Geol. Soc. Malaysia, Bulletin 16, December 1983; pp. 193–213

Strata-related metallic deposits: their economic past, present, and future

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Abstract: Two popular beliefs that strata-related deposits (SRD) are a recently introduced catergory of ores, and that SRD are metal sources of the future, are semiquantitatively evaluated using worldwide data.

Two fundamental obstacles to a convincing numerical analysis are 1) the lack of sharp and precise boundaries of SRD; 2) the gaps in data base and a considerable range in data quality. As a consequence, the selection of members that make up the SRD as a class of metallic deposits is based on contemporary convention rather than on accurate definition, and the imperfection of data adds a considerable margin of uncertainty to the conclusions.

Historical review of the proportion of SRD to non-strata-related metallic ores throughout human history demonstrates that SRD—gold and tin placers have been among the most ancient mineralization types utilized. Apparently SRD as a class has been in existence since the beginning with the strata-terminology and the reevaluation of the more controversial types and newly discovered ones being introduced during the great genetic controversy of the 1950's and 1960's.

The prediction of the future importance of SRD has been based on the assumption that ore grade will continue to decrease. The proportion of SRD among metallic ores has been estimated for periods in which the average grade drops to 75%, 50% and 10% of the present grade. The drop to 75% and 50% causes few abrupt changes—the proportion of SRD of more metals moderately increases. At 10% of the present grade, the grade of the low-factor-of concentration metals (Fe, Al, Ti) approaches the mean crustal content and the "ores" will become indistinguishable from rocks. U, Cr, Mn, Pb, Zn, Ag and Au will have their greater proportion derived from SRD. Only in the case of Cu, Sn and possibly Ni will the SRD represent the minority source.

Overall, the belief that strata-related deposits are the metal sources of the future, has been confirmed.

INTRODUCTION

Geology is, among other natural sciences, well known for its numerous scientific controversies, for the rapid change of many fundamental concepts, and for the influence of fashion on our thought. It is also known for the lack of accuracy of many conclusions and for a tendency to broadly generalize. This may result in the appearance of widespread myths based on unsubstantiated beliefs and superficial evidence.

In the field of economic geology of metalliferous deposits and metallogeny one can recognize two most popular recent subjects that dominate the contemporary literature and geological communications: 1) relation of mineralization to plate tectonics: 2) strata-related mineral deposits. This contribution is concerned with the latter subject. The content of recent publications gives the best indication of the sharply increased interest in strata-related deposits in the past decade. The number of papers in the journal *Economic Geology* dealing with or touching on strata-related deposits, has increased from about 10 % thirty years ago to about 40 % at present. The seven-volume Handbook of Stratiform and Stratabound Ore Deposits published in 1976 (Wolf, 1976), with additional volumes recently published presently in press or in preparation, appears to become the most voluminous treatment of any general, internationl subject of economic geology and metallogeny ever published in the English language. Strata-related deposits figure highly in the minds of exploration geologists and are an important, modern target of search pursued my most mining companies. Many important recent discoveries of metallic mineralizations are members of the strata-related family (Howard's Pass Pb-Zn, Canada; Gamsberg Pb-Zn, South Africa; McArthur River Pb-Zn, Australia; Kara-Udokan Cu, U.S.S.R.; Wyoming uranium basins, U.S.A.; among others). The concept of strata-related deposits is in flux and progressing rapidly, and as a consequence myths and beliefs abound. Two of them are particularly widespread:

firstly, that strata-related deposits are basically a newly recognized class

secondly, that strata-related deposits are the future resource of most metals.

This paper is a summary of a study to test the credibility of the above beliefs, using quantitative data.

The data on economic mineralizations have been derived from published and to minor extent unpublished international literature, and gathered in a computerized file base and precious metallic deposits of the world–MANIFILE (Laznicka, 1973), as well as in the more recent extensions of the file. The accuracy and completeness of gathered data depends naturally on the quality of original sources which vary from excellent to poor. Certain types of data are practically nonexistent for certain parts of the world. Some countries, notably the Communist countries and particularly the U.S.S.R., do not publish any numerical data related to their base and precious metal deposits (although, curiously, they may occasionally release some figures on iron, coal and petroleum-commodities that one would consider more strategic, for example zinc or antimony) and estimates are necessary to fill the gap. As a consequence, figures, used in this paper are products of relatively accurate computation based on frequently relatively inaccurate input data, so they should be considered as approximate only. It is, however, believed that since the figures are based on large sample populations of actual deposits, each individually evaluated, they are far more accurate than summary conclusions found in many recently released statistical treatments based on economic factors such as import/export trends and future requirements. It is felt that the results illustrate satisfactorily at least the general trend.

THE NATURE OF STRATA-RELATED DEPOSITS

Probably the shortest definition of strata-related deposits is that they are economic accumulations of minerals controlled by rock stratification or by stratigraphic relationships of their hosts. Although examples of such deposits had been known since the beginnings of economic geology as a branch of science, it was not until the 1950's and later when the terms stratiform, stratabound and strata-related have been introduced and subsequently widely used.

Stratiform deposits are conformable and contemporary with the stratification of their host rocks.

Stratabound deposits are conformable with their host's stratification, but there is no restriction as to the relative time of formation of the ore and its host rock. Consequently, this is a broader category than the former one. Although stratiform deposits are part of the stratabound group, it is more common to use the latter term for deposits the ore of which is younger than the host, or for deposits where the ore/host relationship is uncertain or unknown.

Strata-related deposits the broadest category, has been coined most recently to include both the above groups, as well as many mineralizations situated on the fringe, where the conformity to stratification or genetic relations of mineralization depart significantly from the ideal case.

The introduction of the three terms mentioned above has been a direct consequence of a great scientific controversy in the 1950's and 1960's, which initiated departure from the formerly almost universal genetic model for most base and precious metal deposits that postulated hydrothermal derivation of metal-bearing fluids from granitic intrusions and important structural control for metal emplacement. The pioneering studies of Schneiderhöhn (1953), Garlick (1953), Oftedahl (1958), Stanton (1960), and others, have managed to convincingly demonstrate that, such deposits as some massive sulphide deposits, lead-zinc deposits in carbonates of platforms ("Mississippi Valley type"), bedded copper deposits, and others, formerly interpreted as hydrothermal-replacements, are genetically related to their host's stratigraphy and origin and are therefore stratiform, stratabound and strata-related. The emphasis on the more controversial mineralization, however, left in neglect those deposits in which the genetic and stratigraphic relations to enclosing sediments has not been in doubt almost since the times of Adalbert Gottlob Werner—such as placer deposits in recent sediments, beds of oolithic ironstones, etc. As a consequence, many conclusions in the literature involving strata-related deposits actually apply only to the more controversial reinterpreted ones, and are not necessarily relevant to the entire strata-related family. As will be shown later, that the strata-related deposits are a new class born in the recent controversy and not known before, is one of the myths.

Strata-related metallic deposits constitute a very broad category, which is gradational into the non-strata related. Sharp and unequivocal boundaries between both categories do not exist and are the subject of personal interpretation by each geologist. Uncertainty in affiliation, however, greatly reduces the accuracy of statistical evaluation, which is the subject of this study. So in the absence of an unequivocal classification logic, one has to turn to convention. Mineralizations treated in (Wolf, 1976) and listed in Laznicka (1981b) have been included in the sample population on which this paper is based.

Table 1 lists the 75 economically most important empirical groups (types) of strata-related metallic deposits. Figures 1 to 7 illustrate graphically the complexity and

TABLE 1

SHORT LIST OF THE MORE COMMON EMPIRICAL GROUPS (TYPES) OR STRATA-RELATED METALLIC DEPOSITS

IRON ORES

1	Phanerozoic submarine-exhalative ores in spilite-keratophyre association-quartz + hematite or siderite; e.g. Lahn-Dill basins, Germany.	5/299 Mt Fe[*]
2	Phanerozoic bedded ironstones in clastic marine sediments, close to volcanics; e.g. Vares, Yugoslavia	12/3, 148 Mt Fe
3	Phanerozoic bedded ironstones in clastic marine sediments, nonvolcanic association; e.g. Birmingham, U.S.A.	72/44, 855 Mt Fe
4	Precambrian banded iron formations in marine volcanic-sedimentary associations; e.g. Wawa, Canada ("Algoma type")	51/83, 777 Mt Fe
5	Weathering-enriched crusts over the above; e.g. Mysore, India.	25/37, 605 Mt Fe
6	Precambrian banded iron formations in marine clastic sediments, nonvolcanic association; e.g. Mesabi Range, U.S.A.	13/58, 084 Mt Fe
7	Weathering-enriched crusts over the above; e.g. Quadrilatero Ferrifero, Brazil.	12/8, 474 Mt Fe
8	Subaerial magnetite lavas; e.g. El Laco, Chile	2/536 Mt Fe
9	"Kiruna type" magnetite deposits; e.g. Kiruna, Sweden	3/2, 390 Mt Fe
10	Magnetite beach sands; e.g. Taranaki, New Zealand	9/688 Mt Fe
11	Diagenetic siderite and goethite in coal association; e.g. W. Pennsylvania, U.S.A.	6/1,141 Mt Fe
12	Stratabound magnetite deposits in high-grade metamorphics; e.g. Dover, U.S.A.	7/1,901 Mt Fe
13	Fe hydroxides in residual weathering crusts over non-ore basement rocks; e.g. Conakry, Guinea.	5/973 Mt Fe

MANGANESE ORES

14	Seafloor ferromanganese nodules; e.g. Pacific ocean floor	3 oceans/ min. 200 Mt Mn
15	Bedded, siliceous Mn ores in chert-jasper-siliceous argillite-submarine mafic volcanics association; e.g. Olympic Peninsula, U.S.A.	20/48.6 Mt Mn
16	Bedded Mn ores in submarine andesite pyroclastics/limestone association; e.g. Santa Rita, Cuba.	9/9.46 Mt Mn
17	Bedded Mn ores in fine detrital and chemical sediments, distal submarine volcanics; e.g. Atasu, U.S.S.R.	4/22 15 Mt Mn
18	Bedded Mn ores in fine detrital sediments, rare volcanics, mobile belts; e.g. Chvaletice, Czechoslovakia.	6/49.64 Mt Mn
19	Mn-rich bands in banded iron formations; e.g. Corumba-Mutun, Brazil and Bolivia.	3/82 Mt Mn
20	Residual Mn oxides in weathering enriched crusts over Mn-bearing volcanic-sedimentary iron formations; e.g. Urandi, Brazil.	7/35 Mt Mn
21	Residual Mn oxides in tropical weathering crusts over low grade Mn protore; e.g. Nsuta, Ghana.	30/306.8 Mt Mn
22	Bedded Mn oxides and carbonates in quartz arenites, claystones, limestones of platforms; e.g. Nikopol, Ukraine.	10/1,313 Mt Mn

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[*] Based on data from 1500 more important strata-related metallic deposits of the world (Laznicka 1981a, 1981b, 1981c). Number of localities listed/cumulative tonnage of *metal* (not ore) content in economic ores, is shown. Abbreviations: Bt = billion tonnes, Mt = million tonnes; kt = kilo tonnes; t = tonnes. + = controversial types not considered to be strata-related by some. Mineralizations where metals are recovered as by-products are not listed.

TABLE 1 *(contd.)*

	ALUMINIUM ORES (bauxite only).	
23	Transported, less residual bauxite over various bedrocks; e.g. Var Dept., France.	65/1,997 Mt Al
24	Residual bauxite and bauxitic laterite over various bedrocks; e.g. Boke, Guinea.	56/2,000 Mt Al
	COPPER ORES	
25	Massive pyrite, chalcopyrite (±sphalerite) deposits in submarine mafic volcanic associations; e.g. Troodos Complex, Cyprus.	28/2.8 Mt Cu
26	Massive pyrite-chalcopyrite ± sphalerite in submarine mafic-felsic volcanic-sedimentary association proximal to volcanics; e.g. Tharsis, Spain.	81/37 Mt Cu
27	Ditto, distal to volcanics; e.g. Besshi, Japan.	28/6.3 Mt Cu
28	Diagenetic Cu sulphides in bituminous shale, argillite, etc; e.g. Mansfeld, Germany.	19/20.25 Mt Cu
29	Cu sulphides in continental arenites of the "red beds" association; e.g. Nacimiento mine (Cuba), U.S.A.	22/9.27 Mt Cu
30	Disseminated Cu sulphides in Precambrian continental and nearshore marine metasediments ("Cu-Schists"); e.g. Zambian Copperbelt.	19/90.6 Mt Cu
31 +	Native copper with silicates in low-grade metamorphosed "plateau basalts"; e.g. Keweenawan amygdaloids, Michigan, U.S.A.	2/2.12 Mt Cu
32	Massive and disseminated Cu-Zn sulphides in high-grade metamorphics; e.g. Manitouwadge, Canada.	38/15 Mt Cu
33	"Exotic" deposits of Cu oxides in recent streams and aquifers; e.g. Exotica, Chile.	4/3.7 Mt Cu
	ZINC AND LEAD ORES	
34	Massive Pb-Zn (Cu) sulphides in submarine, intermediate to felsic volcanic-sedimentary association of mobiles belts; e.g. Rosebery, Australia.	49/29 Mt Zn 14.7 Mt Pb
35	Massive Pb-Zn sulphides in marine (meta) sediments of mobile belts with accessory volcanic, non-carbonate hosts; e.g. Sullivan, Canada.	21/70.5 Mt Zn 45.3 Mt Pb
36	Disseminated Pb-Zn sulphides in nonvolcanic lagoonar carbonates; e.g. Sumsar, U.S.S.R.	6/6 Mt Zn 13.6 Mt Pb
37	Disseminated to massive Zn-Pb sulphides in shallow marine carbonates, nonvolcanic affiliation; e.g. Tri-State district, U.S.A.	51/78.4 Mt Zn 43.2 Mt Pb
38	Disseminated Pb-Zn sulphides in continental sandstones–"red beds" association; e.g. L'Argentiere, France.	8/2.5 Mt Zn 3.16 Mt Pb
39	Massive and disseminated Pb-Zn sulphides in micaschists, gneiss, metaquartzite; e.g. Bleikvassli, Norway.	17/41 Mt Zn 25 Mt Pb
	Massive and disseminated Pb-Zn sulphides in marble, calc-silicate gneiss, skarnoid; e.g. Balmat, U.S.A.	9/6.5 Mt Zn 1.6 Mt Pb
41	Massive Zn-Mn silicates in high-grade metamorphics; e.g. Franklin-Sterling, U.S.A.	1/4.5 Mt Zn
42	Residual Zn-Pb oxides in weathering crusts; e.g. Vazante, Brazil.	4/4.2 Mt Zn 0.3 Mt Pb
	GOLD ORES	
43 +	Dispersed gold in sulphides (arsenopyrite, pyrite), and free in stratabound "lodes" in ultramafic to felsic volcanic-sedimentary association; e.g. Homestake mine, U.S.A.	34/3,391 t Au
44	Recent to Neogene alluvial gold placers; e.g. Klondike River, Canada.	91/12,607 t Au
45	Precambrian gold palaeoplacers; e.g. Witwatersrand, S. Africa	3/28,903 t Au

TABLE 1 *(contd.)*

URANIUM and VANADIUM ORES

46	Dispersed uranium oxides in lagoonar etc. black argillites and thin bedded dolomites; e.g. Lodeve, France.	2/13.5 kt U
47	Disseminated U (V) oxides in peneconcordant bodies, in continental sandstones; e.g. Uravan, U.S.A.	40/438 kt U 200 kt V
48	U-V oxides in karsted carbonates; e.g. Tyuya Muyun, U.S.S.R.	4/18.7 kt U 10 kt V
49	Disseminated U-oxides in Proterozoic quartz conglomerate and quartzite; e.g. Elliot Lake, Canada.	3/310 kt U
50	U oxides in arid soil profiles (calcicrust); e.g. Yeelirrie, Australia.	2/40 kt U 10 kt V

CHROMIUM, NICKEL, COBALT, PLATINUM ORES.

51	Layered chromite in ultramafic sills of mobile belts; e.g. Bird River Sill, U.S.A.	6/9 Mt Cr
52	Chromite in layered intrusions of cratons; e.g. Bushveld Complex, South Africa.	5/4,691 Mt Cr
53	Nickeliferous ochers of redeposited weathering crusts at unconformities; e.g. N. Euboea, Greece.	8/1.32 Mt Cr 4.66 Mt Ni
54	Nickeliferous ochers and hydrosilicates transported into karst; e.g. Khalilovo, U.S.S.R.	4/2.8 Mt Cr 2.01 Mt Ni 60 kt Co
55	Nickeliferous ochers and hydrosilicates in residual weathering crusts over ultramafics; e.g. New Caledonia.	31/21 Mt Cr 59 Mt Ni
56 +	Ni-Cu silphides at base of gabbro-norite-granophyre complexes and at base of gabbro-troctolite sills; e.g. Sudbury, Canada.	8/17.3 Mt Ni 1,240 t Pt
57	Alluvial placers of platinum; e.g. Goodnews Bay, Alaska.	7/641 t Pt
58	Disseminated Pt in layered cratonic intrusions; e.g. Merensky Reef, South Africa.	1/24,300 t Pt

TITANIUM, ZIRCONIUM, RARE EARTHS, THORIUM ORES.

59	Lithogenetic heavy minerals in recent marine beach placers; e.g. Eneabba, Australia.	17/161.4 Mt Ti 21.6 Mt Zr 718 kt RE 209 kt Th
60	Lithogenetic heavy minerals in marine palaeoplacers; e.g. Bothaville, S. Africa.	15/28.7 Mt Ti 1.6 Mt Zr 12 kt RE 22.5 kt Th
61	Ditto, in alluvial placers; e.g. Piedmont, U.S.A.	3/428 kt RE 136 kt Th
62	Ti-magnetite, ilmenite in gabbro-anorthosite layers of differentiated cratonic intrusions; e.g. Bushveld, South Africa.	2/246 Mt Ti
63	Disseminated zircon, eudialyte, loparite, etc. in magmatic layers of felsic alkaline intrusions; e.g. Lovozero massif, U.S.S.R.	2/7.5 Mt Zr
64	Layered Ti-magnetite and ilmenite in anorthosite plutons of high-grade metamorphic terranes; e.g. Lac Allard, Canada.	10/199 Mt Ti
65	Residual ilmenite and rutile in saprolite over high-grade metamorphics; e.g. Roseland, U.S.A	3/16.3 Mt Ti

TIN, TUNGSTEN, MOLYBDENUM, BERYLLIUM ORES.

66 +	Disseminated cassiterite in massive pyrrhotite lenses in black argillite; e.g. Mt. Cleveland, Australia.	2/85 kt Sn

TABLE 1 *(contd.)*

67 +	Stratabound disseminated scheelite in metacarbonates at intrusive contacts; e.g. Grassy, Australia.	4/289 kt W
68 +	Ferberite/hübnerite in bedded lodes in black slate, chert; e.g. Shyorongi, Rwanda.	3/60 kt W
69 +	Disseminated bertrandite with fluorite in reworked felsic tuff; e.g. Spor Mt., U.S.A.	1/24 kt Be
70	Stratabound cassiterite in quartzite (palaeoplacer ?); e.g. Milluni district, Bolivia.	1/100 kt Sn
71	Cassiterite in continental placers; e.g. Stanthorpe, Australia.	50/11.5 Mt Sn 24 kt W
72	Disseminated cassiterite in high-grade metamorphics; e.g. Gierczyn, Poland.	3/210 kt Sn
73	Disseminated scheelite in high-grade metamorphics; e.g. Taryall Springs, U.S.A.	5/301 kt W
74 +	Stibnite in bedded lodes in black slate etc. association e.g. Stadt Schlaining, Australia.	4/600 kt Sb
75 +	Cinnabar in stratabound bodies; e.g. Almaden, Spain.	6/710 kt Hg

the wide range of variation of selected geological properties of strata-related mineralizations. Figures 1 to 5 are self-explaining, whereas Figures 6 and 7 require further comment.

Composite strata-related systems (Fig. 6a) have typically both strata-and non-strata-related elements combined within a single locality. Probably the most common example here are subaqueous exhalative sulphide or oxide deposits (such as empirical groups 25, 26, 34, 35, etc. of Table 1). A fully developed deposit (system) consists of a stratiform ore lens, conformably topped by unaltered sediments or volcanics. The footwall, in places or throughout, displays a distinct hydrothermal alteration (chlorite, sericite, silica, albite, tourmaline, and other assemblages), and disseminated, stringer or vein mineralization which is discordant in respect to the wall-rock stratification—if any.

Fig. 6b illustrates a common case of a low-grade stratabound mineralization (commonly of no economic value such as protore, trace metal enriched band), with superimposed, discordant, higher-grade economic mineralization, considered a product of remobilization. Examples include rich, discordant barite and sulphide masses, pipes and veins superimposed over weakly mineralized stratiform iron formation, baritic and sulphide-bearing chert and siliceous argillite and carbonates, in several deposits in the Atasu district, Uspenski zone, Kazakhstan (Borukaev and Shcherba, 1967–8).

Fig. 6c illustrates a superficially enriched, residual orebody developed on the earth's surface as a product of tropical weathering of a stratabound low-grade ore, protore or a trace-metal enriched rock. Pre-Cainozoic equivalents are usually buried by younger sediments and rest on unconformities. Supergene enriched orebodies have the shape of blankets, pockets and lenses that are conformable with (palaeo) surface, and as such are considered members of the strata-related family : even if the footwall contact is in detail jagged and uneven (as in many nickel laterites). The downward

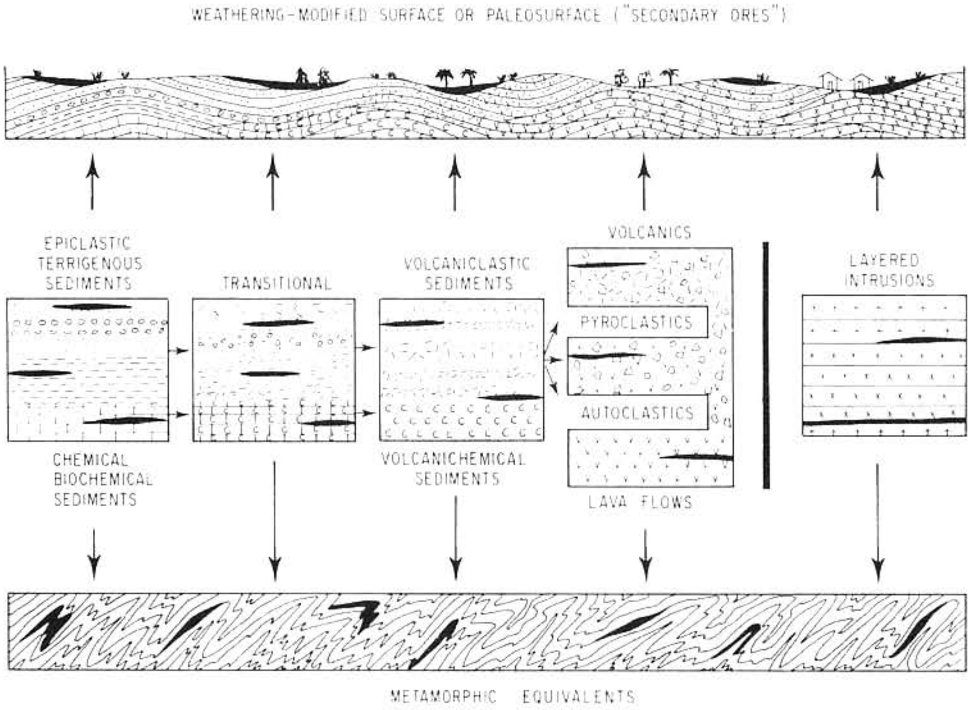

Fig. 1. Strata-related deposits: variations in host-rock category.

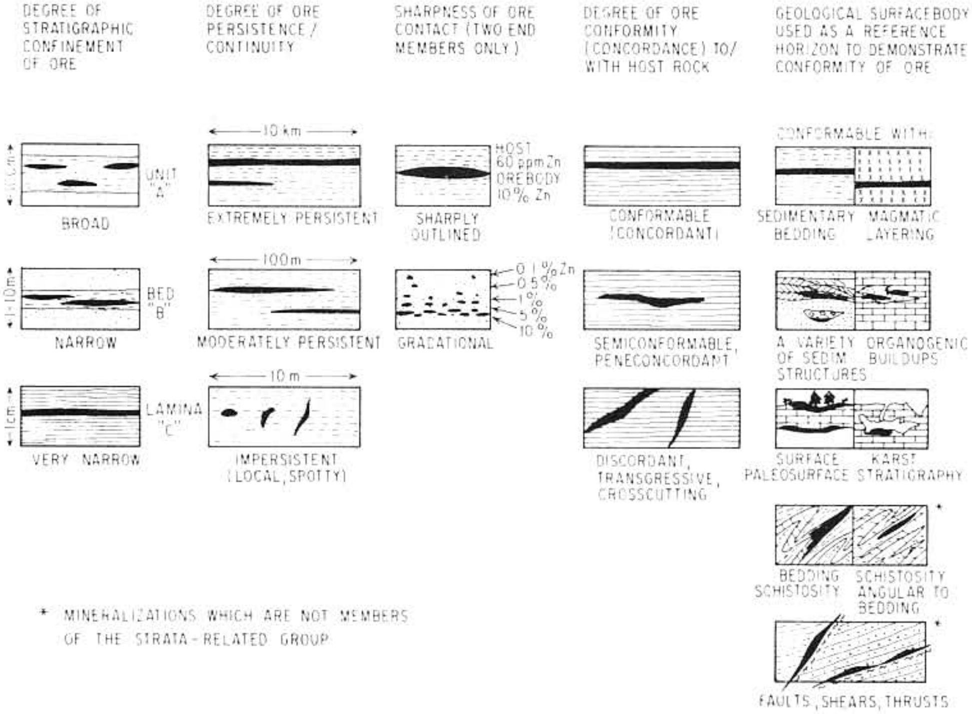

Fig. 2. Strata-related deposits: variations in the degree of stratigraphic confinement, persistence, contact sharpness, conformity and a reference horizon.

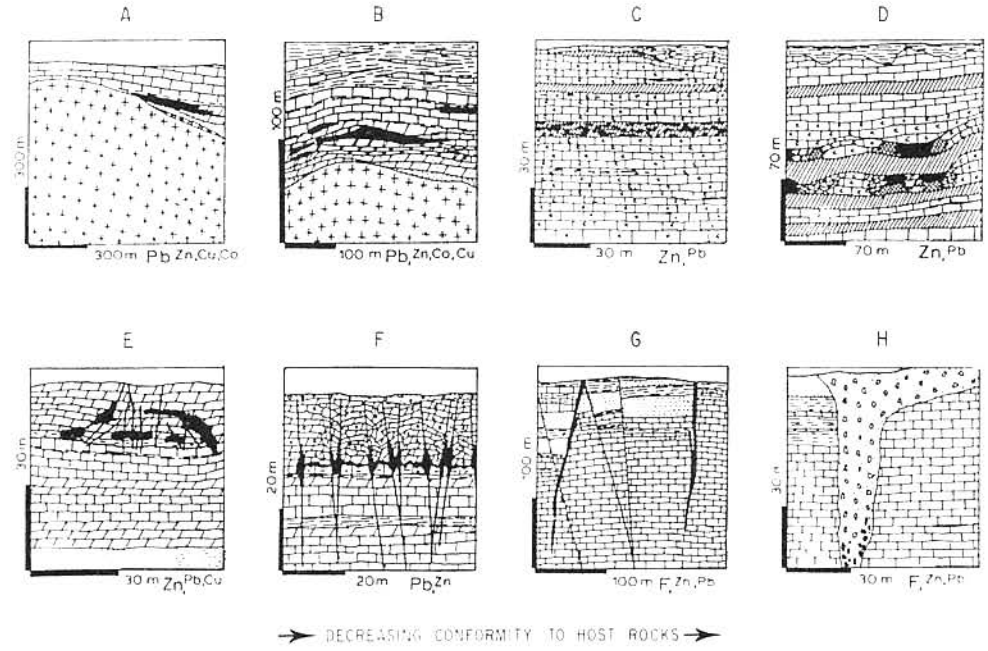

Fig. 3. Application of description of actual strata-related deposits, using attributes assembled in Fig. 2:

A: Broadly confined, moderately persistent, moderately sharply outlined orebody, conformable to semiconformable to sedimentary bedding.
B: Moderately confined, moderately persistent, sharply outlined orebodies, conformable to semiconformable to sedimentary bedding and facies variations influenced by organogenic buildups.
C: Broadly confined, persistent, gradational orebodies, conformable to semiconformable with sedimentary bedding.

Examples A and B are galena orebodies from the South-Eastern Missouri lead district, example C is dominantly disseminated sphalerite from the Tri-State district.

All the eight examples of lead, zinc and fluorite mineralization occur in the Paleozoic platformic sediments of the United States interior and are part of the "Mississippi Valley" mineralization type when this is used in summary generalizations. The mineralizations are arranged by decreasing degree of conformity; the examples E and F from the Upper Mississippi Valley district are at best situated at the fringe of the strata-related family, whereas the examples G and H, from the Lllinois-Kentucky district, are completely transgressive. The sections are from Laznicka (1981a).

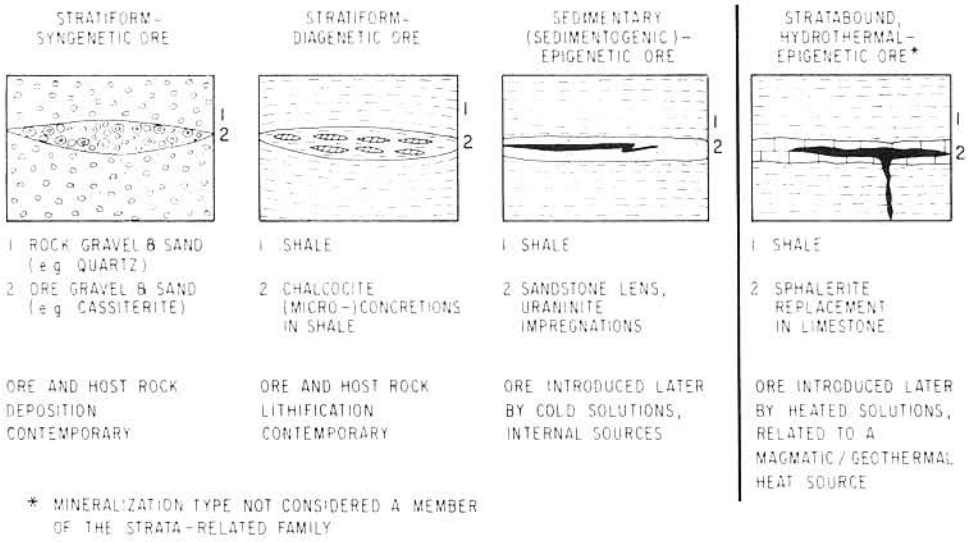

Fig. 4. Strata-related deposits: the ore host rock time relationship.

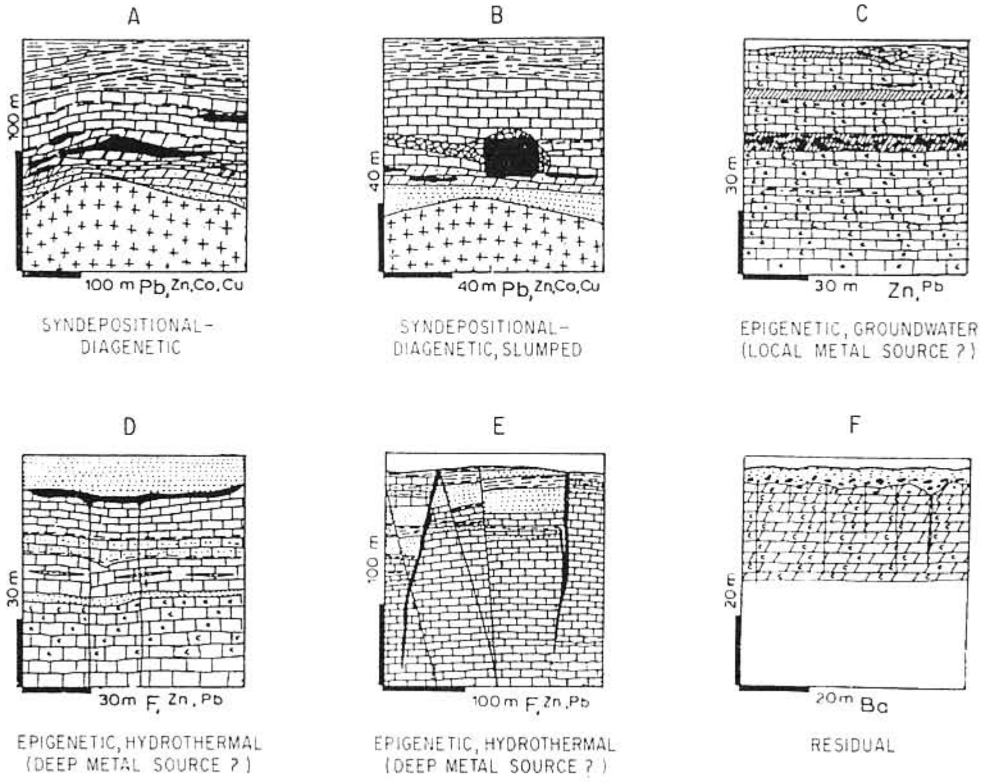

Fig. 5. The ore hot rock time relationship illustrated by actual examples of lead, zinc, fluorite and barite mineralizations tht occur in the platform sediments of the United States interior. Sections are from Laznicka (1981a).

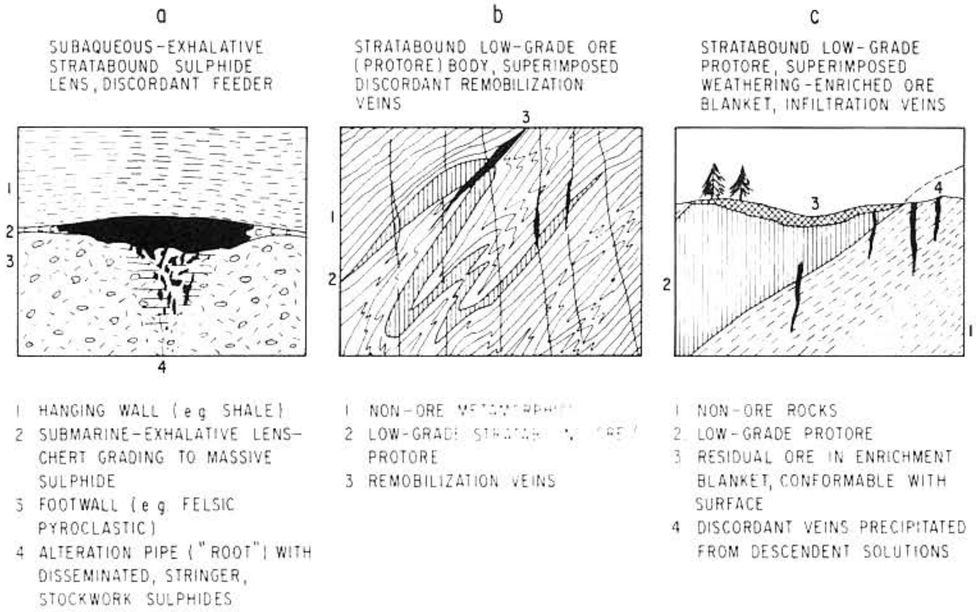

Fig. 6. Composite strata-related ore deposits (systems).

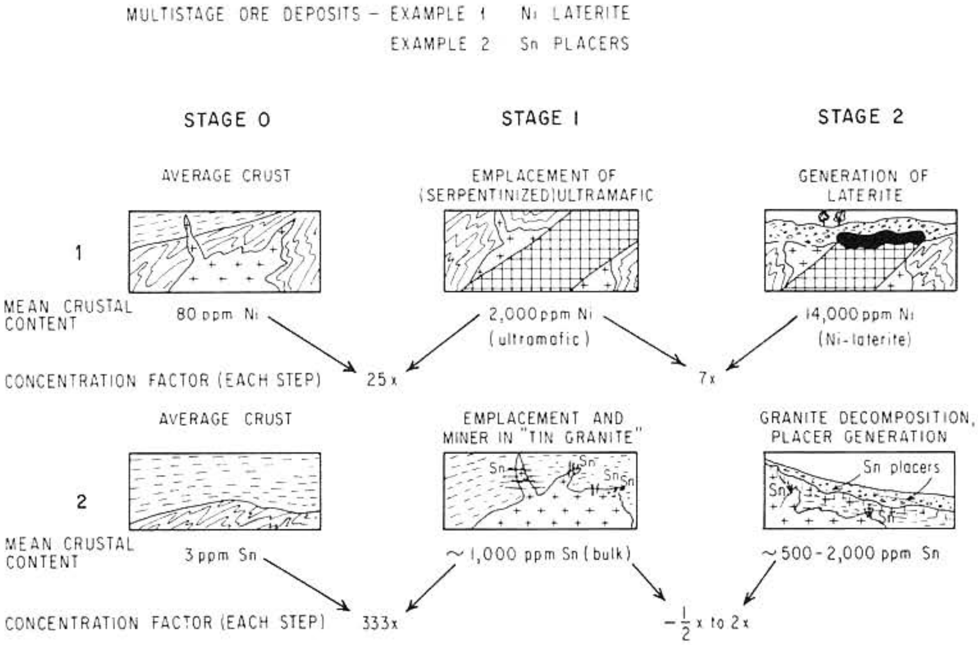

Fig. 7. Multistage ore deposits the final stage (phase) of development considered strata-related.

percolation of a weathering-released metal, however, may reach a considerable depth from the surface and generate infiltration wedges and fissure veins filled from above. Many uranium vein deposits associated with the "unconformity U type" are of similar character for example, in the Lake Athabasca region of Saskatchewan, Canada (Tremblay, 1978). Such orebodies are, however, not considered stratabound.

Many, if not most, metallic ore deposits are now logically interpreted as having formed in more than one stage (phase), usually in a sequence of gradual increase and multiplication of metal concentration and accumulation in each consecutive step. Two simple examples of multistage deposits are shown graphically in Fig. 7.

The first example is a nickel laterite ore. The tonnage and grade data on nickel laterite deposits are available in the literature and can be extracted for the purpose of statistical evaluation such as this one. It is, however, obvious that the final stage (step) of Ni laterite formation is a process with a very low magnitude of nickel concentration (= clarke of concentration 7), whereas the preceding stage : the ultramafic bedrock generation and emplacement, is a process much more impressive in terms of metal accumulation and concentration (= clarke of concentration 25). Ultramafics with 0.2% Ni, however, are (not yet) nickel ores, so nickel laterite is the final product involved in statistics.

The second example in Fig. 7 shows the formation of "tin granite" as the first major step towards generation of an economic tin deposit. The popular image of a "tin granite" is analogic to porphyry copper deposits, in that it consists of discrete, large volume blocks of rocks more or less evenly mineralized by low-grade pervasively disseminated or veinlet cassiterite. It, however, appears that such distribution of cassiterite in the bedrock, that acted as the source of cassiterite now present in supergene deposits (as in the Burma-Malaya-Indonesia tin belt; E. Australia; Cornwall) is relatively rare. Most bedrock cassiterite mineralization from which tin placers form include discrete veins, pipes, carbonate replacements which are of very small size and equivalents of large size hypogene deposits but uneconomic, if mined individually. Patches of tin mineralization are separated by large expanses of barren rock. Surficial decomposition of the bedrock with or without subsequent hydrodynamic reworking, first, causes considerable softening of the bedrock, thus making it locally economical to process (= ore), even if no actual enrichment in tin content took place. Sometimes even a mildly impoverished weathering crust constitute the ore, while the underlying bedrock does not. In most instances, in alluvial tin placers, however, a mild enrichment in tin grades did take place and the patchy tin distribution in the source bedrock being more evenly spread and stratigraphically controlled.

A writer engaged in statistical evaluation of metallogenic processes and ore deposits distribution such as the present one faces a problem as to which of the two fundamental steps in alluvial tin deposits genesis to chose from. In a study like this, the selection can completely reverse the results. Here, the surficial tin deposits have been considered to be tin placers, therefore strata-related mineralizations in sediments. The same mineralized areas, however, serve as justifiable examples of granite-related (= non-stratabound) metallogeny in works of other authors. Tin represents an extreme case of ambiguity in this study — most of the remaining metals, fortunately, present a much clearer choice.

To conclude, it has to be admitted that strata-related deposits are a considerably heterogenous and imperfectly outlined group the present popularity of which started initially as a protest movement in the 1950's and 1960's against the then entrenched belief that almost all metallic deposits were ultimately related to intrusive batholiths. Recognition that the understanding of local stratigraphy can be beneficial in the search for certain types of metallic deposits, hand in hand with new exploration techniques, has been handsomely rewarded by the wave of strata-related mineral discoveries in Canada, the U.S.A., Australia, Japan, S. Africa, Ireland, and elsewhere. In the wave of popularity many previously known mineralizations have been reinterpreted and their strata relation stressed. To many of the present friends of strata-related mineral deposits the stratigraphy-influenced way of interpreting observations appears to be more important than the strict conformity of orebodies to their hosts.

THE PAST OF STRATA-RELATED METALLIC DEPOSITS

In the dawn of the industrial history, the selection of metals produced was restricted to gold, tin, copper and later iron. Due to the lack of sophisticated mining techniques, exploration and dressing, all the products must have come from easy to mine and easy to process surficial deposits. Virtually all the gold and tin came from placers (= stratabound deposits), and iron from superficial limonites. Some of the limonites may have been gossans over non-stratiform deposits, but most known areas of prehistoric iron production generally coincide with the presence of strata-related iron ores. Most of the prehistoric copper, however, appears to have come from secondary enriched outcrops over non-strata-related deposits (Fig. 8, line A).

In the times of Agricola (Fig. 8, line B), the selection of metals utilized by man had been slightly larger and included iron, gold, silver, copper, lead, tin, cobalt and antimony. The mining and smelting technology varied considerably over the then world from the primitive one to the fairly sophisticated and mechanized one, as in the Erzgebirge, Cornwall, and others. Compared with the prehistory, the porportion of non-stratabound metal sources increased, due to the partial depletion of placer deposits of tin and gold in the historical mining regions. The large tin placer belt in the S.E. Asia and the Witwatersrand gold conglomerates were yet to be found.

By the beginning and spread of the industrial revolution of the 1850's (Fig. 8, line C), most metallic elements have already been discovered and isolated in the laboratory, but there was no practical use for many of them (for example, W,V,Mo,Nb,Ti,Al), so deposits of these even if known had not been utilized and studied. The selection of historical metals in production has been enlarged by the addition of zinc, manganese and uranium (for peaceful purposes — such as, paints). The non-stratabound deposits had dominated the production.

By the World War I period, almost all naturally occurring metals have been known and rapid industrialization plus occasional major wars generated demand for

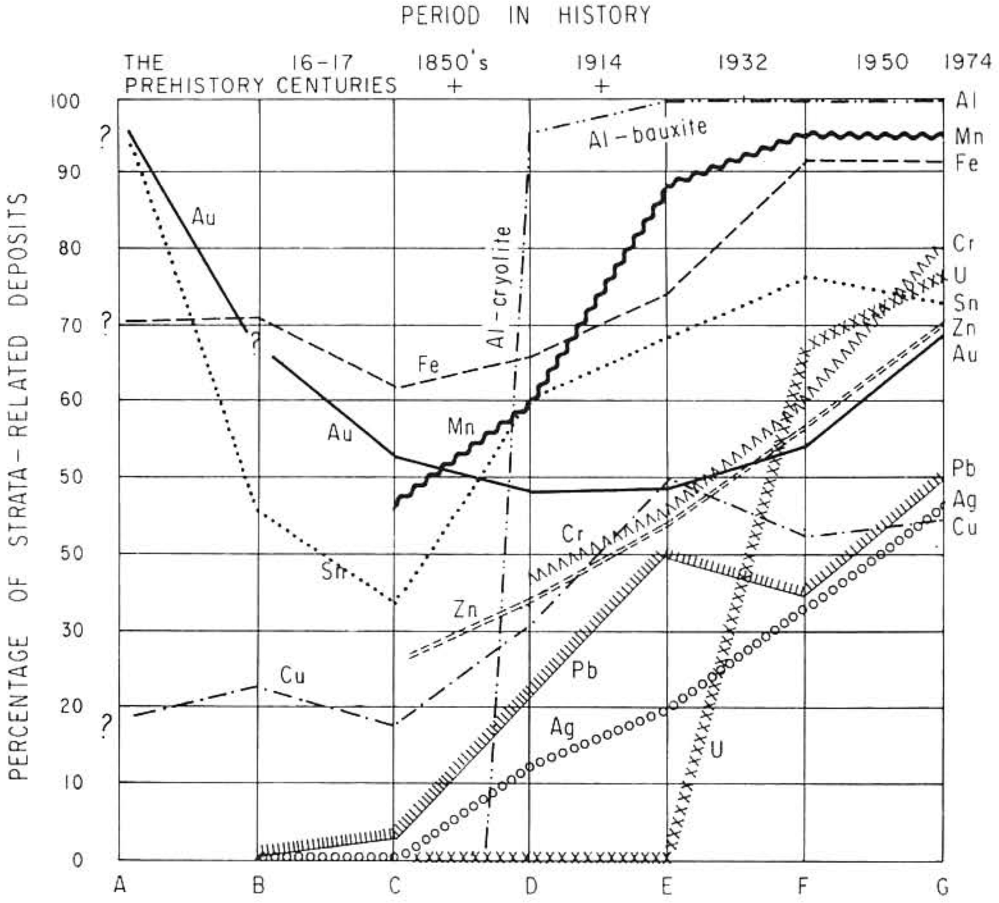

Fig. 8. The changing proportion of metals derived from strata-related deposits in the industrial past.

both the classical metals as well as the newcomers such as aluminium or the steel alloy metals (such as tungsten, molybdenum, chromium, vanadium and nickel) (Fig. 8, lines D, E). The mining and processing technologies underwent rapid development, at least in the industrialized countries. The development of flotation, for example, has made it possible to treat complex, fine-grained and low-grade ores. Most well-known ore deposits and mineralized regions that were to figure prominently in the textbooks of the 1930's through 1950's to influence our education and thought, have been discovered by that period. Several strata-related giants had been known and mined (Rand-Au; Mississippi Valley Zn-Pb; Zambian and Zaire Copperbelt-Cu; Broken Hill, Australia; Rammelsberg, Germany; Flin Flon, Canada-all Zn, Pb, Cu massive sulphides), but in the scientific environment dominated by the epigenesis-structural control—granite dominated ideas, their stratigraphic relationship was either not recognized, or was downplayed. Beginning with the modern age, production statistics have become available, for example in the Minerals Yearbooks.

In the post-World War II period (Fig. 8, line F, G), several unprecedented mining and exploration booms took place. The bulk mining and processing technologies have made it possible to treat complex and low to very low grade ores, so many previously uneconomic mineralizations became mineable. Among important strata-related metallic mineralizations discovered and industrially developed in this period, one might mention: Proterozoic uraniferous conglomerates, as in Elliot Lake, Canada; "roll-type" uranium mineralization in the Colorado Plateau and Wyoming; low-grade uranium bearing phosphates and carbonaceous shales, as in Florida and S. Sweden; very low grade heavy minerals containing beach sands, as in N. Florida; low-grade galena disseminations in arenites as in Laisvall, Sweden and L'Argentière, France; and so on).

Fig. 8 shows changing trends in the proportion of strata-related to non-strata related deposits of various metals through the history.

Out of the metals shown, the curve for iron shows the least variation, and a steady increase in the proportion of strata-related deposits. Although there is a considerable variety of non-stratabound iron deposits, they are of small to medium size. Most of them have already been exhausted and the ore tonnage still being produced becomes insignificant against the background of the sharply increasing production from lower-grade, but practically inexhaustible Precambrian siliceous iron formations.

The curve of copper, surprisingly, also shows only a low degree of variation. Following the exhaustion of numerous rich but small to medium size vein, replacement, and other deposits by the modern age, the strata/non-strata deposit ratio mostly reflects temporary fluctuation between the two principal modern copper sources: porphyry coppers on one side (= non-stratabound) and "copper shales, sandstones and schists", and massive sulphides (= stratabound), on the other.

The curve of tin reflects the depletion of cassiterite placers (= stratabound) in the historical mining areas (such as Cornwall, and the Erzgebirge) by the mid – 1800's and a switch to almost exclusive mining of underground vein and stockwork deposits there. The sharp increase in the proportion of strata-related deposits of tin marks the discovery and subsequent development of the enormous, mostly alluvial (= stratabound) tin accumulations in the S.E. Asian Tin Belt.

The curve of gold indicates the gradual decline in importance of placer deposits (= stratabound) in contrast to the increasing production from lode deposits (= non-stratabound). This decline has been terminated and subsequently reversed by the discovery and large-scale production from the Rand palaeoplacers of South Africa.

The increasing proportion of strata-related silver indicates the gradual switch of silver sources from the "bonanza-type" veins (as in Mexico, Bolivia, Erzgebirge), to various modern "bulk" ore types, such as Pb (and many Zn and Cu) bearing massive and disseminated sulphides, where silver is recovered as a by-product.

The "modern metals" have much shorter history and much steeper trend of variation in some instances. The curve for alumimium reflects the switch from the initial Al ore (cryolite = non-stratabound) to bauxite (stratabound), caused by the suddenly increased demand for uranium as porcelain pigment was easily met by the production from a single high grade vein deposit (= non-stratabound: for example Jáchymov). In the period between the two wars, uranium was a hard-to-sell by-product of radium recovery from deposits of similar type; strata-related uranium deposits were exceptional before World War II (for example Uravan, U.S.A.). Following the A-bomb, an unprecedented worldwide exploration activity resulted in discovery and subsequent development of many uranium deposits, dominated by the strata-related types. The curve for chromium reflects the decline of production from the mostly small and medium-size "podiform" deposits in "Alpine-type" ultramafics (mostly non-stratabound), and a steady increase in production from the magmatic-stratiform chromitite layers in the differentiated complexes of Southern Africa.

THE PRESENT AND THE FUTURE OF STRATA-RELATED DEPOSITS

Fig. 9 shows the proportion of strata-related metallic deposits in mineral deposits of the world, produced or present in known ore reserves to-date. An economic ore is, unfortunately, a substance that results from a combination of geological factors (mostly the degree of geochemical concentration and accumulation), and economic factors (mostly a consideration whether a profit can be gained from mining and processing of the ore). Both groups of factors correlate only very broadly and there are numerous examples of geochemically highly concentrated substances that are not ores, and on the other hand ores, with a very low factor of geochemical metal concentration.

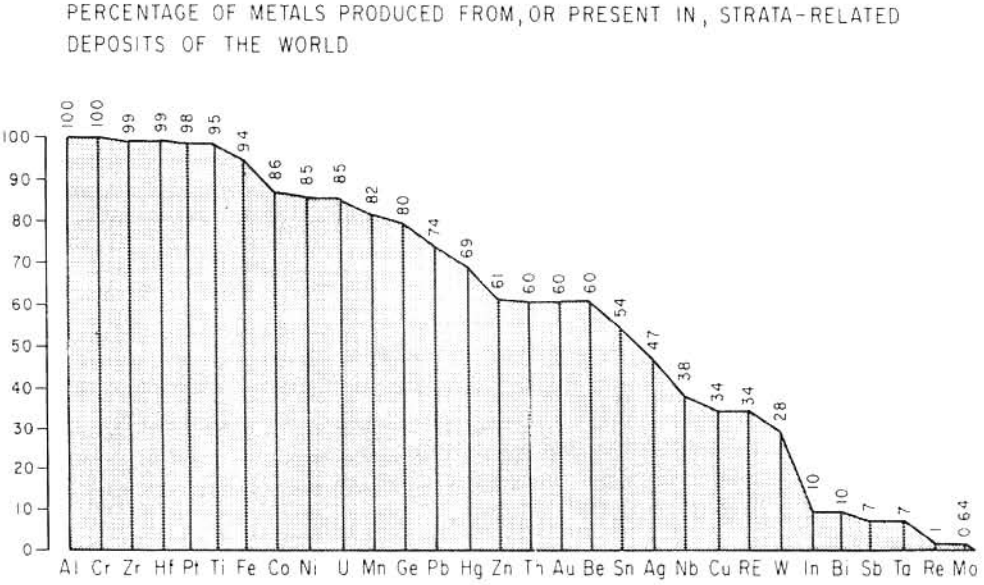

Fig. 9. Graph showing the percentage of metals produced from, or present in strata-related deposits of the world. Based on cumulative figures that include the quantity of metal actually produced to date, as well as available in known reserves. Data from Laznicka (1981c).

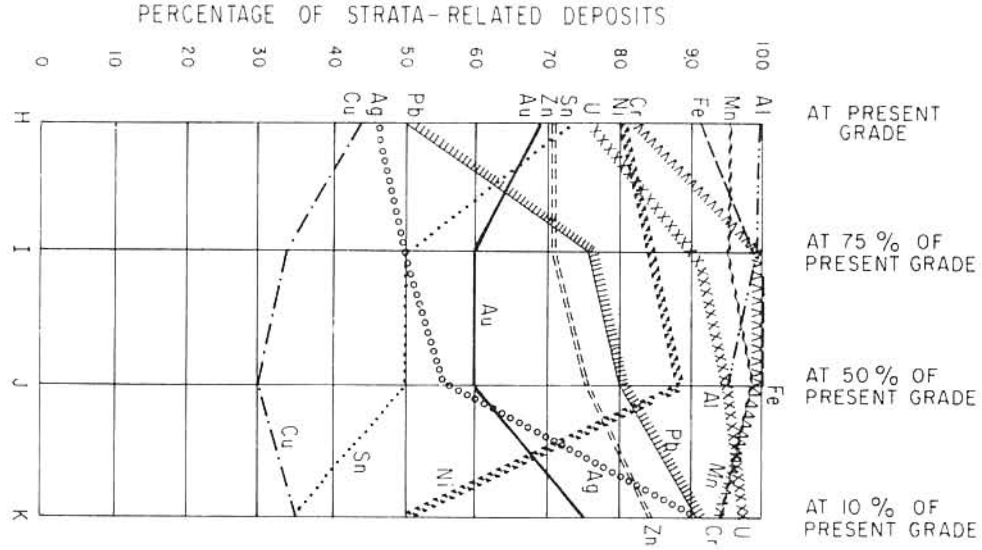

Fig. 10. Estimated future proportion of metals derived from strata-related deposits.

Two fundamental variables for economic geological evaluation of metallic ore deposits are 1) ore grade, and 2) size (tonnage). The average grade of world ores can be employed as a convenient numerical indicator to be used in the evaluation of the future importance of strata-related metallic deposits. From experience it is known that the average grade of *all* metal ores decreases with time, as the richer ores are being exhausted and leaner ores are taking their place. It is obvious that this trend will continue into the future, but there exists not a single reliable method how to predict the grade value for a particular future year*. Consequently, the prediction of the future proportion of strata versus non-strata metallic ores can be made only in relative terms — in terms of the present average grade in ores decreasing to 75 %, 50 % and 10 % of its value in the future (Table 2, Fig. 10).

Grade decrease to 75 % and 50 % of the present average grade will result in few dramatic changes. The proportion of strata-related deposits of lead and uranium will increase sharply, due to exhaustion of higher grade vein and replacement deposits and their substitution by modern "bulk" mineralization types which in the case of both Pb and U tend to be strata-related (the potential of Rössing-like U-bearing migmatites remains uncertain). Strata-related chromium and iron will also increase, the former due to the virtual domination of world's chromium resources by the stratiform-magmatic ores of the Bushveld complex and the Great Dyke of Zimbabwe, regardless

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*The historical decrease in ore grades can be assembled and graphically plotted from literature data (e.g. in case of copper ores it dropped from about 2.2 % Cu in 1900 to about 1.05 % in 1975). The resulting plot shows that the decrease is not linear and shows, among others, the influence of wars and economic crises. There is also no parallelism in the grade decrease among various metals. Extrapolation of grade decrease curves has not been considered a credible means for prediction.

TABLE 2

ESTIMATED FUTURE PROPORTION OF METALS, DERIVED FROM STRATA-RELATED DEPOSITS

metal	average grade, 1970's	grade reduced to 75%	estimated % of strata-deposits	grade reduced to 50%	estimated % of strata-deposits	grade reduced to 10%	estimated % of strata-deposits
Fe	40%	30%	99%	20%	100%	4%	below clarke
Al	20%	15%	100%	10%	95%	2%	below clarke
Mn	19%	14.7%	95%	9.5%	98%	1.9%	95%
Cu	1.05%	0.74%	34%	0.52%	30%	0.105%	35%
Zn	4.5%	3.4%	70%	2.25%	70%	0.45%	85%
Pb	3.9%	2.9%	76%	1.95%	80%	0.39%	90%
Cr	30%	22.5%	100%	15%	100%	3%	95%
Ti	5%	3.75%	95%	2.5%	85%	0.5%	below clarke
Sn	0.45%	0.34%	50%	0.22%	50%	0.045%	35%
W	0.45%	0.34%	28%	0.22%	50%	0.045%	65%
Mo	0.15%	0.11%	0.1%	0.075%	0.1%	0.015%	20%
Ni	1.1%	0.77%	85%	0.55%	88%	0.11%	50%
U	0.13%	0.1%	90%	0.065%	95%	0.013%	97%
Ag	250 ppm	170 ppm	50%	125 ppm	55%	25 ppm	90%
Au	6 ppm	4.5 ppm	60%	3 ppm	60%	0.6 ppm	75%

of grade considerations. Stratiform iron will increase due to the dominance of 20% ± Fe ores by the non-enriched bedded ferruginous rocks : both Precambrian siliceous iron formations (such as the taconites of the Lake Superior region or the itabirites of Brazil), as well as by the bedded Phanerozoic ironstones, close to the Minette-type of Lorraine and Luxembourg. The latter ores have already been mined in several European countries in times of wars and national emergencies, and are partly exhausted. Huge reserves of undisturbed ironstones, however, remain available in large and/or undeveloped areas in countries such as U.S.S.R., Canada, Brazil and Zaire.

The proportion of strata-related deposits of copper, gold, tin and aluminium, is predicted to decrease. With the diminishing copper cutoff grade, the reserves of many known porphyry copper deposits outlined by assay boundaries will become considerably enlarged. This, however, would add much less to existing strata-related copper ores, where, as in the Zambian Copperbelt, the mineralized beds and lenses tend to be higher-grade than most porphyry coppers, with relatively sharp boundaries against their unmineralized host rocks. Discovery of new, low-grade stratabound copper deposits such as Aitik, Sweden may, however, reverse this conclusion.

The proportion of crosscutting tin deposits in granite and porphyries will no doubt increase in the future not so much because of the grade decrease, but because of exhaustion of the surficial alluvial and eluvial deposits. The likelihood of discovery of stratabound bedrock tin deposits such as palaeoplacers and cassiterite-bearing gneisses (particularly Ca-Mg silicate gneisses) may slow down or stop the above rate of increase.

The decrease in proportion of strata-related gold deposits should inevitably follow the exhaustion of the Witwatersrand Basin, and also the still remaining virgin as well as worked-over surficial placers, and their substitution by mostly by-product gold derived from sulphide deposits of base metals (such as porphyry copper) as well as the gold from new types bearing "invisible gold" replacing sediments as in Carlin, Nevada.

Following the depletion of bauxite deposits as well as due to the growing cost of transportation and political problems among producers and processors, the recovery of aluminium from alternate sources (such as clays, shales, alunite, dawsonite, nepheline phonolite, syenites) increases. While aluminous sediments and supracrustal volcanics will not alter the dominance of aluminium by strata-related deposits, the intrusive syenites will.

The decrease of grade to 10% of the present average will have a more profound effect than the previous decreases. The ore grades of iron, aluminium and titanium metals whose ores have the lowest clarke of concentration, will approach (or fall below) the mean crustal contents of the respective metals in other words, half of all ordinary rocks will also become Fe, Al and Ti ores. At this point, contrasting the proportion of strata—to non-strata-related ores becomes meaningless.

The proportion of strata-related deposits of zinc, lead, silver and uranium is believed to further increased in ores with 10% of the present grade. Values of 0.45% Zn have frequently been determined in dolomites, particularly in regions that also locally contain presently economic "Mississippi Valley type" zinc deposits. Many black shales and argillites such as the Permian "Kupferschiefer" of Europe or certain Devonian-Mississippian black argillites of the eastern Yukon locally reach similar zinc, as well as increased lead contents.

The required 0.013% uranium grade will make ores out of several extensive, presently known sedimentary units such as the Devonian-Mississippian Chattanooga shale, or numerous coal and lignite seams. The slight increase in the proportion of strata-related copper ores shown in Fig. 10 is based on the consideration that, at 0.1% grade, not only will several shale schist units located in defined copper provinces achieve the ore status, but also certain horizons of supracrustal mafic volcanics— for example certain Mesozoic pyroxene andesites and basalts located in the copper mettallogenic province of Chile.

The increase in the proportion of strata-related gold deposits is based on the assumption that several trace-gold-enriched portions of stratigraphic horizons that presently contain scattered economic, but crosscutting (vein) gold mineralization, will themselves become economic ore (for example exhalites like chert, ankeritites, iron formations; altered ultramafic flows).

The proportions of strata-related deposits of nickel, tin and chromium, the principal common metals, are believed to decrease with the ten-times reduction of the present average ore grade. At 0.11% Ni, all ultramafic and some mafic magmatic rocks will achieve the ore grade. Although the majority of the above rocks have a non-stratabound character, the unity between strata- non-strata-related Ni deposits in Fig. 10 reflects the addition of all weathering profiles overlying the ultramafic bedrocks which are conformable to the surface. The above considerations are also applicable to chromium. With the required grade of 3% Cr, the importance of layered chromitite diminishes and many peridotites with scattered accessory chromite will become Cr ores.

CONCLUSION

Despite the numerous uncertainities discussed, the present study demonstrates that there is much truth in the belief that strata-related deposits are the principal potential metal sources of the future. Out of the main industrial metals (Fig. 10), it is predicted that only more tin and copper may ultimately be derived from non-strata-related materials. The myth that strata-related deposits are a recently established class is incorrect; only the more controversial, recently reinterpreted examples such as massive sulphides, may be to a certain extent.

ACKNOWLEDGEMENTS

This study has benefitted from financial and logistic support extended to me by three universities during my sabbatical leave. A grant from the University of Manitoba, Winnipeg, has supported a portion of the travel costs. The University of Malaya, Kuala Lumpur, has provided hospitality during my short stay in September 1980, and arranged for a shortened version of this paper to be delivered as a lecture to the Geological Society of Malaysia. Special note of thanks is due to Professor Peter Stauffer and Dr. Teh Guan Hoe. The University of New England, Armidale, Australia, has provided me with office facilities to complete the paper. The assistance is gratefully acknowledged.

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Manuscript received 11 November 1980