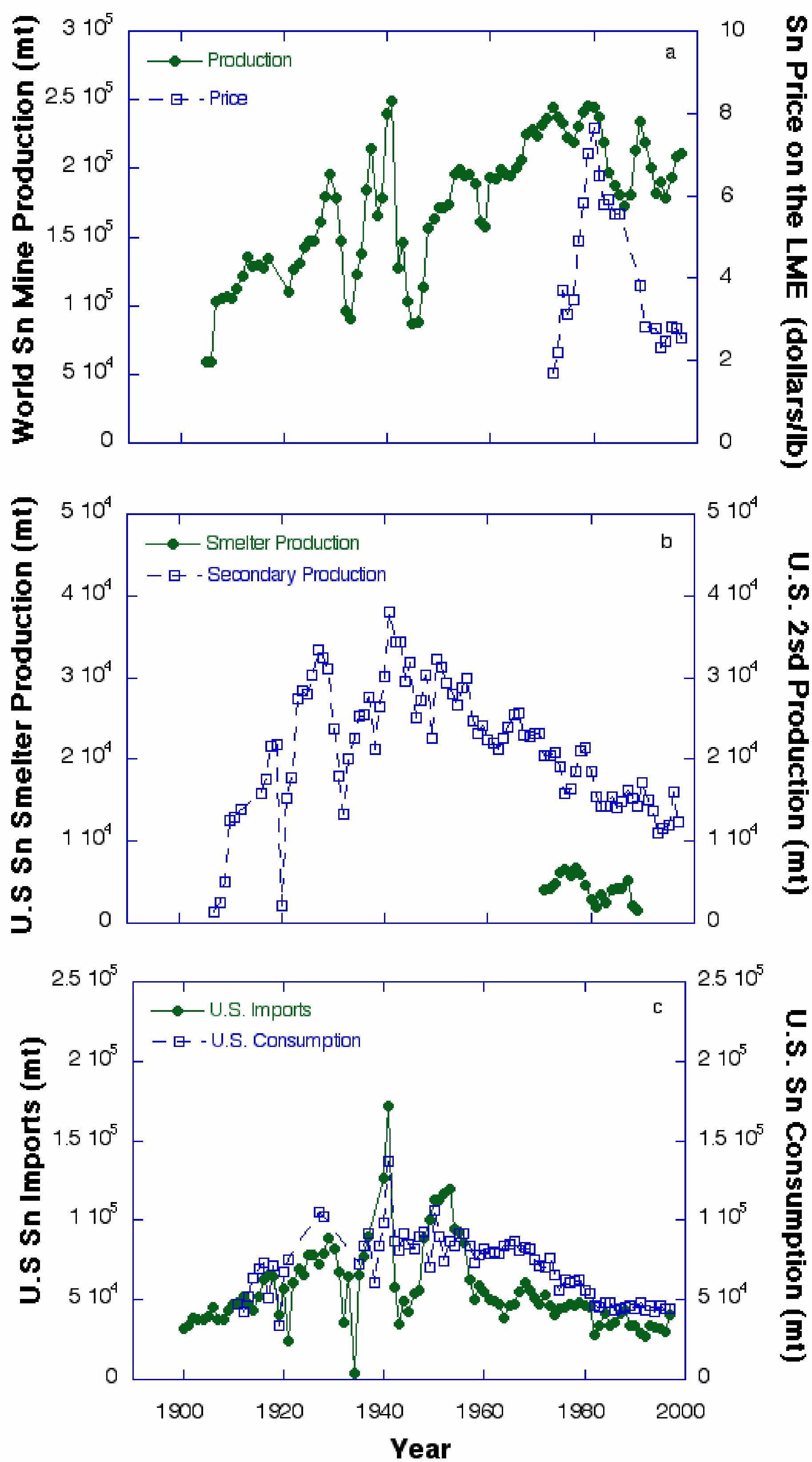

Figure 14. World mine production of tin and price (a), U.S. smelter and secondary production (b), and U.S. imports and consumption (c), all for the 20th century.

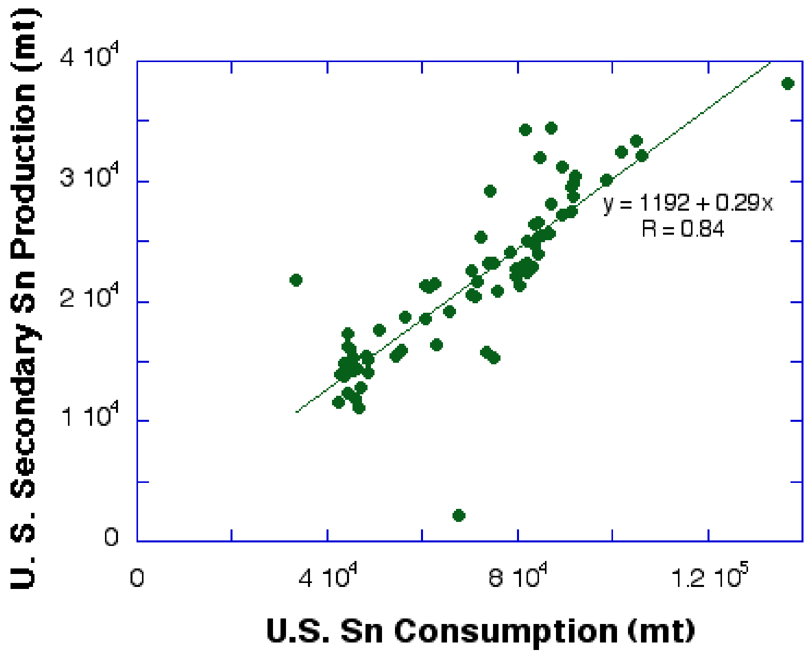

Figure 15. Relation between U.S. consumption of Sn and 2sd Sn production. The linear regression shows that approximately 30 percent of U.S. consumption comes from secondary production, the remainder from imports.

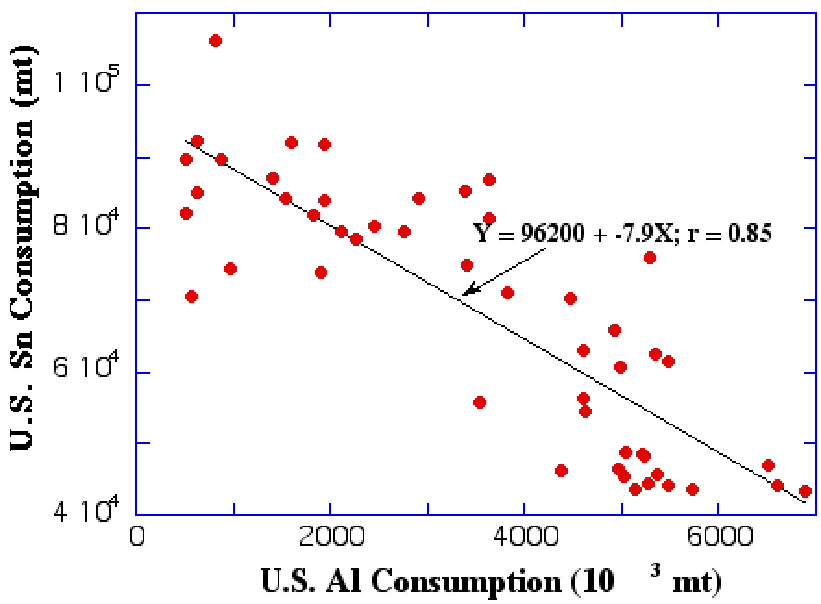

Figure 16. Relation between U.S. Sn consumption and Al consumption. The strong negative slope of this relation demonstrates the growing use of Al at the expense of Sn.

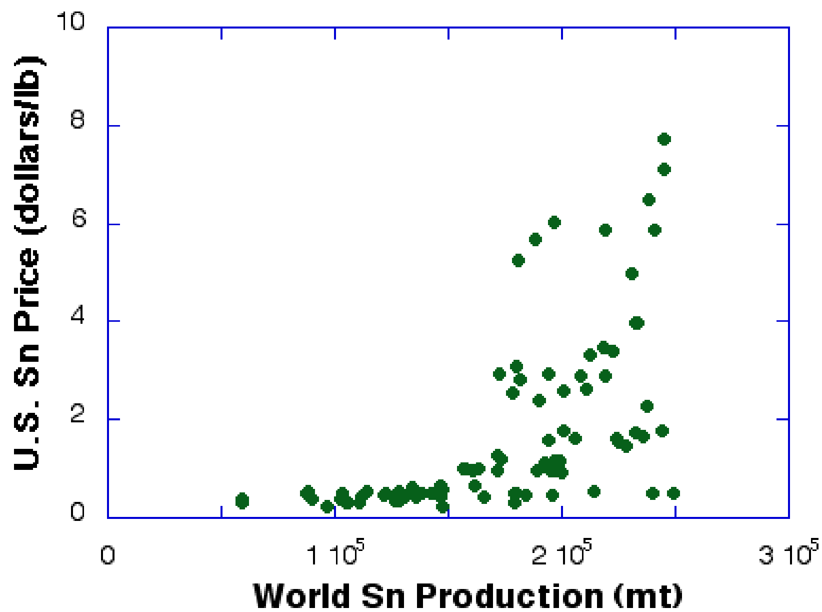

Figure 17. Relation between world Sn production and price.

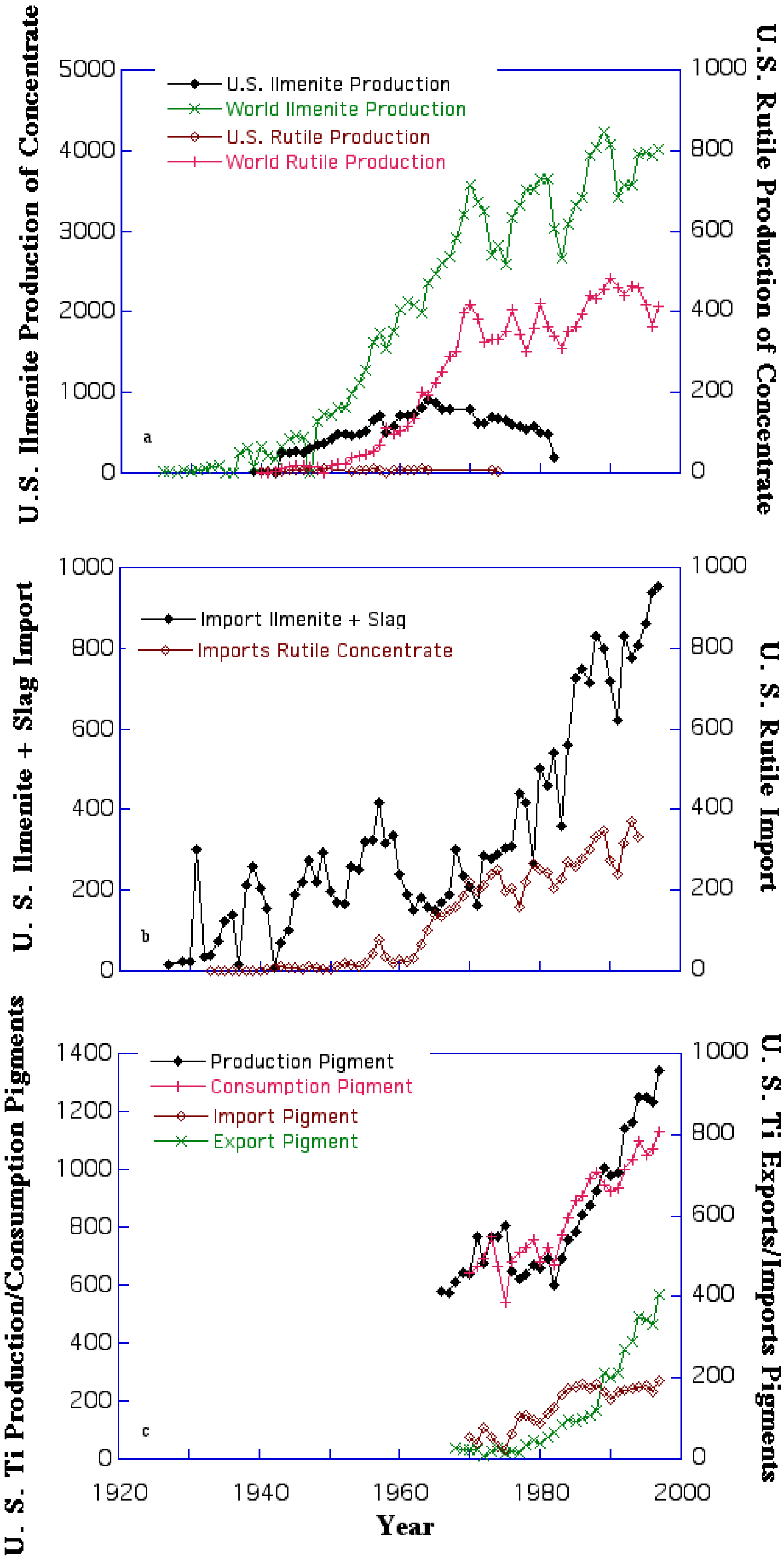

Figure 18. U.S. and world production of rutile and ilmenite (a), U.S. imports of ilmenite and slag and rutile concentrate (b), and U.S. production, consumption, import, and export of pigment (c), all for the 20th century.

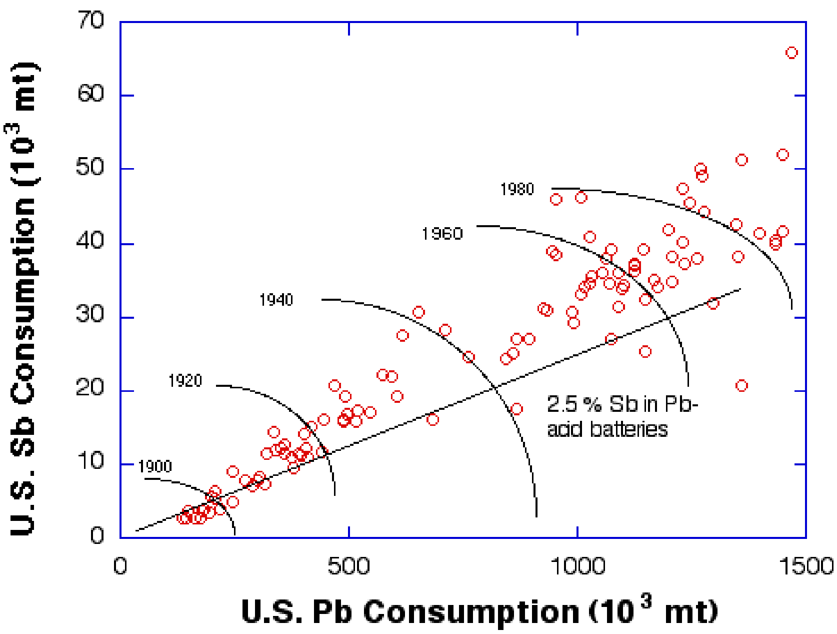

Figure 19. Relation between U.S. Pb consumption and U.S. Sb consumption. The line corresponds to a concentration of Sb to lead of 2.5 percent, a possible relation found in lead-acid batteries throughout much of the early and middle part of the century. The arcs represent time lines.