An Outlook on Supply-demand of Metals for A. D. 2000

By

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(Received June 30, 1990)

Abstracts

A forecast of the supply-demand of metals for A. D. 2000 was attempted based on economic aspects, geochemical aspects and technical feasibility. Reserves (or reserve base), production and rate of growth are fundamental factors in the calculation of the lifetime of metals. These statistics were referred to the published data of the United States Bureau of Mines, and a static index for 2000 was calculated using these data. Resources which ecompass potentially exploitable mineral commodities substitutes are also an important factor, especially in the case of the reserve which is not sufficient to meet the world demand in the future.

The above mentioned items of each metal are expressed in Table 1 in order of crustal abundance.

1. Lifetime

Reserve life expectancies of forty mineral commodities determined by statistical projections for 2000 combined with average annual production growth 1983-2000, are listed in column 10 of Table 1 and Fig. 1. Indeed, world production of Sn and Ge would have completely consumed their reserves by 2000. The world probable cumulative demands of Hg, Ag, Zn, Pb, Ta, Cd, As, Au, Cu, Tl, Sb, Ni, and W will exceed the present known reserves of each metal for the period of 2000-2025. The total world reserves of Se, Mo, Zr, and Ti seem adequate over 2050. However, these estimates obtained from an algebraical method are not in agreement with the actual mining operations or geological conditions. For example, ore minerals of zinc and lead occur together, and in each case two mineral species, sphalerite and galena, respectively, account for most of the world's production. Therefore, most of the zinc-producing mines in the world produce a significant amount of lead as a by-product. The reverse is also true. On the basis of this concept, it is reasonable that zinc and lead will deplete at about same time. In the case of Bi, its supply is dependent upon demand for lead

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Table 1

(1) Element	(2) Crustal abundance of the elements (ppm)	(3) Production in 1983 (1000ton)	(4) Average annual U.S.price in 1983 ($/kg)	(5) Reserves (1000ton)	(6) Reserve base (1000ton)	(7) Average annual growth rate (%)	(8) Demand in 2000 (1000ton)	(9) Cumulative demand between 1983 and 2000 (1000ton)	(10) Static index since 2000	
									reserves	Reserve base
Si	277200	2500	1.3			2.7		55000		
Al	81300	14000	1.5	4400000	4900000	4	36000	400000	110	130
Fe	50000	420000	0.067	73000000	99500000	2.4	640000	9000000	100	140
Ti	4400	60	12	170000	270000	6.2	2800	40000	46	82
Mn	950	8000	0.066	900000	3600000	1.4	11000	170000	66	310
Sr	375	54	73	6800	12000	2	75	1100	76	150
Zr Hf	165 3	70	33 309	21000	46000	5.6	420	4700	39	100
V	135	30	14	4400	17000	5.1	67	790	53	240
Cr	100	2500	0.2	1100000	6800000	4.4	6200	67000	160	1100
Rb	90	0.0015	660	2.0 [1)]	2.5 [1)]	2.8	0.003	0.041	650	820
Ni	75	750	4.9	53000	100000	3	1700	18000	20	48
Zn	70	6400	0.91	170000	300000	2	1700	18000	4	18
Cu	55	7800	1.7	340000	500000	2.7	15000	170000	12	22
REE	60～0.5	37	12～14000	45000	48000	2.6	58	810	760	810
Co	25	20	28	3600	8400	3.7	45	550	69	170
Li	20	6.3	4.3	1900	8300	4.5	14	160	130	600
Nb	20	9.5	12	3400 [2)]	4100 [2)]	5.1	34	400	88	110
Ga	15	0.016	525	110	170	10.2	0.084	0.74	1300	2000
Pb	13	3200	0.48	95000	140000	1.8	7300	61000	5	10
B	10	32 (B_2O_3)	0.22	320000 (B_2O_3)	620000 (B_2O_3)	2.4	1400 (B_2O_3)	20000 (B_2O_3)	210	420
Th	7.2	0.3 (ThO_2)	54	1100 (ThO_2)	1300 (ThO_2)	3.1	0.48 (ThO_2)	6.5 (ThO_2)	2400	2600

Mineral resources

(11) Resources	(12) Substitutes
Silica is one of the most abundant materials, and resources are regarded as unlimited. But quartzite with high purity may be limited.	Various metals and alloys can be substituted for Si. Si is a substitute for other metals.
The potential resources of Al including nonbauxitic deposits are widespread and virtually inexhaustible.	Al can be replaced by many materials when in short supply, but there is no substitute for Al.
Reserves and potential resources of Fe like banded iron formation and laterite are virtually inexhaustible.	The development of substitutes for Fe is not required because of abundant resources and low cost of Fe.
Reserves and potential resources of the Ti minerals are more than adequate for the distant future.	For aircraft and space use there is no substitutes for Ti. For industrial uses high-nickel steel, Zr and superalloy may be substituted.
Mn deposits are present throughout world, including floors of the deep oceans. The potential resources of Mn are virtually inexhaustible.	The development of substitute for Mn is not required because of abundant resources and low cost of Mn.
The resources and potential resources are sufficient to last hundreds of years at the present rate of world consumption.	Ba can replace Sr in some of applications.
Reserve base of Zr is sufficient for the future at the present rate of world consumption. Phosphate, and sand and gravel deposits may yield substantial amounts of zircon as a by-product in the future.	Chromite sand, staurolite, titanium dioxide, Al, Nb and V may be substituted for Zr in certain foundry applications.
The potential resources of V are sufficient at the present rate of world consumption. Most of reserve base are located in South Africa and U.S.S.R..	V is interchangeable to some degree with Nb, Mo, Mn, Ti and W. Metallic platinum can replace V compounds as a catalyst.
Most of the Cr reserves are located in South Africa and U.S.S.R., but low grade potential resources are found on all continents.	For many end-uses substitution can be considered. Substitution possibilities for Cr include:Ni for plating, Fe for pigments and boron for alloying. Magnesite may substitutes for Cr in refractiories.
Meaningful estimates of Rb resources cannot be made, but known reserve base is adequate to last hundreds of years at the present rate of world demand.	The development of substitutes for Rb is not required.
World resources of lower grade Ni deposits are very large. In addition, there are extensive deep-sea resources of Ni in manganese nodules.	Present and potential Ni substitutes include Al, coated steel, nickel-free specialty steels and plastics in certain applications.
The reserves of Zn are not sufficient in future. Potential resources of low grade have not been found.	Al, Mn, Ti, Zr and plastics can replace Zn in limited areas for some applications.
Though land-based resources are estimated at 1.6 billion tons and resources in deep-sea nodules at 0.7 billion tons, potential resources are not known.	Al, Ti, steel and plastics may be substituted for copper in some applications.
The reserves are sufficient to last hundreds of years at the present rate of world consumption.	The development of substitutes for rare earth elements is not required.
Significant amount of Co is obtained as a by-product from Cu, Ni or Ag ore deposits. Potential resources exist in manganese nodules and crusts on the ocean floor.	Ni may be substituted for Co in several applications.
Reserves and potential resources of the Li are sufficient to last handreds of years at the present rate of world consumption.	The development of substitutes for lithium is not required.
Most of the resources occur mainly as pyrochlore in carbonatite deposits. The resources and potential resources are more than adequate to supply demand in future.	V, Mo, Ta, Ti and W may be substituted for Nb in some applications.
Ga is produced as a by-product of almina plants. Small amounts of Ga are present in sulfide ores like zinc ore.	The development of substitutes for Ga is not required.
Resources of Pb are associate with Zn resources. The reserves of Pb are not sufficient in future. Potential resources of low grade have not been found.	For the principle uses of lead-acid storage batteries, there is no substitute for lead because of economic reasons. Al, Ti, Fe and plastics may be substituted for lead in some applications.
Resources of B are sufficient to last hundreds of years at the present rate of world consumption.	The development of substitutes for B is not required.
Large Th resources are found in all continents. Resources of Th are adequate to supply needs at current rates for the foreseeable future. Demands of Th used as a nuclear fuel in future are not known.	The development of substitutes for Th is not required.

Table 1

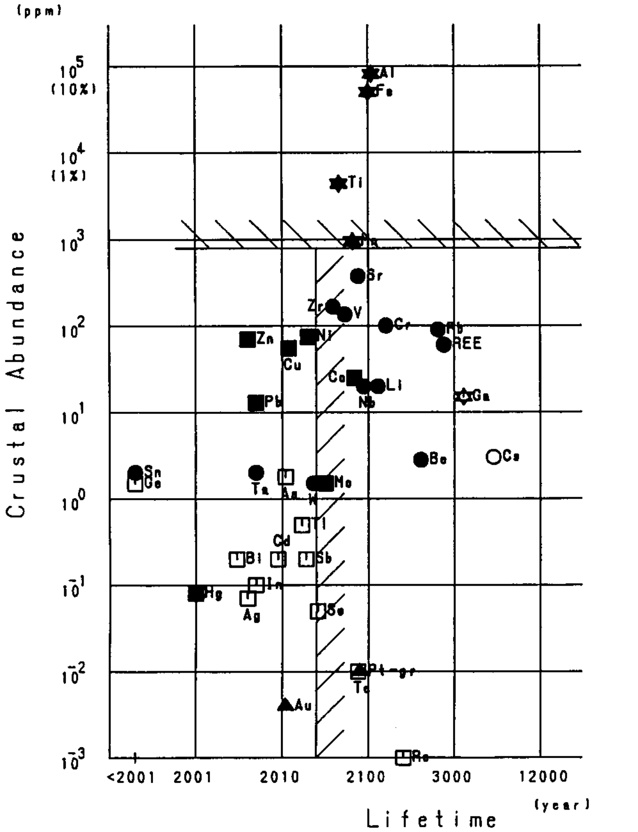
(1) Element	(2) Crustal abundance of the elements (ppm)	(3) Production in 1983 (1000ton)	(4) Average annual U.S.price in 1983 ($/kg)	(5) Reserves (1000ton)	(6) Reserve base (1000ton)	(7) Average annual growth rate (%)	(8) Demand in 2000 (1000ton)	(9) Cumulative demand between 1983 and 2000 (1000ton)	(10) Static index since 2000	
									reserves	Reserve base
Cs	3	0.021	2.3	100	110	3	0.035	0.47	2900	3200
Be	2.8	0.43	390	380	730	4.2	0.9	11	410	800
Sn	2	210	14	3100	3100	1	(250)	3900		
Ta	2	0.83	68	28 [3)]	42 [3)]	3.2	1.5	20	5	15
As	1.8	28	5	1000	1500	1.5	39	590	11	23
Ge	1.5	0.085	1100	2.2 [4)]	2.2 [4)]	6.9	0.27	2.8		
Mo	1.5	69	8	5400	12000	2.5	120	1600	32	86
W	1.5	39	10	2800	3500	2.9	80	970	23	32
Tl	0.5	0.013	77	0.34	0.64	-1.15	0.01	0.2	17	43
Sb	0.2	48	2	4200	4700	1.8	150	1300	19	23
Bi	0.2	4.1	5.1	90	200	1.3	5	77	3	25
Cd	0.2	17	2.5	560	970	1.8	23	350	9	27
In	0.1	0.062	100	1.7	3	1.6	0.081	1.2	5	22
Hg	0.08	6.5	9.4	140	250	1.4	9.7	130	1	13
Ag	0.07	7.4	660	240	340	2.1	20	170	4	8
Se	0.05	1.4	8.8	80	120	2.1	2	28	26	46
Te	0.01	0.16	20	22	34	2.7	0.25	3.4	76	130
Pt -gr.	0.01 ~0.001	0.31	1400 ~19000	37	37	2.7	0.34	4	79	96
Au	0.004	1	14000	40	47	1.8	1.7	21	11	15
Re	0.001	0.0056	550	2.9	10	3.4	0.01	0.15	260	980

1)The reserves and reserve base in Canada. 2) Excludes the reserves and reserve base in U.S.S.R.. 3)Includes Europe and Africa.. 5) The price expressed in the table desclibed above is as follows. Price of Sr is that for price of Th for thorium oxide; price of Fe and Cs for iron ore and cesium ore respectively; the other price

Mineral resources (continued)

(11) Resources	(12) Substitutes
Cs is commonly obtained as a coproduct in the processing of Ti, Be, or Li minerals. Resources Cs are adequate to supply needs at current rates for the foreseeable future.	The development of substitutes for Cs is not required.
The reserves of Be is sufficient to last hundreds of years at the present rate of world consumption.	The development of substitutes for Be is not required.
The resources of Sn are not quite sufficient, but potential resources calculated by USGS are adaquate to meet world demand.	Various metals, alloys and nonmetallic materials can be substitute for Sn. No substitute have been found for Sn in solder.
Ta is commonly obtained as a coproduct in the processing of Nb. Reserves of Ta are not adequate to supply needs in the near future.	Various materials including Nb, Al, ceramics etc., may be substituted for Ta in many applications.
As is produced as a byproduct of the smelting of high-arsenic sulfide minerals.	Substitutes for As in most major end uses have been developed because of the toxicity of As
The reserves of Ge statistically are not quite sufficient, but potential resources are adequate to meet world demand. Ge is produced as a by-product of some zinc and lead-zinc-copper sulfide ores.	Since the development of many end uses of Ge is taken it is difficult to consider substitution for Ge in the new uses.
Resources and potential resources are adequate to supply world needs for the future.	There is little substitution for Mo in the major applications. Potential substitutes for Mo include Cr, V, Nb, B, and graphite,.
The present known reserves are not sufficient. Potential resources of low grade have not been identified.	Mo, Ti, Al, and ceramics may be substituted for W in some applications.
Tl is produced as a by-product of the smelting of zinc ores. An additional resources are Tl contained in coal.	Substitutes for Tl in most major end uses have been developed because of the toxicity of Tl.
Sb is produced from ores as a by-product of the smelting of base metal ores. Reserves of Sb are not adequate to supply needs in the far future.	The chief materials which can substitute for Sb include Ca, Sn, Zn, Cr and hydrated aluminum oxide in some applications.
Bi is recovered as a by-product of the smelting of lead and copper ores.	There is no substitutes for Bi in the developing uses, but some materials including antibiotics, special plastics and resins can substitute for Bi in medicinal applications and in holding devises and jigs.
Cd is recovered as a by-product of the smelting of zinc ores.	Zn, Rb, plastics and so on may be substituted for Cd in some applications.
In is recovered as a by-product of the smelting of principally zinc ores.	Alternate materials are available for most uses of In.
Since substitutes for Hg have been found in meny uses, the world stock of Hg seems to be sufficient to meet the world demand in the future.	Alternate materials are available for most uses of Hg.
Vast amount of Ag is recovered as a by-product from other metal deposits. Potential resources of low grade silver ores have not been found.	Al, Rh, Ta and Au can substitute for Ag in some applications.
Se is obtained as a by-product of the smelting of sulfide ores. A small amount of Se is contained in coal.	Si, Bi, Te, Pb and so on may be substituted for Se in some applications.
Te is obtained as a by-product of the smelting of copper ores. A small amount of Te is contained in coal and manganese modules on the ocean floor.	The chief materials which can substitute for Te include Se, Ge, Bi and S in some applications.
The reserves of platinum-group metals are restricted geographically to South Africa and U.S.S.R.. Resources of platinum-group metals are adequate to supply needs at current rates for the future.	No substitute have been found for Pt-group metales in automotive catalysis. Au, Ag and Ti can be substituted for platinum-group metales in some applications.
Au which has monetary uses, retains a unique status. In the sense of an industrial metal, world resouces of Au are adequate to meet the forecast demand.	Au and Pt can replase in limited areas for some applications.
Re is obtained as a byproduct of the smelting of molybdenum ores in porphyry copper deposit.	Ir, Ga, Ge, Co, Rd and Ta may be substituted for Re.

the reserves and reserves base in U.S.S.R. estimated. 4) Total reserves and reserve base in U.S.A., Canada, strontium carbonate; price of Cr for chromite; price of Li for $LiOH{\cdot}H2O$; price of B for borax pentahydrate; for metal.



The abundant metals in the continental crust (crustal abundances greater than about 0.1 percent).

The metals produced as a by-product from ores of the abundant metal.

The scarce metals mainly found in sulfide minerals.

The metals produced as a by-product from sulfide ores.

The metals occurring in the native state.

The metals produced as by-products from those occurring in the native state.

The metals forming oxides etc., excluding the metals mentioned above.

The metals produced as by-products, mainly from oxide ores.

Fig. 1. Crustal abundances vs. static index since A. D. 2000.
* 75 percent of the world Ag production is obstained as a by-product. A small amount of Sb is produced from Sb ores.
* The small amount Co and Sn is produced as a by-product.
* A small amount of Hg occurs in native state.

and/or copper, because Bi is obtained largely as a by-product from ores of principally lead and copper. In other words, as long as the production of lead or copper is continued, Bi is produced as a by-product from the processing of ores of lead or copper. In the same manner Bi, Cd and Tl are recovered during zinc smelting and refining, and then the world's stocks of these metals are more sufficient than those of zinc according to the static index for 2000 (Table 1). However, it is questionable that the world supply of these metals will last well beyond the lifetime of zinc. Because, it is not realistic that the flue dust and residue produced in smelting are stored over a long term. The figures in Table 1 are available when all kinds of residue produced in smelting and refining are stored in the world. The base metals which include Cu, Pb, and Zn, concentrate principally in sulfide deposits, in which small amounts of rare metals are present as minute inclusions or as atomic substitutes for base metals. Ge, As, Tl, Bi, Cd, In, Te, Re, and so on are by-products of base metal from sulfide deposits, while Ga is produced as a by-product of alumina plants. Vast amounts of Mo, Ag, and Ni are also obtained as a by-product. When the lifetime of a rare metal produced as a by-product is compared with that of a base metal, static indices for 2000 of Ge and Bi produced as a by-product from the processing of ores of other metals, it is shorter than the lifetime of the base metals. The stocks of these resources will be rapidly depleted and the price will begin to rise highly. Higher prices will lead to some substitution. In the case of Ge the estimate of the world demand or supply includes problems about the unreliable high average annual growth rate of 6.9% and about undiscovered reserves. As for other rare metals such as Cd, In, Te, Re etc., which are principally by-products of base metal production, the world supply of these metals should last well beyond the lifetime of the base metals, assuming that the average annual growth rate of each metal in consumption in Table 1 will continue. The lifetime of these rare metals should be replaced by that of the base metals for the reason mentioned before.

2. The Metals of Which the Stock is Rapidly Depleted

Based on the geochemical control between grade and the metal content of the resource base presented by Skinner, the supplies of the abundant metals like Si, Al, Fe, Ti and Mn, are adequate for centuries. As described in 1, the lifetime of metals produced as a by-product is replaced by that of the base metals. Vast amounts of Sb are obtained as a by-product and by recycling. The by-product from sulfide deposits for Ag provide 75% of the world production.

According to the considerations done so far, the metals of which the world's known stock will be depleted by the year 2025, are summarized as follows.

Sn : Sn is one of the earliest metals with a large production. The major Sn production is restricted geographically in Southeast Asia and the eastern side of the high Andes. The crustal abundance is comparatively low and world Sn reserves of 3 million tons is not quite sufficient to meet world demand. However, the Sn resources of the world calculated by USGS in cluding marginal reserves or subeconomic reserves, are 33 million tons. On the other hand, in many used expectations in solder, various kinds of substitutes replace tin compounds. The future problem of Sn is vague.

Hg : In nature, Hg occurs mainly in sulfide mineral and native mercury, and most of the economic deposits are almost entirely in regions of late Tertiary orogeny and volcanic activity. Mercury poisoning may occur in any of the industries in which mercury is used, and can also present an environmental hazard. Although the static reserve index was obtained by relating historical consumption, substitutes for Hg have been found in many formally important mercury uses. The world stock of Hg seems to be sufficient to meet the world demand in the future.

Au : Although Au is an essential industrial metal, it also retains a unique status among all commodities as its widespread monetary use. It is estimated, that the future demand for electronic components, jet aircraft engines, and a host of other products will continue to grow rapidly. However, in the sense of industrial metal, world resources of gold are adequate to meet the forecast demand, but the future price of Au may rise.

Zn, Pb, Cu : Zn, Pb and Cu are traditional metals, consumptions of which are especially high. These metals concentrate principally in sulfide deposits, together with small amounts of numerous rare metals. Potential resources of copper from manganese nodules in the deep oceans are less obvious. Large, low-grade potential resources of zinc and lead have not been identified. There are anxieties over the future supply of these base metals, and of rare metals produced as a by-product from the processing of their ores.

Ni : The static index of Ni for 2000 calculated from the present known reserves is the year 2020. But low-grade deposits of nickeliferous laterites are widespread in the tropics, and constitute the huge known potential resources. They appear to be adequate to meet the forecast demand far into the future.

Ta : Ta and Nb have strong geochemical coherence and are found togeteher in ores which principally occur in carbonatites, in pegmatites or in placers. However carbonatites contain greater amounts of Nb and lesser amounts of Ta. It is estimated that Ta will be in short supply in the near future. Alternate are materials available to take the place of Ta in most of its uses. However using alternate materials would require an increased cost or some sacrifice in physical or chemical characteristics.

W : The major productions and reserves of W are limited in the area of an east-Asian belt running from Korea, through southern China, to Malaya. While the present known reserve of W is relatively poor, data to estimate reserves and potential resources are not sufficient.

3. Balance of Consumption

The holding consumption rate of all mineral resources in stable balance is an important problem of long term supply-demand. Unless the Earth's supply limitations are accurately assessed, a comparison of consumption with the crustal abundance to examine a long term outlook has been carried out (e. g. Skinner (1976), Mckelvey (1960)). In Fig. 2, a comparison of production of each mineral resource in 1983 with crustal abundance

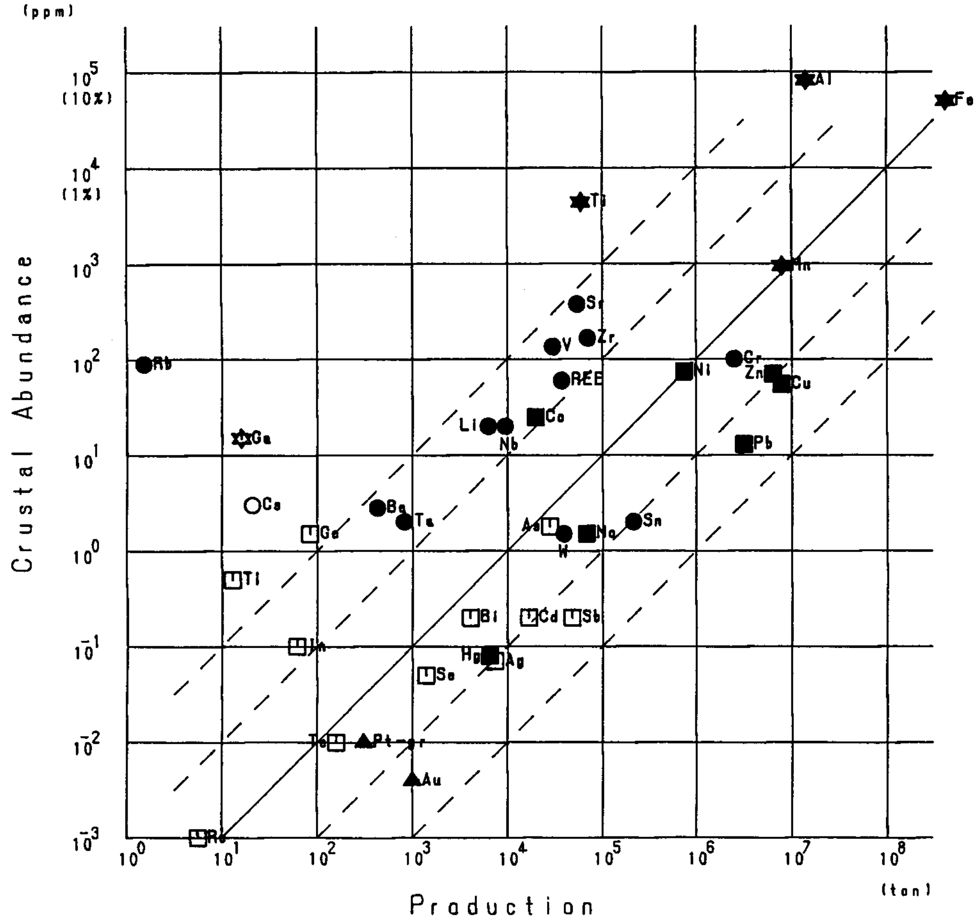


Fig. 2. Crustal abundance vs. production. See Fig. 1 for abbreviations.

* B and Th are excluded from the figure since these elements are represented in oxide-forms in Table 1.

* Pt-group and REE are expressed as abundances of Pt and Ce respectively.

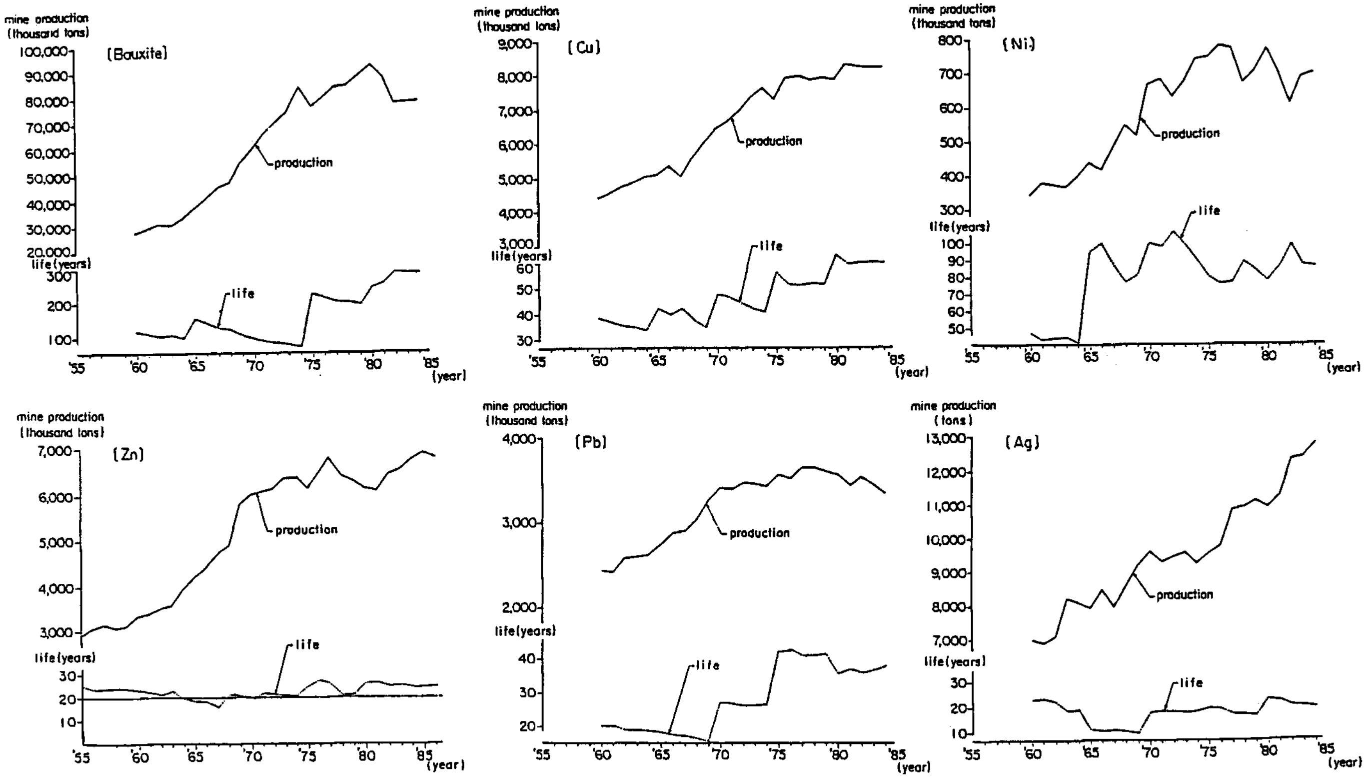


Fig. 3. Change of production and lifetime for six elements.

is illustrated. The depletion rate of Pb is the highest of them and those of Au, Sb, Cu, Sn, Ag and Zn fall in the range of 40-10 times the rate of Ni and the depletion rates of Hg, Cd, Mo, Se, Cr, Bi, W and As in the range of 1-10 times the rate of Ni. As mentioned before, the mineral resources which have shorter lifetime including Pb, Au, Cu, Zn, Sn and Ag except Ge and Ta agree with high depletion rates of the elements.

4. Change of Lifetime Based on Time

The change of static lifetime of some mineral resources based on time are examined

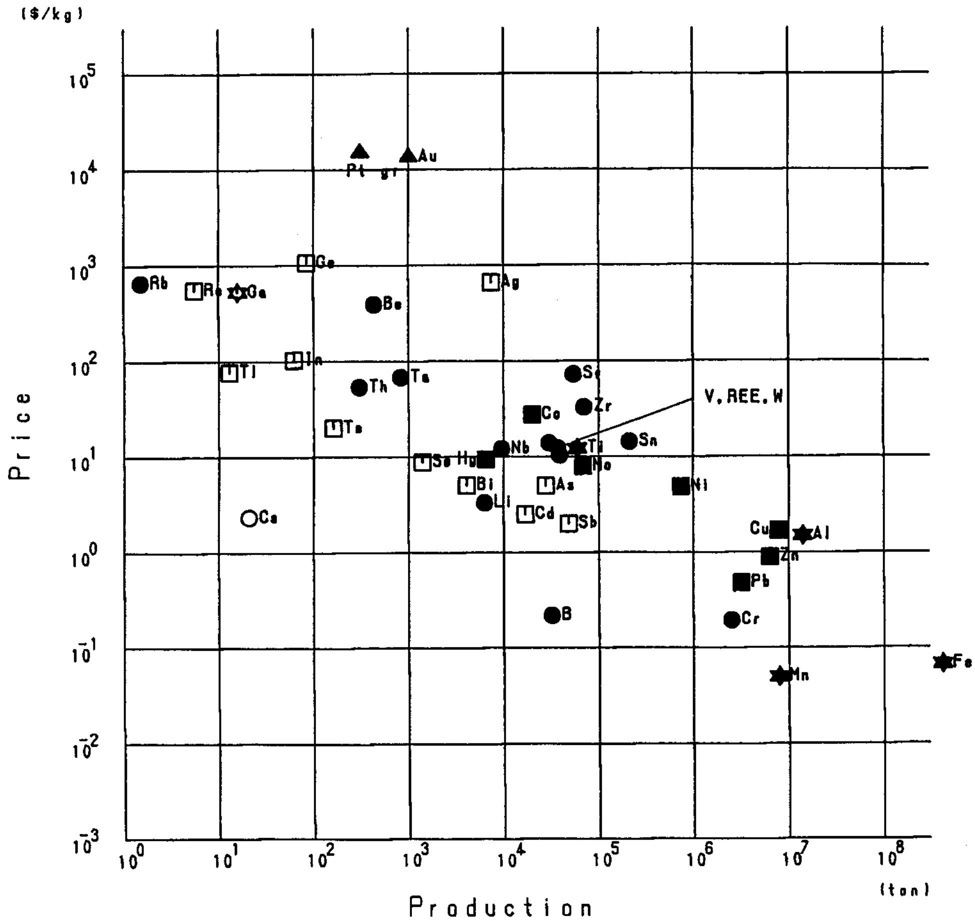


Fig. 4. Production vs. prise in 1983. See Fig. 1 for abbreviations.
*Sr is the price of strontium carbonate ; Cr the price of chromite ; Li the price of lithum hydroxide monohydrate ; B the price of boron oxide ; and Th the price of thorium oxide ; Fe, Mn and Cs are value of ore ; the other price for metal.

in Fig. 3. No tendency of depletion of the resources has been found under the present condition. New reserves, more the consumption, have been discovered in the last few decades. It is contrary to the outlook on the long-term supply-demand. The result means that the static lifetime at present depends upon economic factors, but it is not affected by geochemical factors.

5. Production vs Cost

The relationship between production and cost in 1983 is shown in Fig. 4. The cost of the traditional metals is relatively low, because supplies are plentiful and production large. The cost of precious metals, of which productions are small, is high. Rare metals are valued at middle price between traditional and precious metals. The price of Cu, Pb, Zn, Cr and Ni are relatively similar. It is understood that Ni and Cr substitute for the base metals like Cu, Zn and Pb that there is anxiety about depletion from a geochemical point of view.

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