



This document was produced
by scanning the original publication.

Ce document est le produit d'une
numérisation par balayage
de la publication originale.

PAPER 75-15

**MINERALIZATION PROCESSES IN
ARCHEAN GREENSTONE AND
SEDIMENTARY BELTS**

R.W. BOYLE



**GEOLOGICAL SURVEY
PAPER 75-15**

**MINERALIZATION PROCESSES IN
ARCHEAN GREENSTONE AND
SEDIMENTARY BELTS**

R.W. BOYLE

1976

©Minister of Supply and Services Canada 1976

Available in Canada through

authorized bookstore agents
and other bookstores

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Hull, Québec, Canada K1A 0S9

and from

Geological Survey of Canada
601 Booth Street
Ottawa, Canada K1A 0E8

A deposit copy of this publication is also available
for reference in public libraries across Canada

Cat. No. M44-75-15 Canada: \$2.50
ISBN 0-660-11390-2 Other countries: \$3.00

Price subject to change without notice

Reprinted, 1983

CONTENTS

	Page
Abstract/Résumé	v
Introduction	1
The nature of Archean greenstone and sedimentary belts	1
The origin of mineralization in Archean greenstone and sedimentary belts ...	14
Iron formations	14
Manganese formations	19
Gold deposits	19
Arsenic and antimony deposits	23
Tungsten deposits	24
Massive and disseminated sulphide deposits	25
Massive and disseminated iron-copper-zinc sulphide deposits	25
Massive and disseminated nickel-copper-cobalt sulphide deposits	29
Disseminated and stockwork copper-molybdenum deposits	31
Chromite deposits	33
Asbestos deposits	33
Other industrial minerals	34
Pegmatites	35
Summary and conclusions	36
Acknowledgments	38
References in the text	38
Selected general references	43

Tables

Table 1. Archean volcanic, sedimentary, tectonic, granitization, magmatic, and mineralization events	6
2. Gold and silver contents of some Canadian Archean iron formations ...	10
3. Chemical analyses of some Canadian Archean sulphide tuffs, slates, schists, etc.	11
4. Range or average trace and minor element content of some Canadian Archean sulphide tuffs, slates, schists, etc.	12
5. Major, minor, and trace element contents of porphyry bodies with an intrusive aspect, Yellowknife, Northwest Territories	13
6. Gain or loss of volatiles and metals during granitization of a cubic mile and cubic kilometer of Archean greenstone belts, sedimentary belts, and ultrabasic rocks	20
7. Gain or loss of some constituents during extensive carbonatization of a cubic mile and cubic kilometer of Archean greenstone belts and ultrabasic rocks	22
8. Average lithium and boron contents of rocks of the Yellowknife area, Northwest Territories	36

Illustrations

Figure 1. World distribution of primary gold deposits and occurrences of Precambrian age	2
2. Archean volcanic, sedimentary, tectonic, granitization, magmatic, and mineralization events	4
3. Elemental enrichments during the various phases of Archean mineralization	37

MINERALIZATION PROCESSES IN ARCHEAN GREENSTONE AND SEDIMENTARY BELTS

Abstract

The principal types of mineral deposits in Archean greenstone belts and their associated sedimentary terranes are briefly described and their probable origins outlined. They comprise iron formations, manganese formations, gold-quartz deposits, arsenic and antimony deposits, tungsten deposits, massive and disseminated Fe-Cu-Zn and Ni-Cu-Co sulphide bodies, disseminated Cu-Mo sulphide deposits, chromite deposits, chrysotile asbestos bodies, and pegmatites.

The Archean iron formations are sedimentary rocks, whose volatile components (CO_2 , S) originated from extensive degassing of volcanic flows in a submarine environment and whose principal constituents such as silica and iron were derived from the submarine leaching of ignimbrites and tuffs aided mainly by the solubilizing action of CO_2 , H_2SO_4 , and HCl. The manganese in certain Archean manganese deposits may have had a similar origin in some belts, although many of the economic deposits in India appear to be chemical sediments derived by normal weathering processes. The gold-quartz deposits, arsenic and antimony deposits, tungsten deposits, massive and disseminated sulphide bodies, and pegmatites were derived by various mechanisms involving metamorphic secretion processes.

Résumé

L'auteur décrit brièvement les principaux types de gisements métalliques que l'on retrouve dans les zones de roches vertes de l'Archéen et dans les terrains sédimentaires connexes, et émet quelques hypothèses sur leur origine. Ces zones sont constituées de formations ferrifères et manganifères, de gisements de quartz aurifère, d'arsenic et d'antimoine, de tungstène, de gisements de sulfures de Fe-Cu-Zn et Ni-Cu-Co massifs et disséminés, de gisements de sulfures de Cu-Mo disséminés, de dépôts de chromite, de gisements d'amiante à chrysotile, et de pegmatites.

Les formations ferrifères de l'Archéen sont des roches sédimentaires, dont les éléments volatiles (CO_2 , S) proviennent de la dégazéification intensive des coulées volcaniques dans un milieu marin, et dont les principaux constituants comme la silice et le fer proviennent du filtrage sous-marin des ignimbrites et des tufs aidés principalement par l'action solubilisante du CO_2 , du H_2SO_4 et du HCl. Il est possible que dans certains dépôts de manganèse de l'Archéen, le manganèse ait eu une origine semblable pour ce qui est de certaines zones, quoique plusieurs des dépôts rentables en Inde paraissent être des sédiments d'origine chimique résultant de l'action météorique. Quant aux dépôts de quartz aurifère, d'arsenic et d'antimoine, de tungstène, aux gisements de sulfures massifs et disséminés, et aux pegmatites, il proviennent de divers mécanismes mettant en jeu la sécrétion métamorphique.

INTRODUCTION

The Archean (older than 2480 m. y.), one of the longest and greatest periods of mineralization in the earth's history, accounts for numerous large and rich deposits of iron, manganese, gold, copper, molybdenum, zinc, nickel, and asbestos. Various rare metals, mainly in pegmatites, and including lithium, cesium, rubidium, beryllium, niobium, tantalum, tungsten, antimony, and bismuth are also related to this period. Most Archean deposits are closely associated with greenstone belts, their related sedimentary piles, and their derivative granitic bodies — in essence the basement rocks of the Precambrian Shields of Canada, Australia, India, Africa, Arabia, U. S. S. R. and Brazil-Guiana.

This paper is an extension of that published in the Golden Jubilee Volume of the Geological, Mining, and Metallurgical Society of India. It is a current synthesis of the writer's thoughts on the origin of mineralization in the Archean greenstone and sedimentary belts of the world, based on his work in many of these belts in the Canadian Shield and on an extensive literature review concerned with the geochemistry of gold, platinoids, and their deposits in these belts throughout the world. The paper is admittedly philosophical; only references to the factual data are given in the text. The deposits discussed include those of iron, manganese, gold, arsenic, antimony, tungsten, disseminated copper-molybdenum deposits, massive and disseminated zinc-copper sulphides, massive and disseminated nickel-copper-cobalt sulphides often containing the platinoid elements, chromite deposits, and asbestos bodies. Pegmatites are mentioned only briefly.

THE NATURE OF ARCHEAN
GREENSTONE AND SEDIMENTARY BELTS

Most Archean greenstone and sedimentary belts differ in detail from place to place and often to a marked degree, but in general the geology and geochemistry of the volcanism, sedimentation, granitization, and magmatic activity of most of the belts are essentially similar. The basement rocks on which the Archean greenstone belts were laid down have only rarely, if at all, been observed. In some areas the basal rocks are apparently granitized sediments of the greywacke-slate assemblage, but these may be only part of the sequence within the observed belt; in other areas no basement rocks can be seen, the volcanics and their associated sediments being granitized or invaded by a variety of later granitic rocks. In actual fact we are here dealing with the nature of the original crust, a feature about which Hutton could "find no vestige of a beginning".

Morphologically, the Archean greenstone and sedimentary belts are elongated, often irregular lensoid,

keel-like bands of volcanics and sediments immersed in a sea of granitic and gneissic rocks as a glance at the geological maps of the Canadian and Indian Shields will show. In general the greenstone belts are composed of steeply dipping, extensively faulted and sheared marine volcanic rocks with characteristic interbedded sedimentary rocks overlain in most areas by an intricately folded and faulted greywacke-slate sequence, the whole having been granitized and intruded by granitic rocks. The details of the greenstone belts and their associated sedimentary piles are of importance in the mineralization history of the belts.

Most greenstone belts are composed of basaltic and andesitic flows, dacite, trachyte, and rhyolite flows, and their corresponding pyroclastics. Many of the basic and intermediate flows are pillowed indicating, together with the evidence of interflow sedimentation, that much, if not all of the volcanism took place in a marine environment. In most belts the lower members of the volcanic piles are basic, and there is a trend toward acidic (rhyolitic) volcanism, commonly of an ignimbritic or pyroclastic nature toward the tops of the assemblages. There are, however, numerous exceptions to this volcanic evolution; some belts exhibit no particular systematic trends, others may show more than one basic-acidic cycle. In some belts ultrabasic flows, often with distinctive platy (spinifex) structures and unusual dark clots, are present although it is not always easy to differentiate these from sills of similar composition. In the Onverwacht Group of the Swaziland Sequence in the Barberton Mountain Land of South Africa the lower three formations (Lower Ultramafic Unit) are characterized by an abundance of ultramafic and mafic volcanic rocks, many of which are ultramafic flows (komatiites).

The earliest "intrusive rocks" in most greenstone belts are gabbro and diorite sills and irregular concordant and ramifying masses; in some belts, as noted above, ultrabasic sills may be present. These early intrusive rocks are generally cut by swarms of diorite and gabbro dykes of several ages, and these in turn are intruded in places by late gabbroic stocks or by irregular masses of ultrabasic rock. The early sills in most belts were injected prior to the main period of folding; the swarms of dykes and the late gabbroic masses postdate the early period of folding. All of the basic sills, irregular basic and ultrabasic sills, irregular basic and ultrabasic bodies, most of the dyke swarms, and late gabbroic and ultrabasic stocks predate the main periods of shearing and faulting. The penultimate types of "intrusives" in the greenstone belts are quartz-feldspar porphyry dykes, stocks, and irregular masses, and lamprophyres. Most of these predate the main periods of shearing and faulting, but some may be later. The detailed age relationships of the porphyries and lamprophyres are generally difficult to determine accurately in most greenstone belts because there are often several generations of both types of rocks. The last "intrusives" are granitic

Original manuscript submitted: August 15, 1975

Final version approved for publication: November 18, 1975

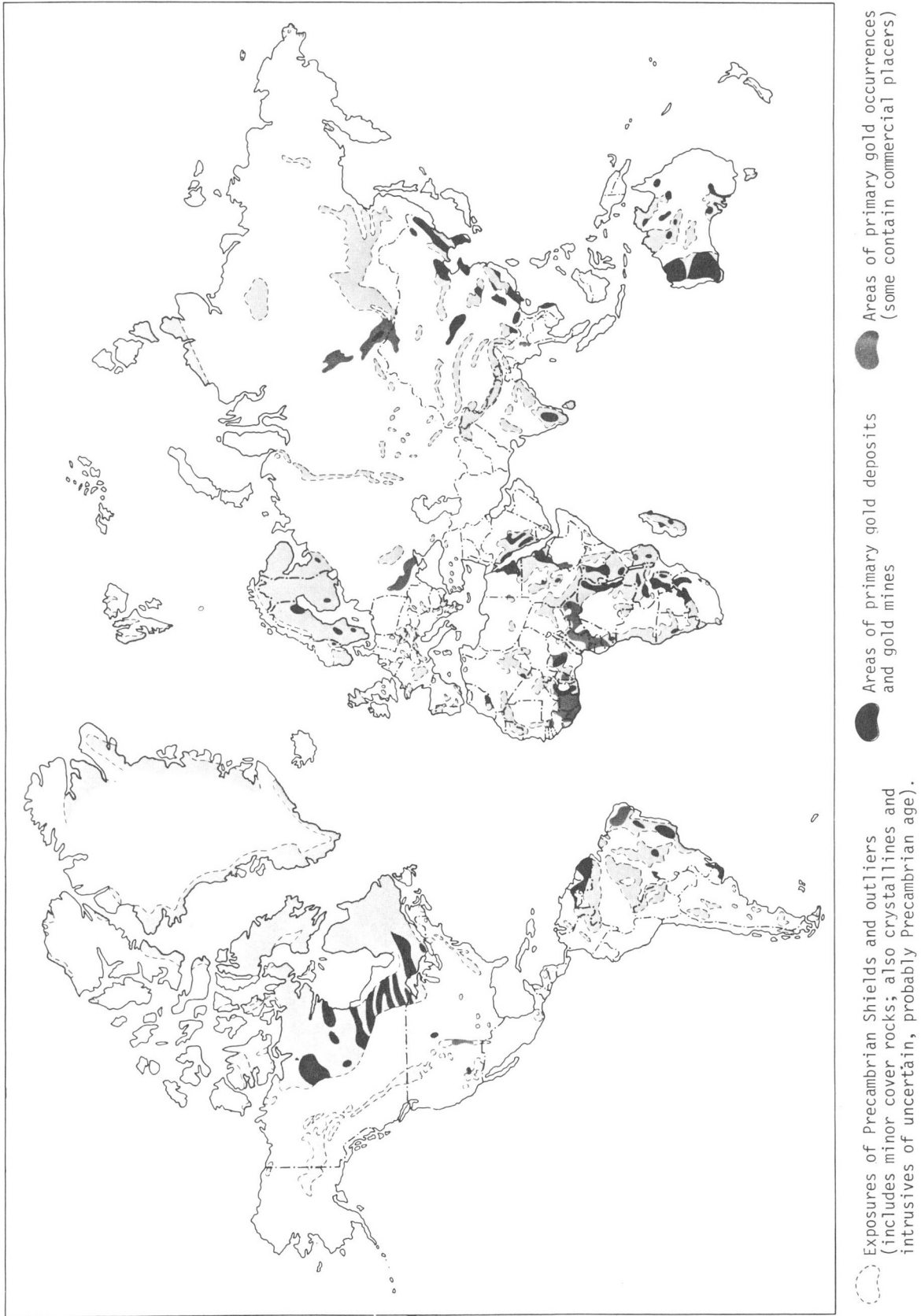


Figure 1. World distribution of primary gold deposits and occurrences of Precambrian age. (With a few exceptions, e. g. Witwatersrand and certain deposits in Europe and Asia, the auriferous areas mark Archean greenstone and sedimentary belts.)

dykes, stocks, and batholithic masses which intrude or invade most greenstone belts along much of their extent. In places some of these granitic bodies are cut by mineralized shear zones. Locally, a few lamprophyres and basic dykes may cut the granitic rocks, shear zones, and their contained orebodies. Some of these basic dykes (diabase) belong to extensive regional dyke swarms and are of (post-Archean) Proterozoic age.

The distribution of the exposed Precambrian rocks of the world and their auriferous belts (essentially the Archean greenstone belts and their associated sedimentary belts) is shown in Figure 1. The various volcanic, sedimentary, tectonic, and similar events which took place during Archean time are detailed in Figure 2 and described briefly in Table 1. It will be noted from Figure 2 that many of the events overlap or are repetitive and this should be kept in mind in the discussion that follows.

The origin of the early basic and ultrabasic "intrusive bodies" in greenstone belts has not been satisfactorily solved. Some are certainly sills related to early volcanic phenomena; other concordant bodies and masses that ramify through the flows have unusual outlines and contact relationships and seem to have originated by some process of dioritization (Henderson and Brown, 1966). The origin of the great swarms of diorite and gabbro dykes in most greenstone belts is even more obscure. In this writer's experience they are not the feeders of the flows in the greenstone belts since they cannot be traced into individual flows on the present plane of observation. They appear to have been magmatic in origin and may represent the basic components (basic front) expelled during granitization processes involving the greenstones and associated sediments (Boyle, 1961, p. 75).

In some districts the volcanic piles were gently folded and then overlain by a rhythmically interbedded greywacke-slate sequence of sediments as witnessed by angular unconformities which separate the two sequences of rocks; in other districts the two sequences are conformable. The greywacke-slate sequence consists generally of a preponderance of greywacke with subsidiary slate, conglomerate, and quartzite. Interbedded volcanic rocks are found in some sequences, but they are relatively rare in most belts. Thin beds and lenses of carbonate rocks occur in some sequences (Armstrong, 1960), but extensive beds of carbonates are not characteristic of Archean sedimentation. The origin of the greywacke-slate sequence is an enigma, particularly the large amount of quartz and alkalic feldspar they contain. Their mineralogical and chemical compositions suggest a sialic provenance which would seem to rule out the predominantly basic volcanic piles. The writer has long considered that the source of these sediments was the original granodioritic crust, but this is only a guess. One cannot observe the rocks of the original crust and make comparisons with the derived

sediments¹. Even the mode of deposition of the greywacke-slate sequence is uncertain. Some investigators consider them to be turbidites, but there are many features which suggest that they are related in some manner to glacial processes as MacLean (1956) maintained.

All volcanic piles and their associated greywacke-slate sediments are extensively folded, faulted, and sheared and have been granitized and injected by granitic rocks over large areas. The volcanics have been altered by regional metamorphism, the metamorphic facies being distinctly related to the granitic rock-greenstone contacts. They generally comprise a contact amphibolite facies, an intermediate epidote amphibolite facies, and a greenschist facies, the last developed regionally only in some belts but locally in most belts along great shear zone systems. Commonly three distinct metamorphic facies are present in the greywacke-slate sequences, and these are related to the granitic rock-sediment contact. These facies comprise a high grade nodular quartz-mica schist and hornfels zone next to the granitic rocks in which kyanite, staurolite, andalusite, cordierite, and garnet are present; an intermediate nodular zone in which the above minerals are nascent or poorly developed; and an outer greywacke-slate-quartzite zone in which the rocks are relatively unmetamorphosed.

Evidence of early life is present in many of the Archean sedimentary sequences. Interflow sediments in many greenstone belts contain disseminated carbon particles which may signal the former presence of the very earliest forms of life. Some of these carbon particles have an ovoid form and may represent colloidal forms of archeoprotoplasm (coacervates) which ultimately evolved into more organized unicellular organisms. The latter appear in certain Archean cherts and other sediments (Onverwacht Group, South Africa) said to be older than 3.1×10^9 years (Muir and Hall, 1974). Colonies of blue green algae or rather their relict

¹The basal conglomerates of the greywacke-slate sequence, lying on the greenstone belts commonly contain granitic pebbles and cobbles, the origin of which has long been a mystery. Some investigators have considered that these pebbles and cobbles were derived from an early Archean (Laurentian) granite intrusive into the greenstones, whereas others have denied that these pebbles are in reality "granites" but rather felsic porphyritic volcanic rocks penecontemporaneous with the greenstones. No particular conclusive radioactive age differences between the (Laurentian) "granitic" pebbles and the Algoman granite have been noted, and so the controversy as regards the origin of the pebbles rages on. My observations and geochemical research on these "granitic" pebbles, which is not yet complete, suggests that there was some kind of an extensive "granitic" rock in the early Archean terrane from which the pebbles and cobbles in the so-called "Timiskaming" conglomerates were derived. I suspect that this "granitic" rock was the original crust or remobilized original crust.

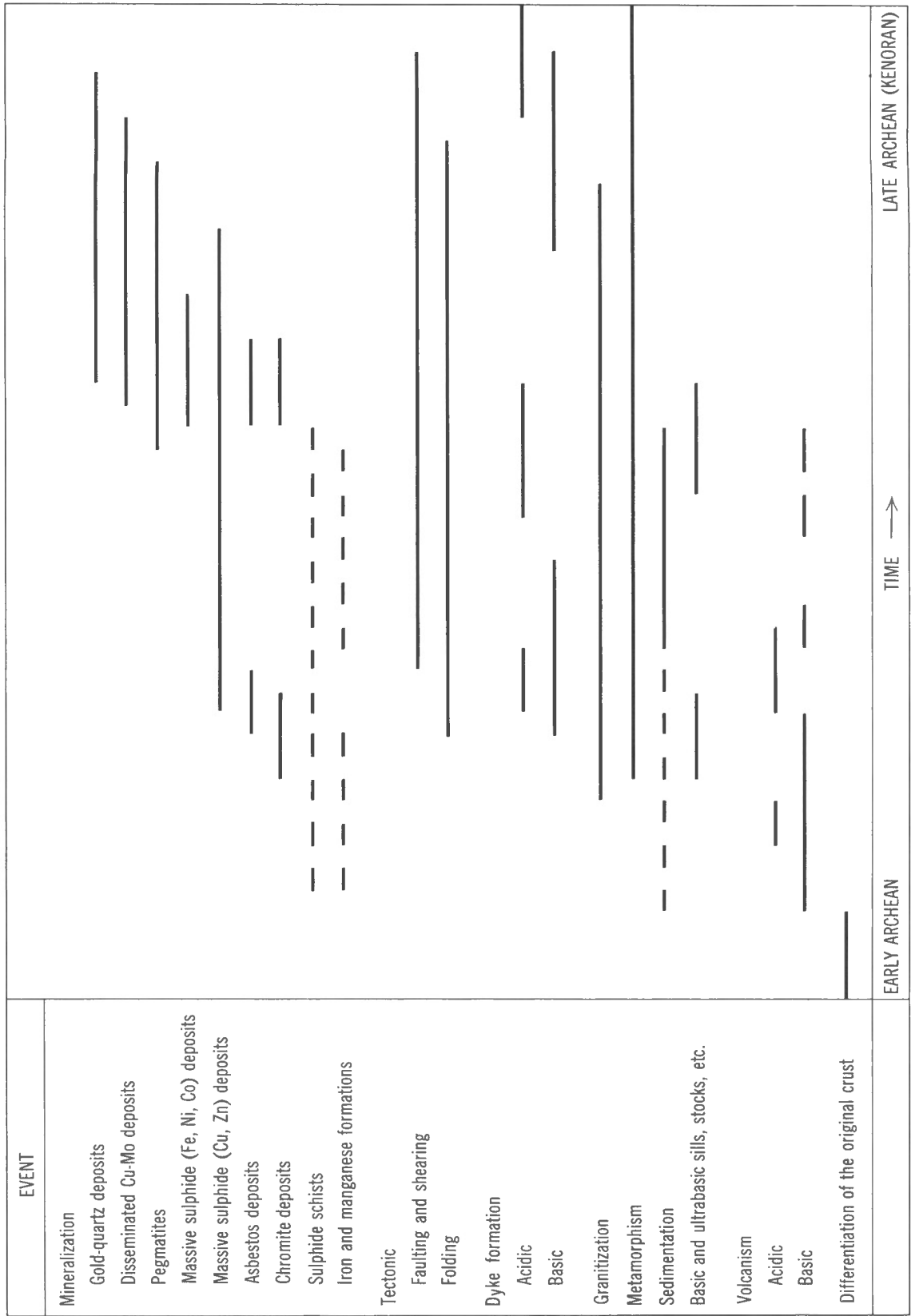


Figure 2. Archean volcanic, sedimentary, tectonic, granitization, magmatic, and mineralization events.

stromatolitic structures appear as fossils in Archean rocks in the Steep Rock Series in the Atikokan region of Northwestern Ontario and in Rhodesia and have recently been reported from Archean rocks in the Snofield Lake area, Northwest Territories, Canada (Henderson, 1975a, 1975b).

This brief generalized description of Archean greenstone and sedimentary belts indicates that most are very complex bodies of rocks that have had a long and intricate geological and chemical history (Table 1; Fig. 2), features that are not adequately emphasized in most papers on their geology and geochemistry. In fact the details of the geology and chemistry of most of these belts are very poorly known despite decades of study and provide a challenge for the future.

There are five types of rocks in Archean greenstone and sedimentary belts that deserve special mention and brief description since they appear to play important roles in the mineralization of these belts. They include banded iron formation, sulphide schists, various quartz-feldspar porphyries which have an intrusive aspect, various ultrabasic-basic intrusive bodies, and extensive carbonated zones.

The Archean banded iron formations are the most characteristic sediments in the greenstone and sedimentary belts. They are well known to Precambrian geologists and have been extensively studied for decades. Detailed descriptions are given by Gross (1965). More recent descriptions are by Goodwin (1973) and others in the series of papers edited by James and Sims (1973) and in the Proceedings of the Kiev Symposium on Precambrian iron and manganese deposits (UNESCO, 1973).

Gross refers to these iron formations as Algoma-type from their common occurrence in the District of Algoma, Ontario. They do not occur in all greenstone and sedimentary belts; for example the belts in the Superior Province of the Canadian Shield contain abundant iron formations whereas the Slave Province has only isolated occurrences. Algoma-type banded iron formations are also not solely restricted to Archean rocks as some would have us believe. Identical types of iron formation in nearly identical volcanic formations and in remarkably similar geological environments occur in Ordovician rocks in New Brunswick and elsewhere (Boyle and Davies, 1973).

Four facies can be recognized in Archean iron formations — a chert-oxide facies, a carbonate facies, a silicate facies, and a sulphidic black slate facies. Briefly, the chert-oxide facies consists essentially of alternating, often highly contorted bands of white to reddish or black chert and magnetite and/or hematite. The carbonate facies generally comprises thin- to thick-bedded deposits of banded siderite, and the silicate facies, generally rare in most greenstone and sedimentary belts, now consists of banded chloritic or amphibolitic rocks often with magnetite and/or hematite. The sulphide facies is represented mainly by disseminated pyrite, and commonly other sulphide minerals such as pyrrhotite, chalcopyrite, arsenopyrite, galena, and sphalerite, in black carbonaceous phyllites and slates. In places lenses and irregular bands of nearly massive

pyrite and pyrrhotite may occur in the sulphide facies. Not all Archean iron formations exhibit the four facies: the chert-oxide facies is the most abundant followed by the carbonate. The silicate facies is relatively uncommon as is the sulphide facies in some greenstone and sedimentary belts. What are called rocks of the sulphide facies in some greenstone belts are in reality interflow sulphidic phyllites, slates, and schists that seem to bear no particular relationship to iron formations. These are described next below. Before passing to the sulphide schists, however, it is of interest to note that considerable enrichments of gold (and silver) are commonly encountered both in the sulphide and oxide facies of Archean iron formations in many parts of Canada. Representative values are given in Table 2. It should be noted that some of the values exceed by one or two orders of magnitude the gold content characteristically found in most rocks (0.004 ppm Au). This enrichment is probably due to the adsorption and coprecipitation of gold by iron oxides and sulphides (pyrite) from the ancient Archean oceans.

Archean sulphide phyllites, slates, and schists have been studied by the writer for many years (Boyle, 1968). They occur in all greenstone belts and associated greywacke-slate sequences of the Canadian Shield and are referred to constantly in the descriptions of other greenstone belts throughout the world. Briefly their occurrence, petrography, and chemistry can be summarized in a few paragraphs.

Many of the sulphide schists¹ are interbedded with the greenstone flows in the volcanic belts of Precambrian Shields and appear to represent periods during which reducing, sapropelic sedimentation conditions prevailed. Many are extensive and extend up to 10 miles or more along strike. Others are more restricted and appear to have formed in local reducing basins. In thickness they range from a few inches to several hundred feet. Some of the sulphide schists have associated thin beds of limestone (Armstrong, 1960). At Yellowknife (Boyle, 1961) they are tuffaceous in part and have been called tuffs. In other greenstone belts the tuff component may be minor, and they are more properly called sulphide schists or slates. Some are associated with highly siliceous sediments or iron formations and are commonly found along strike from the oxide and carbonate facies of the latter; these have been referred to as the sulphide facies of iron formations as noted above.

The sulphide schists in the sedimentary sequences associated with greenstone belts form a part of the greywacke-slate assemblage. They also appear to represent periods when reducing, sapropelic conditions prevailed. They are invariably interbedded with greywackes, quartzites, argillites, and slates.

The mineralogy of the sulphide schists and gneisses is relatively uniform, exhibiting few differences from

¹To avoid repetition the term "sulphide schists" will be used. The term includes all sulphide-bearing shales, phyllites, slates, and schists; also sulphide gneisses in zones of high grade metamorphism.

Table 1

Archean volcanic, sedimentary, tectonic, granitization, magmatic, and mineralization events

Geological events in chronological order, youngest first					
Volcanic events	Sedimentary events	Tectonic events in chronological order, youngest first	Mineralization events	Geochemical features	Remarks
	Diabase dykes and sills.	Late faulting.			Probably most dykes and sills are of Proterozoic age.
Post-gold-quartz vein basic (lamprophyre) and granitic dykes. Post-vein pegmatites occur in some belts.		Late faulting.	Minor carbonate veins.		Post-gold-quartz dykes are rare in most belts, but are common in some. Post-vein pegmatites generally occur in sedimentary belts.
Waning stage of granitization and metamorphism. Some late quartz-feldspar porphyry and lamprophyre dykes.		Waning stage of transcurrent shearing and faulting with formation of dilatant zones. Extensive shearing and faulting of ultrabasic bodies in some belts.	Main gold-quartz stage. Main stage of auriferous arsenic and antimony deposits. Formation of some asbestos deposits. Formation of some chromite deposits. Formation of some Fe-Ni-Co sulphide deposits. Formation of disseminated Cu-Mo deposits.	Carbonatization of greenstone belts. Concentration of SiO ₂ , Au, Ag, Te, As, Sb, etc. in gold-quartz and arsenic-antimony deposits. Concentration of Fe and Cr in some ultrabasic bodies. Concentration of Fe, Ni, Co, S in certain basic and ultrabasic bodies. Concentration of Cu, Mo, etc. in disseminated bodies.	Main gold-quartz stage; main stage of deposition of arsenic and antimony. Main stage of formation of asbestos deposits in most belts; probably main stage of formation of massive and disseminated Fe-Ni-Co sulphide deposits in most belts. Main stage of formation of disseminated Cu-Mo deposits.
Continued granitization. Development of pegmatites mainly in sedimentary terranes;		Waning stage of folding and attendant shearing along flow contacts, etc.	Main pegmatite stage; formation of some gold-quartz deposits; formation of some massive	Concentration of SiO ₂ , Na, K, B, Be, Li, Nb, Ta, etc.	Main pegmatite stage.

Table 1 (concl'd)

Geological events in chronological order, youngest first			
Volcanic events	Sedimentary events	Magmatic and granitization events	Tectonic events in chronological order, youngest first
	deposition of Algom-type iron formation in many belts; deposition of manganese for- mations in some belts.		mainly in sulphidic sediments. Possible minor magmatic seg- regation of Fe, Ni, Co, sulphides in thick ultrabasic flows.
			S, As, Sb, Cu, Pb, Zn, Ni, Co, Au, Ag, and other chalcophile elements in sulphidic sediments. Enrichment of Fe, Ni, and Co in sul- phide segre- gations in thick ultra- basic flows.
Minor submarine volcanism with out-pouring of thin basic flows.	Deposition of greywacke and shaly rocks.	Initiation of volcanic period.	Weathering of primordial crust attended by mainly clastic sedi- mentation with minor hydro- lysates. Minor basic volcanism.
		Formation of pri- mordial ocean. Formation of pri- mordial crust of granodioritic (?) composition.	Not observable in most belts. Couching of Lawson probably represents this period. Origin of life manifest by low order forms (coacervates).
		Magmatic (?) differentiation to produce rocks rela- tively rich in Si, Al, Na, K, and minor Ca, Fe, Mg, etc. Composition of primordial ocean unknown.	Primordial crust not observable; geo- chemical features mainly speculative.

Table 2
Gold and silver contents of some Canadian Archean iron formations

Locality	Facies of Iron Formation	Au (range) ppm	Ag (range) ppm
Temagami, Ontario	Oxide	0.050	2.4
	Sulphide	0.020 - 0.060	0.7 - 2.0
Balmer Lake, Ontario	Oxide	<0.005	0.6
Kukatush, Sudbury District, Ontario	Oxide	<0.005 - <0.01	0.4 - 0.9
	Carbonate	<0.005 - <0.01	0.9 - 1.6
Geraldton, Ontario	Oxide	<0.005 - 0.085	0.8 - 1.1
	Carbonate	<0.005 - 1.030	0.8 - 2.0
	Sulphide	0.01 - 1.030	0.9 - 2.0
Schreiber, Ontario	Sulphide	0.040 - 0.070	2.2 - 4.7
Michipicoten, Ontario	Oxide	<0.005 - 0.025	1.1 - 1.8
	Carbonate	<0.005 - 0.025	1.0 - 2.1
	Sulphide	<0.005 - 0.005	1.0 - 1.8
Kirkland Lake, Ontario	Oxide	<0.01 - 0.031	0.1 - 0.5
Hearne Lake, Northwest Territories	Oxide	<0.005 - 0.235	0.5 - 1.9
	Sulphide	0.235	1.9
Kaminak Lake, Northwest Territories	Oxide	<0.005 - 0.760	0.3 - 1.5
	Carbonate	<0.005 - 0.150	0.8 - 2.4
	Sulphide	<0.005 - 0.760	0.4 - 13.0

Analyses: Bondar-Clegg and Co. Limited, Ottawa, Canada.

belt to belt. In polished and thin sections the mineral constituents in the lower grade metamorphic facies are quartz, carbonates, feldspars, sericite, chlorite, and sulphides. In the higher grade facies the stable minerals are quartz, feldspar, garnet, amphiboles, carbonates, cordierite, andalusite, and sulphides. Graphite¹ is present in many of the sulphide schists and gneisses, but it tends to diminish with increasing metamorphism. Some sulphide schists and gneisses have little if any graphite or carbonaceous substance.

The sulphides identified in most of the Canadian Archean sulphide schists and gneisses are pyrite, pyrrhotite, chalcopyrite, arsenopyrite, galena, and sphalerite in about that order of frequency. Not every sulphide schist contains all of these; some only have

pyrite and pyrrhotite and others only pyrite and arsenopyrite. From analyses there is a suggestion that tetrahedrite, stibnite, and other antimony-bearing minerals may occur in some of the more graphitic varieties.

The disseminated sulphides invariably lie in the bedding laminae or in the foliation of the rock in a manner suggesting that they either replaced minerals of the matrix or filled micro-dilatant features. Small lenses and stringers parallel to the foliation are common; lenses and stringers transgressing the foliation tend to be rare. Many of the sulphides, especially pyrite and arsenopyrite, have a metacrystic habit and obviously grew by accretion in the solid rock. Microfolds tend to have their crests and limbs filled with the sulphides.

The sulphides are generally sharply restricted to the confines of specific beds in the lower grade metamorphic facies. In the higher grade facies the sulphide boundaries tend to become blurred.

The sulphides generally exhibit a paragenetic sequence in all grades of metamorphism, similar to that found in veins. The sequence as shown by cross-cutting relationships is first pyrite, pyrrhotite, and arsenopyrite, followed by chalcopyrite, galena, and sphalerite.

¹The term graphite as used here is a field term. Actually most of the black material in these rocks does not yield a sharp X-ray pattern for graphite. Hence the black material which by analysis is shown to be solely composed of carbon, is best referred to as carbonaceous substance. In highly metamorphosed terranes much of the black material is true graphite as revealed by X-ray.

Table 3

Chemical analyses of some Canadian Archean sulphide tuffs, slates, schists, etc.

Constituent per cent	Archean graphitic tuff, greenstone belt, Yellowknife, N. W. T.	Archean pyritized cherty sediment, greenstone belt, Yellowknife, N. W. T.	Archean banded chloritic and graphitic tuff and chert, greenstone belt, Yellowknife, N. W. T.	Archean graphitic phyllite, slate, and schist, greenstone belt, Yellowknife, N. W. T.	Archean graphitic schist (interflow sediment in greenstones) Cobalt area, Ontario
SiO ₂	60.74	57.5	69.9	66.1	52.6
Al ₂ O ₃	15.83	17.1	13.2	13.9	10.3
Fe ₂ O ₃	0.50	2.4	1.2	2.5	17.0
FeO	1.80	5.5	4.8	3.1	
CaO	4.03	4.3	2.4	1.2	1.3
MgO	2.04	1.8	1.5	1.2	3.9
Na ₂ O	0.39	4.3	0.9	1.0	3.9
K ₂ O	3.95	1.0	2.4	3.4	1.1
H ₂ O (total)	1.56	2.0	2.1	2.2	2.7
TiO ₂	0.67	1.41	1.07	0.67	0.71
P ₂ O ₅	0.25	0.09	0.11	0.07	0.09
MnO	0.08	0.21	0.22	0.25	0.16
CO ₂	5.55	0.2	0.2	0.1	0.40
S	1.45	0.82	0.37	0.56	5.1
Cl	0.03	<0.02	<0.02	<0.02	n. d.
C	1.28	<0.1	0.1	4.8	4.87
Total	100.15	98.75	100.49	101.07	104.13
Less O ≡ S, F, Cl	0.54	0.31	0.15	0.22	1.9
Total	99.61	98.44	100.34	100.85	102.23

Analyses: Analytical Section, Geological Survey of Canada.

Analyses of some Canadian Archean sulphide tuffs, slates, schists, etc. are shown in Table 3. It is immediately evident that many of these rocks are considerably enriched in carbonate, potassium, phosphorus, sulphur, and carbon. These constituents are those generally associated with life processes in a sedimentary environment. It has long been considered that bacteria played a major role in the formation of these black sulphide schists. This would seem to apply to all of the rocks studied by this writer; support is found in the isotopic analyses of the sulphur in these rocks (Wanless *et al.*, 1960). The archeoprotoplasmic (coacervate) bodies and bacteria that gave rise to the concentrations of carbon and sulphur in the Archean sulphide schists probably represent the earliest form of life known on earth.

As shown in Table 4 most of the sulphide-bearing schists are greatly enriched in metals and metalloids.

Particularly interesting is the presence of relatively large amounts of gold and silver, lead, zinc, copper, molybdenum, arsenic, and antimony. The contents recorded are generally many times those commonly found in ordinary shales and other rocks.

The metals and metalloids are bound in various ways. Where metal- and metalloid-bearing sulphides are present in the rock the bulk of the metals and metalloids occur mainly in these minerals. Where only pyrite or arsenopyrite is present in the rocks the metals are associated with these sulphides as shown by analyses of concentrates of these two minerals. In many cases the metals and metalloids appear to substitute in the lattices of pyrite and arsenopyrite; in other cases the two sulphides probably contain submicroscopic specks and blebs of minerals such as galena, chalcopyrite, etc. In low-grade metamorphic terranes there appear to be considerable amounts of metal associated with

Table 4
Range or average trace and minor element content of some Canadian Archean sulphide tuffs, slates, schists, etc.

ND=not determined

Constituent ppm	Archean sulphide tuffs, slates, schists, etc., greenstone belt, Yellowknife, N. W. T.		Archean sulphide and graphitic schists and chert (interflow sediments in greenstones), Cobalt area, Ontario	
Cu	2	- 650	400	- >5,000
Ag	<0.4	- 2.0	2	- 50
Au	0.01	- 0.07	0.03	- 0.4
Zn	10	- 1,500	500	- >5,000
Cd	<0.4	- 7		ND
Hg	<0.002	- 0.4		up to 50
U	<0.1	- 4.8		<0.3
Sn	8	- 22		ND
Pb	<4	- 37	500	- >5,000
As	<6	- 250		80
Sb	<1	- 4		5
Bi		<0.5		0.83
Se	<1	- 2.5		ND
Te	<0.2	- 2		ND
Mo	<0.5	- 3		3
W	<2	- 2		<2
Co	4	- 129		80
Ni	11	- 187		130
S	5,000	- 15,000	5,000	- 30,000

Analyses: Geochemistry Section, Geological Survey of Canada.

the carbonaceous substance. As the grade of metamorphism increases the metals and metalloids are segregated into pyrite and other sulphides leaving a graphitic residue relatively devoid of metals.

To summarize the various data on Archean sulphide schists: It seems highly probable that the various metals and metalloids are of syngenetic origin and were precipitated as a result of reducing conditions in a sapropelic environment where abundant sulphur in one form or another was available in the Archean oceans. This conclusion seems justified on the basis of the great strike length of most of the beds and the fact that the sulphides are largely restricted to the graphitic beds. Diagenetic and metamorphic processes have affected the sulphide schists only to a small extent in most greenstone belts, the main effects being local migrations of some elements, a coarsening of grain of the sulphides, and a metacrystic development of pyrite and a few other minerals. The importance of the sulphide schists

as a source of the mineralization in Archean rocks is discussed in the next section.

Quartz-feldspar porphyries with an intrusive aspect are widespread in Archean greenstone belts. Petrographically most of these rocks resemble quartz-feldspar porphyry flows in that they contain quartz and feldspar phenocrysts in a matrix of quartz, feldspar, and mica minerals. Most of those with an intrusive aspect are now highly altered: the feldspar phenocrysts to a mass of sericite and carbonates and the groundmass generally to an aggregate of fine grained quartz, feldspar, sericite, chloritized biotite, and carbonates. Some porphyries are greatly enriched in pyrite and a few contain molybdenite (3R type), pyrrhotite, and chalcocopyrite, all of which appear to have been original constituents of the rocks in most places. Their chemistry is unusual in that they are enriched in elements such as copper, silver, and molybdenum. Some contain what, for acidic rocks, are relatively large amounts of

Table 5

Major, minor, and trace element contents
of porphyry bodies with an intrusive aspect,
Yellowknife, Northwest Territories

Major and minor constituents per cent	Composite sample of quartz-feldspar porphyry in greenstone belt
SiO ₂	73.09
Al ₂ O ₃	14.01
Fe ₂ O ₃	0.32
FeO	0.89
CaO	2.05
MgO	0.37
Na ₂ O	4.15
K ₂ O	1.63
H ₂ O ⁺	0.72
H ₂ O ⁻	0.05
TiO ₂	0.20
P ₂ O ₅	0.05
MnO	0.02
CO ₂	1.80
S	0.80
Cl	trace
Cr ₂ O ₃	0.04
Total	100.19
Less O ≡ S, Cl	0.34
Net total	99.85
Trace constituents, ppm	
Cu	20 - 150
Ag	0.6 - 2.0
Au	0.10
Zn	20 - 100
Sn	5
Pb	5 - 25
As	140
Sb	5 - 10
Mo	5 - 20
W	5
Co	5 - 10
Ni	30 - 50

Analyses: Analytical Section and
Geochemistry Section, Geological Survey of Canada.

chromium (Table 5). Most are enriched in sodium and have a low K₂O/Na₂O ratio (<1).

The origin of the quartz-feldspar porphyries with an intrusive aspect in greenstone belts has not yet been satisfactorily explained. Whitman (1927), Evans (1944), and Holmes (1944) considered those in the auriferous Porcupine (Timmins) district of Ontario to be of metamorphic origin, whereas Robinson (1923) and Moore (1954) considered them to be igneous intrusions. Reid (1944) leaned toward replacement processes for the origin of the porphyries. He concluded: "It would seem a reasonable assumption to consider that the whole range of igneous phenomena, from true igneous fusion at one end to hydrothermal activity at the other, when looked at in a broad way, can be regarded as a continuous process without necessarily any definite breaks along its course, and that given favourable circumstances or conditions, a concentrated solution or emanation from the lower part of the hydrothermal zone, heavily charged with rock making constituents, may produce the same results by replacement that is ordinarily ascribed to emplacement by igneous intrusion". Gustafson (1945) outlined the extremely complex nature of the porphyries in the Porcupine district and reserved judgment concerning their origin. Henderson and Brown (1966) gave an excellent account of the features of the porphyries in the Yellowknife greenstone belt and concluded that they were formed by replacement processes rather than by intrusion. The writer after examining many of these porphyries in greenstone belts in many parts of the Canadian Shield still concludes as he did originally (Boyle, 1961, p. 76) that the origin of the porphyry dykes and masses is an enigma requiring further research. On the one hand the porphyries present metasomatic features and may have formed by processes of metamorphic differentiation. This is borne out by the facts that some contain an abundance of sulphides and carbonates and are enriched in chromium, features foreign to granitic rocks. On the other hand they display sharp contacts, are dyke-like, and as regards their major components, have a similar composition to marginal phases of granitic rocks that invade the greenstone belts. This suggests that they may have originated either by magmatic or granitization processes. The latter appears to fit the facts best, and it would seem that the porphyries represent concentrations of various elements mobilized during granitization at depth.

These porphyries are of interest because they may have been one of the sources of the metals, metalloids, sulphur, etc. during mineralization of the various gold and base metal deposits in Archean rocks. In a few belts they contain disseminated copper-molybdenum deposits.

The ultrabasic-basic rocks of interest have a varied origin. In places in some belts the bodies are obviously sills injected between the volcanic flows or into the sedimentary strata; in other places the irregular to partly concordant and sometimes ramifying bodies are evidently intrusives, but some appear to have originated by some uncharacterized process of "ultrabasification" of basic lavas or to "ultrabasic-basic fronts" associated

with deep-seated granitization of the Archean greenstone and sedimentary belts. Finally, some of the ultrabasic-basic bodies are evidently flows, although this is often difficult to prove. Some of these flows have platy (spinifex) structures in their upper parts as have some of the discordant bodies. Many of the so-called ultrabasic flows on close study often turn out to be multiple intrusions.

Most of the Archean ultrabasic bodies are highly altered and are now essentially serpentinites; some have been extensively carbonated. In places some are injected by granitic dykes or cut out by granitic stocks and batholithic bodies of Kenoran age.

The various ultrabasic-basic bodies have a wide-spread distribution in the Archean belts of the world, particularly in the Canadian, Australian, Indian, and Brazil-Guiana shields. Typical examples in the Canadian Shield include the ultrabasic-basic stocks and plugs with which the nickel-copper-cobalt sulphide bodies at Lynn Lake, Manitoba are associated; the ultrabasic-basic Bird River sill in Eastern Manitoba with which are associated nickel-copper-cobalt occurrences and in which chromite bodies are present; the metaperidotite bodies with associated nickel-copper deposits at Gordon Lake, Ontario; the irregular serpentinite mass in the Obonga Lake area of Ontario that contains chromite occurrences; the ultrabasic-basic composite sill in Munro Township, Eastern Ontario in which asbestos bodies are developed and with which an ultrabasic-basic (komatiite) series of flows are associated; the ultrabasic-basic body near Goward, Eastern Ontario with closely associated copper-nickel-platinum-gold orebodies (Cuniptau mine); the Dumont serpentinite sill-like lens in northwestern Quebec which constitutes a low grade nickel deposit; the irregular metaperidotite masses in the Malartic district of Quebec which have an associated nickel deposit (Marbride mine); and the numerous conformable ultrabasic-basic masses of the Chibougamau ultramafic belt of Quebec that contain asbestos bodies. These examples include only a few of the ultrabasic-basic bodies that are definitely Archean in age. Another belt of these bodies lies in the zone marking the boundary between the Superior and Churchill geological provinces and contains a number of nickel orebodies (Thompson mine, Moak Lake mine, etc.). The age of these metaperidotite and other ultrabasic-basic bodies is uncertain. They are probably late Archean.

Details of the geology of the various ultrabasic-basic bodies mentioned above can be found in the publications by Ruttan (1955), Bateman (1943), Graham (1930), Hendry (1951), Satterly (1952), Pyke *et al.* (1973), Fleet and MacRae (1975), Sandefur (1942), Ekstrand (1975), Clark (1965), Duquette (1966), Wilson and Brisbin (1961), and Zurbrigg (1963).

The final feature of importance in Archean greenstone belts is the great linear and irregular zones of carbonatization that occur in most of the mineralized belts. The effects are pervasive; in places almost total carbonatization of sheared greenstones has taken place, and in some belts the ultrabasic rocks and sediments are greatly affected. The principal carbonate developed

is ankerite with subordinate amounts of dolomite and calcite. These carbonate zones follow lines of shearing and brecciation and are extensive, usually several tens of miles in length; in width they may exceed 1000 feet or more. In some belts the shears are so numerous that great irregular patches of carbonatization occur in the greenstones. The petrographic effects are notable, the feldspars, amphiboles, pyroxenes, olivine, epidote, and micaceous minerals being wholly or partly replaced by ankerite and other carbonates, leaving a pervasive mass of carbonates in which wisps and patches of one or more of chlorite, talc, serpentine, sericite (commonly fuchsite), and quartz are embedded. The chemical effects are, likewise, profound, the Ca, Fe, Mn, and Mg of the mafic silicates being bound by the carbonate radical into the carbonates with the release of large amounts of silica. Some of this silica may be precipitated locally in quartz stringers in the great carbonated zones, but more generally much of it migrates upwards or laterally into nearby dilatant zones (faults and fractures) where it is precipitated as quartz veins. The mechanism of the formation of quartz veins by carbonatization and hydration has been discussed in detail by the writer (Boyle, 1961), and it will be referred to again in the next section. Not only quartz veins are derived by carbonatization, but also much gold, arsenic, antimony, and other elements are released during the process and concentrated in nearby dilatant zones (Table 7). Where basic and ultrabasic bodies of rock are affected nickel and cobalt may be released and redistributed to form nickel-copper-cobalt sulphide bodies; similarly much silica and magnesia is set free when ultrabasic bodies are carbonated, and these components find their way into local dilatant fractures where they crystallize as chrysotile.

THE ORIGIN OF MINERALIZATION IN ARCHEAN GREENSTONE AND SEDIMENTARY BELTS

The types of deposits to be discussed include iron formations, manganese formations, gold-quartz deposits, antimony and arsenic deposits, tungsten deposits, massive iron-copper-zinc and nickel-copper-cobalt sulphide deposits, disseminated and stockwork copper-molybdenum deposits, chromite deposits, chrysotile asbestos bodies, and pegmatites, the last only briefly.

Iron Formations

The origin of the Archean cherty iron formations has exercised the minds of geologists for more than a century, and innumerable original theories and variations of these theories have been put forward. Gross (1965) has summarized these at length; they embrace concepts as divergent as chemical sedimentation, replacement of sediments of various kinds, hydrothermal activity, and derivation by igneous processes. More recent contributions may be found in the series of papers on Precambrian iron formations of the world edited by James and Sims (1973). Despite all this effort, proof of the mechanism of formation of Archean

iron formations remains elusive notwithstanding statements to the contrary. We can, however, say with some assurance that the iron formations (including all their facies) are of sedimentary origin, probably deposited in an eugeosynclinal environment, and that they exhibit a positive correlation in space and time with marine volcanic activity. Beyond this the details of the formation of Archean iron formations are by no means clear.

The problem of the origin of Archean cherty iron formations can be resolved into (1) the source of the iron and silica, (2) their mode of transport, and (3) their mode of precipitation in characteristic rhythmic layers or bands.

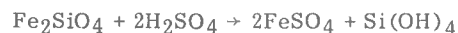
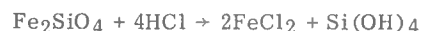
The Algoma-type iron formations are invariably enclosed within marine volcanic sequences, most occurrences, in this writer's experience, being closely associated with tuffs, ignimbrites¹, and other volcanoclastic rocks which frequently lie immediately below or on strike with the ferriferous formations. Even in the sedimentary belts this association exists. The iron formations are, therefore, most certainly volcanic derivatives, but the exact source of their constituent silica, iron, carbonate, and sulphur is problematical. Two principal sources seem to encompass the possibilities – localized submarine hot springs or fumaroles associated with submarine volcanism (exhalites) or submarine leaching of tuffs and other volcanoclastic rocks. These sources have long been advocated by numerous students of the problem, but in actual fact it is difficult to find unequivocal evidence for either.

Present day hot springs and fumaroles associated with volcanism are commonly enriched in silica, iron, carbonate, and sulphur. While most of the data available are for terrestrial hot springs and fumaroles there is every reason to suspect that similar hot springs and exhalations exist today and have existed in the past in regions of submarine volcanism. Since the total amount of material delivered through any one hot spring or fumarole within a reasonable time is relatively small there is a problem in identifying the traces of the numerous hot springs and fumaroles in the volcanic assemblage which would be required to provide the large amounts of iron and silica found in the iron formations. One should expect to find evidence of a plethora of conduits which would presumably be marked by intensely altered rocks. Such conduits, as far as this writer is aware, have not been unambiguously identified. At Yellowknife, detailed mapping of the greenstone belt, which contains abundant chert and lean iron silicates and in places traces of the oxide facies, failed to reveal any hot spring conduits. In fact, no volcanic conduits of any kind could be identified

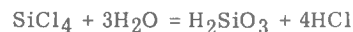
which suggests that the submarine volcanoes or fractures which supplied the lavas must have lain outside the confines of the present greenstone belt. Perhaps detailed mapping in other Archean volcanic belts, containing cherty iron formations, will provide evidence of hot spring and fumarolic conduits, since their identification is critical if a localized volcanic (exhalite) source of iron and silica is postulated.

We may, however, be looking for localized fossil hot springs and fumaroles in old Archean volcanic belts when actually none ever existed. There is abundant evidence to suggest that many of the flows were highly fluxed with gases as witnessed by the abundance of amygdules, gas cavities, and frothy tops. In present day volcanic phenomena it is not uncommon to see extensive sheets of lava that act like one great fumarole emitting from their surface vast amounts of CO₂, H₂S, SO₂, H₂SO₄, and HCl, and forming sublimates on their surface often high in iron, various salts, silica, etc. Field evidence suggests that in many of the Archean greenstone belts such phenomena were commonplace.

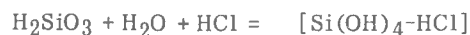
The alternative to localized volcanic (exhalite) sources for iron and silica is the submarine leaching of tuffs and other volcanoclastic sediments. The pH conditions under which this may have taken place can only be surmised. If the seas were acidic, reducing, and charged with constituents such as HCl, H₂SO₄, H₂S, or CO₂, as seems at least probable in basins where submarine volcanism was active, the release of iron, silica, manganese, alumina, and other constituents from finely comminuted silicates would be extensive. For a hypothetical iron silicate the reactions can be written schematically as follows:



Similar reactions can be written for manganese-bearing silicates. Michard (1975) has shown thermodynamically that basalt-seawater interaction can give a relatively high manganese concentration in the water. It will be noted that in the above reactions silica is released as the monomer (monosilicic acid). Where highly acid conditions prevailed in the presence of abundant HCl some silica may have been dissolved as the chloride, SiCl₄ or its complexes. This would be transient since silicon chloride is rapidly hydrolyzed in water to the so-called "silicic acid" which is in reality probably the monomer or a hydrated form of the colloid. In any case the hydrolysis reaction is usually written



and



which is the monomer stabilized by HCl. In addition, under near neutral conditions the alkali silicates may yield soluble silicates, the species being of the type

¹As used in this paper the term ignimbrites includes mainly quartz-feldspar porphyries and other porphyritic clastic rocks that exhibit a crude stratification. Their origin is uncertain. Some appear to be welded tuffs; others are interbedded flows and welded tuffs. Many are now quartz, feldspar, or quartz-feldspar augen schists.

Na_2SiO_3 . In general the pH at which leaching of iron and silica from volcanoclastic rocks took place would seem to have been in the range 5-7. This is suggested by the general observation that most Archean iron formations are low in aluminum, the oxide of which, being amphoteric, has a low solubility in the pH range 5-8.

We see, therefore, that all of the constituents of Archean iron formations may have been derived by submarine leaching of tuffs and other volcanoclastic rocks under slightly acid to neutral conditions. Initially the constituents would be relatively mobile and capable of migrating. If, however, the seas were alkaline, as is now the case, there would be considerable difficulty in rendering iron mobile and capable of migration. A similar situation would obtain for manganese. One could resort to alkaline complexes or colloidal transport of these elements, but this seems improbable on two accounts. Firstly, the maximum amount of complexed iron in alkaline brines under reducing conditions appears to be about 3 ppm, hardly enough to transport large amounts of iron in the short periods of time which one can assume for the formation of the relatively restricted Archean iron formations. Secondly, iron and manganese colloids are rapidly coagulated and precipitated in alkaline brines and hence have a low mobility. The conditions were, therefore, apparently acidic and reducing at the sites of leaching to maintain the iron and constituents such as manganese in the lower valence states, thus permitting their migration at least for short distances in the submarine basins.

There are two problems that beset the leaching hypothesis. One is that the minerals of the tuffs and other volcanoclastic rocks in the marine volcanic sequences are remarkably uncorroded when viewed in thin sections. This, however, may be due to later metamorphism which has largely removed the corrosive effects. Another feature is that the tops of flows and tuffs, which must have been in contact with the seawater, appear to be relatively unaffected by leaching with respect to their central and lower parts. If extensive zones leached of their silica and iron were formed on the tops of tuffs and flows one would have expected that metamorphism would have accentuated these zones. On the other hand, many of the Archean ignimbrites and tuffs associated with iron formations are profoundly altered (spilitized) throughout their beds, and some are relatively enriched in aluminum. Much of this alteration may well have taken place by reaction with seawater containing CO_2 , HCl , etc.

This brief discussion indicates that neither the localized exhalite nor the submarine leaching hypotheses provide entirely adequate explanations for the source of iron and silica in Algoma-type iron formations. Obviously much more detailed research is necessary before the problem can be satisfactorily solved. The submarine leaching hypothesis seems to take into account much of the factual evidence, namely the frequent occurrence of Algoma-type iron formations with tuffs and other volcanoclastic rocks which should have yielded considerable amounts of soluble iron and other constituents when acted upon by acidic waters.

Widespread exudation of reactive gases from extensive flows and ignimbrites, successively poured out on the ancient ocean floors, seems to have been the major source of the volatiles, CO_2 , SO_2 , H_2SO_4 , HCl , H_2S , etc., necessary first to transport and finally to bind the iron in its various minerals.

While we may reasonably conclude that the source of the volatiles was volcanic, their exact form is a matter of speculation. Probably much of the carbon dioxide (carbonate) was delivered to the Archean submarine basins as the gas or as the gas entrained in steam which ultimately became dissolved in the Archean seawater. Similarly, we can speculate that HCl followed a similar course. The sulphur, however, may have had a complicated history. Initially it may have been delivered to the seawater in the form of hydrogen sulphide, sulphur dioxide, sulphuric acid, or dissolved sulphate. In the case of the last three it seems probable that primitive bacteria reduced much of the oxidized sulphur species to H_2S . We can assume, therefore, that the hydrous milieu in which iron, silica and other constituents of iron formation were transported and precipitated was characterized by the presence of relatively large amounts of CO_2 , HCl , H_2S , and probably also SO_4^{2-} . The concentration of any one of these species at any one site probably varied widely, how widely we have no particular idea.

We are largely reduced to speculation when we consider the mode of transport and precipitation of the iron and silica that gave rise to the Archean iron formations. Since volcanic emanations and solutions appear to have been involved in the formation of these rocks the most probable modes of transport for iron are the hydrogen carbonate complex $[\text{Fe}(\text{HCO}_3)_2]$, the chloride, FeCl_2 , and sulphate, FeSO_4 . Hydrous ferric oxide sols may have been important where seawater was only slightly acidic and oxidizing. The role of humic complexes and other organic compounds in the transport of the iron in Archean seas is uncertain. The presence of abundant carbonaceous matter in the black cherts and slates of some iron formations indicates that organic compounds were probably present in the seas, but their original nature cannot be accurately characterized at our present state of knowledge. Some of the carbonaceous matter now present in the sediments may represent the degradation products of iron humates, the humate component being derived from the decomposition products of marine humus (sapropel) composed of the remains of algae and bacteria or their primitive precursors. It is perhaps significant that in detail the sediments rich in carbonaceous matter are removed in both space and frequently in time of deposition from the iron-rich oxide, carbonate, and silicate facies of iron formations, and that these first two facies are generally relatively low in carbonaceous matter, features which suggest that humates and similar soluble or colloidal organic compounds played little part in the transport of iron. This conclusion is, however, not entirely unequivocal since the organic components of the iron humates may have been completely oxidized to CO_2 , H_2O , N_2 , etc. and returned to the seawater during deposition of the oxide facies of the iron formations.

The problem is again a case of attempting to logically interpret natural chemical processes only from the observed products of the reactions.

A number of modes of transport of silicon in natural waters are possible depending on the pH and other factors. These include: (1) as silicic acid, $[\text{Si}(\text{OH})_4 - \text{HCl}]$, stabilized by HCl under acid conditions; (2) as an anion (silicate) in alkali-rich solutions; (3) as monosilicic acid, $\text{Si}(\text{OH})_4$, in the pH range 2-9; (4) as the colloid, $\text{SiO}_2 \cdot x\text{H}_2\text{O}$, in the pH range 2-9; (5) as various soluble organosilicon complexes; and (6) as adsorbed silica or silicate species on humus, silt, and various other particulates. Of these only the first four modes merit serious consideration, and of these (1), (3), and (4) appear the most probable. The last two seem incapable of transporting the vast amounts of silica present in the cherty iron oxide facies mainly because these facies are relatively free of residual organic matter, silt, etc.

The geological setting of the Archean iron formations indicates that their deposition took place in relatively local depressions on the bottoms of ancient seas characterized by abundant submarine volcanism. Relatively deep water conditions out of contact with wave action are also implicit in the geological settings, otherwise the delicate banding of the iron formations and the persistence of thin bands of tuffaceous material would not have been preserved. Oxidizing conditions, likewise, prevailed as witnessed by the presence of the various iron oxides. The existence of oxygenated waters in the ancient (Archean) oceans is not readily explained, especially as regards the origin of the oxygen. The element may have been present in the Archean atmosphere from which it found its way into the deep oceanic waters, or alternatively, and what seems more probable, it may have been derived directly from submarine volcanic exhalations¹. Further discussions of these possible origins is beyond the scope of the present paper.

The precise details of the chemistry of precipitation of the oxide and chert facies of the Archean iron formations can only be surmised from what we know about the laboratory behaviour of iron and silica, and to a lesser extent from what we observe in present day situations, such as iron bogs, where iron and silica are being deposited. We are uncertain about the manner of transport of the iron and silica in the Archean seas, but in the discussion above we have assumed that iron was probably transported as the hydrogen carbonate $\text{Fe}(\text{HCO}_3)_2$, the chloride, FeCl_2 , or the sulphate, FeSO_4 , depending on various conditions, but essentially on the availability of CO_2 , HCl, H_2SO_4 ,

etc. Iron humates and other organic complexes probably played no part, or only a very limited role, in the transport of iron during Archean time. Silica was probably present mainly as the monomer, $\text{Si}(\text{OH})_4$, but transport as dissolved silicate or as the colloid $\text{SiO}_2 \cdot x\text{H}_2\text{O}$ cannot be ruled out. There may also have been considerable transport of iron either as colloidal ferrous hydroxide, $\text{Fe}(\text{OH})_2$, or as colloidal hydrous ferric oxide, $\text{Fe}_2\text{O}_3 \cdot x\text{H}_2\text{O}$.

Dissolved iron is precipitated from solution by a variety of reactions depending on the Eh and pH conditions. Of these, oxidation of the ferrous iron followed by hydrolysis reactions are the most important as regards the sulphate and chloride. The schematic reactions probably run as follows:



Similar reactions may induce precipitation of hydrous iron oxide where the waters contain the hydrogen carbonate complex. The reactions are oxidation of Fe(II) to the Fe(III) state followed by hydrolysis and precipitation of the hydrous oxide. Condensed the reactions can be represented as:



Splitting out of water from the gelatinous hydrous ferric oxide yields limonite, goethite, hematite, maghemite, or magnetite depending on the redox potential and on how much water is lost during the aging and crystallization of the gels.

This is not the place to engage in a polemic on the intricacies of the mechanisms of the oxidation of ferrous iron to the ferric state in solution, a subject that is not yet entirely understood. It is sufficient to state that the potential of the $\text{Fe}^{3+} - \text{Fe}^{2+}$ couple is such that molecular oxygen can convert ferrous to ferric iron in mildly acid solutions; in neutral and basic solution, the oxidation process is even more favourable. If the ancient seas were mildly acidic (pH >4) as has been suggested above there would have been no particular difficulty in precipitating iron oxides from dissolved iron chloride or sulphate. Similarly, iron oxides would be precipitated in neutral and alkaline seas where the iron was dissolved as the chloride, sulphate, or hydrogen carbonate.

The presence of magnetite in Archean cherty iron formations can be interpreted in two ways. In many places its presence is undoubtedly due to metamorphism. In other places, however, magnetite seems to indicate that a low oxidation potential prevailed in the basins of deposition. The initial gel precipitates of iron probably contained the element as ferrous hydroxide, $\text{Fe}(\text{OH})_2$ mixed with hydrous ferric oxides, $\text{Fe}_2\text{O}_3 \cdot x\text{H}_2\text{O}$. Splitting out of water from the combined gels, concomitant with crystallization processes, yielded magnetite.

¹Molecular oxygen is common in high temperature volcanic gases. It is probably an integral (and original) component of these gases and not a contaminant from the atmosphere as many have supposed. The implication of this is clear - the earth's atmosphere may have contained considerable amounts of oxygen from the initiation of degassing of the globe.

Precipitation of iron as siderite in the carbonate facies may have resulted from a number of possible processes, only a few of which will be mentioned here. Where the iron was carried as $\text{Fe}(\text{HCO}_3)_2$ any process which removes or isolates CO_2 from the system results in the precipitation of siderite. Several such processes can be envisioned in the Archean seas, e. g. a rise in temperature of the seawater due to extensive outpouring of submarine lava; increase in acidity due to increased exhalation of HCl , H_2SO_4 , etc.; and extraction of CO_2 by primitive organisms. In all cases the reactions to produce siderite are similar:



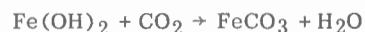
Alternatively a high concentration of CO_2 from volcanic sources may enter a system where FeSO_4 is abundant resulting in the precipitation of siderite:



Introduction of alkali carbonates has the same effect:



and finally volcanic CO_2 entering a system where ferrous hydroxide is present may precipitate the carbonate:



We need not pursue the possible mechanisms further; it is sufficient to say that there are many which could lead to the precipitation of siderite. Each siderite occurrence probably requires individual study as regards its chemical history.

The iron oxide facies of the Archean iron formations are invariably highly siliceous, the silica being present mainly as chert or recrystallized chert. The reason for the precipitation of such quantities of silica as occur in iron formations has long been a problem. Some have suggested organic agencies whereas others consider inorganic processes more probable. There is no unambiguous fossil evidence for the extensive existence of silica-secreting organisms in Archean time, a feature that probably rules out organic agencies as effective precipitants of silica in the iron formations of this age. This leaves inorganic processes for consideration.¹

¹The possible presence of organisms such as the phytoflagellates (silicoflagellates) or their precursors in Archean time should not be dismissed. Such organisms, capable of precipitating silica and those capable of precipitating iron, seem to have been present in Proterozoic time and may well have extended back into the Archean. The reactions that lead to the precipitation of silica and iron by organisms do not differ from those of an inorganic nature, although the rate and catalytic action of organisms is usually greater and highly efficient.

It was suggested earlier that the most probable forms in which silica was transported in the Archean seas was as the chloride stabilized silicic acid, $[\text{Si}(\text{OH})_4 - \text{HCl}]$, as the monomer, $\text{Si}(\text{OH})_4$, or as the colloid, $\text{SiO}_2 \cdot x\text{H}_2\text{O}$. In fact, the first two are essentially the same, their precipitation reactions being similar.

The solubility of silicon as the monomer, $\text{Si}(\text{OH})_4$, or its stabilized forms, is not affected by the Eh. Small changes in the pH in the range 2-9, such as might occur in oceanic environments, likewise, probably have little effect on the solubility of the monomer, although it should be remarked that the effect of pH on the solubility of silica and the stabilized forms of its monomer and polymers are subtle, and the long term geological consequences as regards precipitation of silica may be considerable. Thus, it appears from the experiments of Ginzburg and Sheidina (1974) that polymerization is markedly affected by pH and aging. From our experiments the presence of carbonate and sulphate appears to have a decided influence on lowering the solubility of silica. This feature is of interest because much of the iron in the Archean seas may have been present as the hydrogen carbonate or sulphate. Whatever the manner of reducing the solubility of the monomer, supersaturation leads to the formation of either silica colloid, an amorphous silica precipitate, or a gel. The process is a complicated polymerization one (Iler, 1955) which can be represented as follows:



Where direct precipitation of silica took place in the amorphous or gel forms the resultant deposits would be mainly cherts. On the other hand where silica sols appeared in a milieu where iron was abundant and precipitating, the silica and iron colloids would be mutually precipitated as shown many years ago by Moore and Maynard (1929).

Little more need be said regarding the sulphide facies of Archean iron formation than what was outlined for the origin of the sulphide tuffs, slates, schists, etc. The various sulphides, principally pyrite, pyrrhotite, and arsenopyrite, were undoubtedly precipitated in a reducing sapropelic environment where abundant sulphur, probably in the form of H_2S , was available. The H_2S may have been derived directly from volcanic exhalations, although it seems more probable that primitive organisms operating in the sulphur cycle reduced dissolved sulphate in the Archean seas to H_2S which in turn bound the various metals as their insoluble sulphides.

The characteristic banding in Archean iron formations has been variously interpreted as due to rhythmic precipitation, interdiffusion banding in gels, and metamorphic differentiation processes. Probably all three were responsible agents depending on the chemical and geological situation. Certainly in some iron formations one can see what is obviously rhythmic sedimentary precipitation of iron and silica separated by very thin tuff beds. The cause of the rhythms is, however, obscure. It may have something to do with periodic

supersaturation of the Archean seas first with iron and then silica, and again with iron and so on. Alternatively, the banding may result from interdiffusion cyclic supersaturation-nucleation-precipitation processes in silica-iron gels such as take place during the formation of Liesegang rings, and for which there is yet no detailed satisfactory explanation. Metamorphic differentiation may later accentuate these two effects; it seems unlikely, however, that this process is the prime cause of the phenomenon.

In summary it can be stated that Archean iron formations are sedimentary bodies, their volatile components (CO_2 , S) originating from extensive degassing of volcanic flows in a submarine environment and their principal constituents such as silica and iron being derived from submarine leaching of ignimbrites, tuffs, and other volcanoclastics aided mainly by the solubilizing action of CO_2 , H_2SO_4 , and HCl. The precipitation of the silica and various iron oxides and the formation of the characteristic banding probably involved complex colloidal interactions and interdiffusion phenomena.

To some investigators, a much simpler and more appealing mechanism for the origin of Archean iron formations is that the silica and iron and the various volatiles were exhaled from submarine fumaroles and hot springs directly into the Archean ocean, where they were precipitated in nearby basins. Unfortunately this simple, unencumbered hypothesis is not in accord with the field evidence — at least not in this writer's present opinion.

Manganese Formations

The Archean (Algoma type) iron formations commonly contain some manganese but seldom in economic amounts. A search of the literature reveals that most iron formations of this age generally contain less than 0.5 per cent MnO. There is some doubt about the exact age of the great manganese formations in the Indian Shield. According to Roy (1966) some are of Archean age and probably others are Proterozoic.

The syngenetic bedded manganese deposits of India are interbanded with phyllites, schists, gneisses, cherty quartzites, and marbles. The principal manganese minerals are braunite, bixbyite, jacobsonite, hollandite, manganite, pyrolusite, and cryptomelane. The ores lie in the chlorite, biotite, garnet, and sillimanite-kyanite regional metamorphic facies; in the higher grade facies a number of manganese silicates are developed in the siliceous parts of the manganese formations.

The source of the manganese in the various manganese formations has long been problematical. According to Roy (1966) there is no evidence for volcanogenic sediments, and he considers the manganese formations to be chemical sediments derived as a result of normal weathering processes. They have been intricately folded and metamorphosed, some now appearing as relatively high grade metamorphic manganese rocks (gondites).

The geochemistry of manganese will not be further described except to note that the element behaves much the same as iron in sedimentary processes. Manganese is, however, more acidic in its reactions than iron, a feature which endows the element with greater mobility under neutral and alkaline conditions. This commonly permits a separation of the two elements during sedimentation processes, the iron precipitating in one basin or layer and the manganese in another.

Gold Deposits

The gold deposits of the Archean greenstone belts (Fig. 1) are generally quartz veins and lenses, silicified stockworks, and impregnations in fractures, faults, shear zones, and linear carbonated schist zones. The deposits in the greywacke-slate sequences associated with the greenstone belts are quartz veins, lenses, and irregular bodies in contorted and dragged schist zones, faults, slips, shears, and openings both along and across the bedding. Particularly characteristic are saddle-shaped bodies and legs on the crests of folds (saddle reefs) and steeply dipping bodies in sheared and ruptured zones along the axes of isoclinal folds¹.

The mineralogy of the deposits in both settings differs only in detail. Pyrite, pyrrhotite, and arsenopyrite are the principal sulphides, and there are commonly small amounts of chalcopyrite, sphalerite, and galena. Stibnite, tetrahedrite-tennantite and other sulphosalts are usually local. Scheelite and molybdenite are commonly present but generally only in small amounts. The principal auriferous minerals are native gold, aurostibite, a number of gold-silver tellurides, and gold-bearing pyrite and arsenopyrite in which the gold is present in both microscopic and submicroscopic particles. The tellurides tend to be concentrated mainly in gold deposits in volcanic rocks. The gangue is invariably quartz and carbonate, usually ankerite,

¹The auriferous quartz-pebble conglomerates, the largest and most productive gold deposits in the world, are intentionally excluded here because they are not really members of Archean greenstone and sedimentary belts. The great deposits of the Witwatersrand appear from isotope age dating to be of Archean age, but they lie unconformably on older auriferous greenstone and sedimentary belts (Swaziland System). The deposits in Ghana, the auriferous Tarkwa conglomerates, similarly overlie auriferous greenstone and sedimentary belts (Birrimian System). The relationship to greenstone belts of the auriferous quartz-pebble conglomerates in Brazil, the Jacobina System, is not clear. Similar but only faintly auriferous quartz-pebble conglomerates carrying abundant uranium in the Blind River-Elliott Lake region of Canada overlie Kenoran granitic rocks with profound unconformity. These conglomerates are generally considered to be of early Proterozoic age. All of these deposits are discussed in great detail in a forthcoming publication by the writer on gold.

Table 6

Gain or loss of volatiles and metals during granitization of a cubic mile and cubic kilometer of Archean greenstone belts, sedimentary belts, and ultrabasic rocks
(Assumed specific gravity of rocks = 3)

Constituent	H ₂ O%	CO ₂ %	S%	As (ppm)	Sb (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)	Ni (ppm)	Co (ppm)	Cr (ppm)	Au (ppm)	Ag (ppm)
Content in volcanic (greenstone) belts prior to granitization	1.80	0.262	0.094	7.0	1.0	80	6	93	123	50	240	0.007	0.12
Content in derived granodioritic rocks	0.97	0.084	0.024	2.0	0.2	10	12	55	10	5	5	0.003	0.05
Gain (+) or loss (-) in short tons (or troy ounces) x 10 ⁶ during transformation of a cubic mile of greenstone rocks to granodiorite. Numbers in brackets refer to metric tons or grams x 10 ⁶ gained or lost during transformation of a cubic kilometer of greenstone rocks to granodiorite	-114.4 (-24.9)	-24.5 (-5.34)	-9.65 (-2.1)	-0.069 (-0.015)	-0.011 (-0.0024)	-0.965 (-0.210)	+0.082 (+0.018)	-0.524 (-0.114)	-1.558 (-0.339)	-0.620 (-0.135)	-3.239 (-0.705)	-1.608 (-12.0 g) oz. troy	-28.14 (-210.0 g) oz. troy
Content in pelitic (greywacke and slate) sedimentary belts prior to granitization	3.13	0.30	0.250	20	1.0	65	15	110	70	26	135	0.012	0.20
Content in derived granitic rocks	0.97	0.084	0.024	2.0	0.2	10	12	55	10	5	5	0.003	0.05
Gain (+) or loss (-) in tons (or troy ounces) x 10 ⁶ during transformation of a cubic mile of pelitic rocks to granite. Numbers in brackets refer to metric tons or grams x 10 ⁶ gained or lost during transformation of a cubic kilometer of pelitic rocks to granite	-297.7 (-64.8)	-29.77 (-6.48)	-31.15 (-6.78)	-0.248 (-0.054)	-0.011 (-0.0024)	-0.758 (-0.165)	-0.041 (-0.009)	-0.758 (-0.165)	-0.827 (-0.180)	-0.289 (-0.063)	-1.792 (-0.390)	-3.618 (-27.0 g) oz. troy	-60.31 (-450.0 g) oz. troy
Content in ultra-basic rocks prior to granitization	7.80	0.67	0.047	4.0	0.4	80	4	97	1285	135	2000	0.005	0.08
Content in derived granodiorite rocks	0.97	0.084	0.024	2.0	0.2	10	12	55	10	5	5	0.003	0.05
Gain (+) or loss (-) in tons (or troy ounces) x 10 ⁶ during transformation of a cubic mile of ultra-basic rocks to granodiorite. Numbers in brackets refer to metric tons or grams x 10 ⁶ gained or lost during transformation of a cubic kilometer of ultra-basic rocks to granodiorite	-941.46 (-204.9)	-80.78 (-17.58)	-3.170 (-0.690)	-0.028 (-0.006)	-0.003 (-0.0006)	-0.965 (-0.210)	+0.110 (+0.024)	-0.579 (-0.126)	-17.575 (-3.825)	-1.792 (-0.390)	-27.500 (-5.985)	-0.80 (-6.0 g) oz. troy	-12.06 (-90.0 g) oz. troy

dolomite, or calcite. Tourmaline is common in some veins, especially in the sedimentary belts.

The characteristic types of wall-rock alteration in the greenstone belts, are chloritization, carbonatization, pyritization, sericitization, and silicification. The veins, lodes, and stockworks are generally flanked by zones of carbonate-sericite schist, which grade imperceptibly into zones of chlorite-carbonate and chlorite schist. In general these alteration zones represent a loss of silica and some of the chalcophilic elements, and major increases in water, carbon dioxide, sulphur, and potassium. Sodium is generally leached. The reactions to produce the alteration zones are complex and have been discussed in detail by the writer (Boyle, 1961). The most significant feature is the transfer of silica to the vein sites where it probably crystallizes as quartz. By means of detailed chemical profiles it has been shown that most of the vein quartz owes its origin to this process. Where the deposits occur in rhyolites or dacites the alteration effects are less marked. Sericitization, pyritization, and silicification are, however, characteristic. Sediments, interbedded with the volcanic rocks, are not markedly affected in most places, although there may be a development of pyrite, arsenopyrite, sericite, and some carbonate minerals near the veins.

In the sedimentary belts the wall-rock alteration is usually minimal, but tourmalinization is marked in places. Adjacent to the quartz bodies there is commonly a narrow, and often diffuse, zone of chloritization, sericitization, pyritization, and arsenopyritization. The source of the silica that constitutes the quartz veins is probably local, but related more to metamorphic processes and medium distance migration than to short distance migration as a result of wall-rock alteration reactions. This feature is discussed further below.

Both the deposits in the greenstone and sedimentary belts exhibit two principal generations of gold. The first is associated with the deposition of paragenetically early pyrite and arsenopyrite; the second major generation, characterized by the deposition of gold, aurostibite, and tellurides, is invariably late. In fact, the auriferous minerals are generally the last to crystallize in most deposits.

Within the metamorphic-granitization-tectonic framework of the greenstone belts the gold deposits are late. The structures in which they occur cut across the metamorphic facies and transect the quartz-feldspar porphyries with intrusive aspect as well as the granitic bodies which inject or were developed from the greenstone rocks. Similarly, in the sedimentary belts, the gold deposits are invariably later than the granitic intrusives which invade or were developed from the sediments. The only rocks which consistently cut gold deposits in Archean greenstone and sedimentary belts are diabbases which in most places are considered to be of Proterozoic age.

Four general sources of gold and silver and the processes whereby they are concentrated in Archean deposits seem probable.

(1) Granitization of the composite pile of volcanics and sediments comprising the greenstone-sedimentary

belts: As granitization proceeded and melts developed, the various volatiles, base metals, gold, and silver were expelled during crystallization of the melts (granite-granodiorite bodies) ultimately finding their way into available structures such as faults, drag folds, shear zones, etc. where they were precipitated. This is essentially a variation on the magmatic-hydrothermal theme. It is open to severe criticism as regards timing and the chemistry of melts. For instance, the gold deposits appear to have formed long after the crystallization of the granitic rocks and hence could not in any sense have been derived by differentiation processes. Furthermore, differentiation does not yield the base and precious metals, sulphur, and arsenic at the end of the process. The trend is toward a decrease in metals, sulphur, arsenic, etc. as differentiation proceeds as one can readily see by studying the trace metal, sulphur, arsenic, etc. content of the sequence of igneous rocks — ultrabasic-basic-intermediate-acid. These and other similar criticisms have been discussed by the writer in earlier papers (Boyle, 1963, 1970).

(2) Metamorphic secretion of gold from the composite pile of volcanic-sedimentary rocks comprising the greenstone-sedimentary belts: The mechanisms involved are thermal mobilization of volatiles, gold, silver, base metals, etc. during the metamorphism of the belts accompanied by concentration in faults, fractures, shear zones, etc. as a result of the dilatant action of these structures. There is no problem with the timing nor with the source of the constituents in the deposits as emphasized in a series of papers by the writer (Boyle, 1961, 1970). Thus, as granitization and metamorphism engulf the greenstone-sedimentary belts enormous amounts of constituents are released as shown in Table 6. The mode of migration is essentially by diffusion, the possible mechanisms being explained in another paper by the writer (Boyle, 1963). Probably many of the gold-quartz deposits in greenstone rocks were formed by this mechanism or by a combination of this mechanism and that in (3) below. In the greenstone belts the most favourable source rocks for gold and silver would seem to have been the sulphide schists, iron formations, quartz-feldspar porphyries with intrusive aspect, and the basic lavas in about that order of importance. The CO₂ and probably much of the S, As, and other volatiles probably came largely from the lavas. In the sedimentary belts the source rocks of the precious metals would seem to have been mainly the sulphide-rich carbonaceous slates, although the quartzites and greywackes may also have made their contributions. The quartz in the deposits in the greenstone belts was probably largely derived from alteration processes involving carbonitization and hydration as discussed below for the carbonated zones. The deposits in the sedimentary belts appear to be due solely to metamorphic secretion and dilatancy induced by the opening of structures such as those on the noses of folds (saddle reefs). The quartz was most probably derived from nearby siliceous rocks, e.g. greywacke, quartzite, etc. as a result of metamorphic differentiation (secretion) processes.

Table 7

Gain or loss of some constituents during extensive carbonatization of a cubic mile and cubic kilometer of Archean greenstone belts and ultrabasic rocks.
(Assumed specific gravity of rocks = 3)

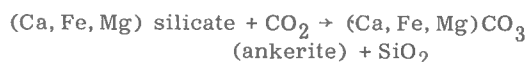
Constituent	CO ₂ %	SiO ₂ %	S%	As(ppm)	Sb(ppm)	Cu(ppm)	Pb(ppm)	Zn(ppm)	Ni(ppm)	Co(ppm)	Cr(ppm)	Au(ppm)	Ag(ppm)
Content in volcanic (greenstone) belts prior to carbonatization	0.26	53	0.094	7.0	1.0	80	6	93	123	50	240	0.007	0.12
Content in carbonated greenstone rocks ¹	8.00	15	0.040	2.0	0.5	25	2	50	80	30	210	0.003	0.05
Gain (+) or loss (-) in short tons (or troy ounces) x 10 ⁶ during carbonatization of a cubic mile of greenstone rocks. Numbers in brackets refer to metric tons (or grams) x 10 ⁶ gained or lost during carbonatization of a cubic kilometer of greenstone rocks.	+1066.9 (+232.2)	-2067.64 (-450.0)	-7.444 (-1.620)	-0.0689 (-0.0150)	-0.0069 (-0.0015)	-0.758 (-0.1650)	-0.0551 (-0.0120)	-0.593 (-0.1290)	-0.593 (-0.1290)	-0.276 (-0.0600)	-0.414 (-0.0900)	-1.608 (-12.0 g) oz. troy	-28.14 (-210.0 g) oz. troy
Content in ultrabasic rocks prior to carbonatization	0.67	40.1	0.047	4.0	0.4	80	4	97	1285	135	2000	0.005	0.08
Content in carbonated ultrabasic rocks ¹	8.00	30	0.040	2.0	0.2	30	2	50	200	35	1000	0.002	0.05
Gain (+) or loss (-) in short tons (or troy ounces) x 10 ⁶ during carbonatization of a cubic mile of ultrabasic rocks. Numbers in brackets refer to metric tons (or grams) x 10 ⁶ gained or lost during carbonatization of a cubic kilometer of ultrabasic rocks.	+1010.4 (+219.9)	-1392.2 (-303.0)	-0.9649 (-0.210)	-0.0276 (-0.006)	-0.0028 (-0.0006)	-0.6892 (-0.150)	-0.0276 (-0.006)	-0.6479 (-0.141)	-14.956 (-3.255)	-1.3784 (-0.300)	-13.784 (-3.00)	-1.206 (-9.00 g) oz. troy	-12.06 (-90.0 g) oz. troy

Note: ¹These contents are rough estimates from selected carbonated zones. With increase in carbonatization most of the metals decrease significantly to low values, usually only a few parts per million.

(3) Secretion from carbonated zones in greenstones and sediments: Many of the great gold deposits in Archean rocks are closely associated with linear and diffuse belts and zones of carbonitization of greenstones and subordinately of associated sediments. These carbonate zones lie in sheared, crumpled, and dragged zones that crosscut the stratigraphy of both the greenstone and sedimentary belts and should not be confused with the carbonate facies of iron formation. In detail, the carbonated zones are composed essentially of ankerite or dolomite with wisps and residuals of country rock now highly altered to chlorite, talc, and sericite. Quartz stringers may be abundant in the zones or they may be entirely lacking. Pyrite and occasionally arsenopyrite occur in places but are usually relatively sparse in amount. The gold content is generally very low, commonly about half of what was originally present in the replaced rock. The other metals are also commonly reduced in amount where carbonatization has been intense (Table 7).

Some of the gold deposits in Archean rocks are located within the confines of these great carbonated and chloritized zones. Examples are the orebodies of the Giant and Con Mines in the Giant-Campbell system, Yellowknife, Northwest Territories and the orebodies of the Kerr Addison and Chesterville Mines at Larder Lake, Ontario. Other deposits are in fractures, faults, and shear zones that are subsidiaries of the great carbonated zones. Examples are widespread throughout the world, being present at Yellowknife (Negus-Rycon system subsidiary to the Giant-Campbell system); at Kirkland Lake (Kirkland Lake fault subsidiary to the Kirkland Lake-Larder Lake Break); at Ramore, Ontario (Ross Mine where the orebodies are adjacent to extensive carbonated zones); at Porcupine (Timmins), Ontario where belts and patches of carbonitization are widespread both in the productive vein zones and well outside these zones; at the McWatters and other mines in the Rouyn area of Quebec which are in or adjacent to the carbonate-chlorite-talc schist zone that marks the Cadillac Lake fault; in the Kalgoolie gold belt of Australia (Golden Mile zone); in Rhodesia; South Africa, and elsewhere.

These extensive carbonated zones have had marked effects on the chemistry of many elements. As carbonitization proceeded large amounts of silica (Table 7) were released as shown schematically in the following reaction:



The silica so released migrated into dilatant zones (drag folds, contorted zones, fractures, shears, etc.) which were either within the confines of the carbonated zones or subsidiary to them. There it crystallized as quartz. The amount of silica liberated was enormous, generally about four times that normally required to account for that present in the associated gold-quartz veins on a material balance basis (Boyle, 1955, 1961). Not only silica was involved; it is evident that in many places gold, likewise, migrated out of these intensely carbonated zones and ultimately into the silicified zones

and quartz veins. It is estimated that a cubic mile of highly carbonated rock may produce up to two million ounces of gold through the process of carbonatization and hydration. Relatively large amounts of sulphur, arsenic, antimony, and base metals, the ingredients of many of the Archean gold-quartz bodies, may have been similarly derived (Table 7).

In a recent paper Pyke (1975) has proposed that Archean ultramafic volcanic rocks formed the principal source bed for the gold in the auriferous deposits in the Timmins (Porcupine) area of Ontario. During extensive carbonatization of the ultramafic rocks gold and silica were leached and concentrated in structurally favourable dilatant zones.

(4) Secretion from iron formations: A number of gold deposits in Archean rocks occur in iron formations or are closely associated with these rocks, particularly with the sulphide schists (sulphide facies of iron formation). Some of the deposits lie within the confines of the iron formation in a more or less conformable manner; others cross the iron formations at a high angle. Deposits of both types are widespread throughout the Archean greenstone belts of the world. Two productive deposits occurred in the Crow River greenstone belt of Northwestern Ontario, the Central Patricia mine, and the Pickle Crow mine. The orebodies of the former were essentially conformable with the iron formation, but in detail the auriferous pyrrhotite-arsenopyrite-pyrite stringers cut at a high angle across the chert, iron carbonate, and magnetite bands. At the Pickle Crow mine one of the productive quartz veins strikes and dips across the iron formation at angles of some 40 degrees or more; in the iron formation the stopes are wider and more productive than in the greenstones. At another deposit, the Hard Rock mine at Geraldton, Ontario the auriferous sulphide and quartz veins are essentially conformable with the iron formations. Elsewhere in the world there are a number of deposits in or near iron formations in Brazil, South Africa, Rhodesia, Australia, and India (Kolar). Some of the so-called "sulphide and graphitic lodes" in the last field are probably sulphide facies of iron formation.

It is generally recognized that gold deposits in iron formation are localized mainly as a result of structural considerations, the iron formations being highly brittle and hence susceptible of forming extensive dilatant zones. But this is probably only half the story. It would seem from our research (Table 2) that iron formations are in general a good source of gold and of such components as silica, sulphur, etc. localized in gold-quartz and auriferous sulphide bodies. As dilatant zones were formed in iron formations, much silica, carbonate, sulphur, gold, and silver were extracted from these formations and concentrated in local shoots either conformably within them or in veins across them.

Arsenic and Antimony Deposits

The Archean arsenic and antimony deposits are essentially similar to the gold-quartz deposits just described; in fact most of the deposits that yield arsenic and antimony are gold producers, the other two elements

being byproducts in most cases. The origin of the arsenic and antimony deposits is essentially the same as that outlined for the Archean gold deposits.

In the Canadian Shield many of the auriferous Archean deposits are greatly enriched in arsenic and antimony. Examples are the extensive deposits in the Yellowknife greenstone belt and numerous deposits in western Quebec, particularly the Beattie mine.

The Yellowknife deposits are veins and silicified zones in great schist (shear) zones in greenstones (Boyle, 1961). The principal arsenic mineral is arsenopyrite, and the main antimony mineral is stibnite. Tetrahedrite-tennantite carries both arsenic and antimony in these deposits and there are a number of antimony sulphosalts including bournonite, jamesonite, boulangérite, berthierite, semseyite, meneghinite, and jordanite. Arsenic and antimony are not recovered commercially from the ores.

The Beattie mine in western Quebec developed orebodies in silicified, bleached and brecciated volcanics (mainly tuffs) and syenite porphyry (Davidson and Banfield, 1944). The principal arsenic mineral was arsenopyrite. The mine marketed arsenic trioxide as a byproduct.

In the Murchison Range of the northeastern Transvaal, South Africa, there are a number of gold-antimony deposits in the Archean Swaziland System. The orebodies lie in shear zones and drag folds (the Antimony Line) in greenstones and sediments intruded by granites (Sahli, 1961). There is considerable carbonatization and chloritization associated with the orebodies, some of which contain up to 0.5 oz/ton Au and 10 per cent antimonial ore. The chief antimony minerals are stibnite and a number of antimonial sulphosalts of which berthierite, chalcostibite, and tetrahedrite are the most common. The sequence of mineralization along the Antimony Line is first pyrite-arsenopyrite-gold-quartz reefs, followed by stibnite-gold-quartz reefs, and terminated by cinnabar-quartz reefs. The presence of cinnabar is interesting since these deposits are about the only cases where the mineral occurs in Archean deposits. Mercury does occur, however, in other Archean deposits mainly in tetrahedrite-tennantite and sphalerite, but the tenor of the ores rarely exceeds a few parts per million of the element.

Tungsten Deposits

Most Archean bedrock tungsten deposits are small or low grade and hence not of economic interest at present. The types of deposits of Archean age include tungsten-bearing granites, aplites, pegmatites, skarn bodies, and quartz veins, the last often auriferous. Many of these types of deposits are exemplified by those in the Yellowknife greenstone and sedimentary belts, Northwest Territories.

Scattered crystals of scheelite and wolframite occur here and there in the granites and pegmatites that occur in or near the greywacke-slate sequences of sediments of the Yellowknife Supergroup. None of these are of any commercial interest. Similarly, scattered crystals of scheelite occur at several places in skarn lenses in

the greywacke-slate assemblage and its metamorphic equivalent the quartz-mica schists. The scheelite is generally intergrown with garnet, tremolite, pyroxene, carbonates, quartz, epidote, and muscovite. The skarn lenses appear to have resulted from the regional metamorphism of small interbedded sedimentary lenses of impure limestone (Boyle, 1961). None of the skarn lenses seen by the writer is of commercial interest.

Practically every quartz vein and silicified zone in the Yellowknife greenstone and sedimentary belts contains traces of tungsten, and some contain concentrations of scheelite or wolframite. Some of the auriferous quartz veins and silicified zones in the greenstone belt contain up to 1 per cent WO_3 , present as scheelite. The scheelite is irregularly distributed in the quartz veins occurring in patches and disseminated crystal aggregates. It is accompanied by carbonates, pyrite, arsenopyrite, chalcopyrite, sphalerite, galena, stibnite, various sulphosalts, native gold, and aurostibite (Boyle, 1961). The scheelite is an early mineral in the paragenetic sequence. Shoots rich in scheelite are commonly low in gold.

Vast numbers of quartz veins, irregular quartz segregations, and silicified zones in the greywacke-slate sequence and quartz-mica schists of the Yellowknife Supergroup contain traces of tungsten and many contain visible scheelite or wolframite. Other than quartz the principal minerals in these veins are small amounts of carbonates, feldspar, arsenopyrite, pyrrhotite, pyrite, galena, sphalerite, chalcopyrite, and native gold. In the occurrences in basic rocks (altered gabbro dykes and sills) at Tibbitt Lake the quartz veins also carry some garnet, zoisite, clinozoisite, and chlorite. On Outpost Island numerous gold-quartz veins and irregular silicified zones occur in shear zones in quartz-mica schist and gneiss, quartzite, and conglomerate of the Wilson Island Group (equivalent to the Yellowknife Group). The principal tungsten mineral is wolframite (ferberite) with minor scheelite; these minerals are associated with mica, andalusite, chalcopyrite, pyrite, magnetite, hematite, cassiterite, ilmenite, bornite, covellite, molybdenite, and native gold. Most of the deposits just described are small and relatively low grade, the tungsten-bearing shoots only rarely averaging 0.5 per cent WO_3 .

Elsewhere in the Canadian Shield scheelite and wolframite occurrences similar to those described above occur in Archean greenstone and sedimentary belts, mainly in gold-quartz deposits. During the Second World War scheelite concentrates were obtained from the auriferous quartz ores of the Hollinger and other nearby properties in the Porcupine gold belt of Ontario (Little, 1959).

The Archean rocks in other shields of the world also seem to have some tungsten occurrences and deposits, but these are not particularly well documented with respect to the exact ages of the deposits. In Nigeria the quartz vein and stockwork deposits associated with early Paleozoic and mid-Jurassic granites that invade Basement Complex (Archean?) gneisses give rise to economic eluvial and alluvial deposits (Li and Wang, 1947; Jacobson *et al.*, 1964).

In most tungsten deposits scheelite and wolframite are generally early minerals precipitated at about the same time as quartz. Like the latter mineral they were probably derived in a similar manner by secretion from the enclosing host rocks. The source of the tungsten is mainly the sediments of the greywacke-quartzite-slate and graphitic schist types. It is of interest to note that both tin and tungsten deposits of various ages throughout the world have a high frequency of occurrence in terranes marked by these assemblages of rocks especially where they are intensely granitized or intruded by granites. One need only recall the geological settings of the extensive tungsten deposits of China, the tin-tungsten deposits of Bolivia, and the tin deposits of Cornwall, all in or near granitic bodies that intrude thick sequences of quartzites, greywackes, phyllites, slates, and graphitic schists. Current research, not yet complete, indicates that Archean slates and graphitic schists are enriched in both tungsten and tin probably as a result of hydrolysis phenomena which markedly affect the sedimentary chemistry of these two elements.

Massive and disseminated sulphide deposits

The massive and disseminated sulphide bodies in Archean terranes are generally of two types: (1) massive and disseminated pyritic bodies with subordinate amounts of pyrrhotite and base metal (Cu, Zn) sulphides; (2) massive and disseminated pyrrhotite-pyrite bodies with subordinate amounts of base metal (Ni, Cu, Co) sulphides; and (3) disseminated and stockwork copper-molybdenum deposits, mainly in granitic rocks. Each of these are described in turn.

Massive and disseminated iron-copper-zinc sulphide deposits:

The majority of the massive and disseminated pyritic, copper-zinc sulphide bodies occur in volcanic terranes commonly in contorted tuffaceous and pyroclastic horizons and in sheared, dragged, contorted and brecciated zones in or near massive andesites, dacites, and particularly quartz-feldspar porphyry complexes (flows, ignimbrites, and bodies with intrusive aspects). Some of these deposits occur in graphitic and cherty interflow bands in the greenstone belts, and others are present in rocks of the greywacke-slate assemblage and their metamorphic equivalents.

The morphology of the sulphide bodies is varied. Some are great lenses and bed-like bodies (mantos) that have a stratiform aspect (e. g. Flin Flon, Manitoba; Kidd Creek, Ontario); others are massive, irregular bodies, often stacked one above the other, in breccia pipes that cut through the volcanic assemblage at a steep angle (e. g. Noranda, Waite Amulet, Quebec); still others are great lenses that occur on the noses of folds or in shears and dilatant structures that transect volcanic and sedimentary strata near the noses of folds, between regional shears and faults, etc. (e. g. Opemiska copper deposit, Quebec). Nearly all of the bodies are

discordant with respect to their enclosing rocks; even those with a stratiform aspect when examined in detail exhibit discordant features.

The sulphides composing the bodies occur in four ways – in massive, compact aggregates; in massive, compact, crudely banded bodies; in a disseminated manner either indiscriminately scattered through the rock or in small seams, pods, and veinlets constituting stockworks; and in cross-cutting vein-like bodies. Replacement features abound in most massive sulphide deposits, especially those developed in sheared and brecciated zones. The banding has been variously interpreted: Some consider it a sedimentary feature, but in most bodies individual bands can rarely be traced far before they begin to merge with others or fade out into massive aggregate material. It seems more probable that the banding is a replacement feature, particularly the replacement of schist bands, thin-bedded tuffs, iron formation, cherty tuffs, etc. In many bodies it can be shown that this is undoubtedly the process that has operated. The disseminated sulphides have no preference with respect to their loci. In some bodies they favour the hanging-wall rocks, in others the footwall, and in still others both. Disseminated bodies of sulphides are also commonly found as lateral extensions of the massive lenses. The cross-cutting veins and vein-like masses intersect the body of the massive lenses but do not seem to pass into the wall rocks in most deposits; they are invariably enriched in copper and zinc sulphides, particularly the former. Some contain quartz and/or carbonates.

The textures of the massive sulphide ores tend to reflect those present in the host rocks. Thus, where the rocks are schistose, highly crenulated, dragged, or banded due to the development of schistosity or original sedimentation processes, similar features are found in the sulphides. I interpret this feature as due to intimate replacement of host rock constituents by sulphides attendant upon dilation of the rocks (due to development of schistosity, dragging, etc.) during tectonic activity. In some deposits this activity continued for some time after deposition of the bulk of the sulphides, the effects, under low temperature conditions, being manifest in the development of schistosity in the sulphides, flowage of sulphides, brecciation, comminution, and recementing by mobilized material or new generations of sulphide material. Under high temperature conditions (amphibolite to granulite facies of metamorphism) porphyroblasts of sulphides appear, and the textures of the sulphides are coarsened. Where the sulphide bodies are developed in breccia pipes, as saddle-shaped bodies on the noses of folds, and in lens-shaped dilatant zones in fractures through the noses of folds, the textures of the ores are relatively uniform and commonly medium grained and equigranular. There may be some local banding especially near the contacts of the orebodies. Replacement features are again common especially in the breccia pipes where all degrees from minimal to complete replacement of the breccia fragments by sulphides can be seen.

The origin of the breccia pipes in Archean terranes is problematical; some have argued that they are volcanic in origin, others that they are related to tectonic activity. The latter is most probable, the mechanism being essentially that described by Mitcham (1974), namely extensive fissuring and brecciation developed on sections of a multiplane fault which are not parallel to the movement vector. The sites of fissuring and brecciation constitute relatively open dilatant zones in which the sulphides were deposited, hence the more massive equigranular nature of the ores.

An attempt has been made by some authors to show that all of the massive sulphide bodies in Archean greenstone and sedimentary belts are underlain by breccia or alteration pipes, the idea being apparently to prove that these were the feeders for the massive sulphides which were deposited as a sediment on the ocean bottom. This is certainly an erroneous supposition. Disseminated or stringer sulphide zones commonly occur in the footwalls of most massive sulphide bodies, but close study shows that these are invariably localized by sheared, dragged, contorted, or brecciated zones. Such zones with sulphides are also not uncommon as lateral extensions of massive sulphide lenses and also occur in the hanging-walls of some orebodies.

The mineralogy of the massive pyritic, copper-zinc sulphide bodies is relatively simple. Most contain pyrite, pyrrhotite, magnetite, sphalerite, chalcopyrite, arsenopyrite, chalcocite, and bornite in about that order of abundance. Galena is not abundant in most Archean bodies of this type. Tetrahedrite-tennantite, native silver, native gold, and a variety of tellurides are often present. The paragenesis of these minerals is as follows: pyrite and arsenopyrite commonly replaced by magnetite or replacing magnetite, followed by pyrrhotite, chalcopyrite, sphalerite, galena, tetrahedrite, tellurides, native silver, and native gold. There are numerous minor reversals of parts of this sequence as regards the base metal sulphides in some bodies, but in general pyrite, pyrrhotite, and arsenopyrite are early and the precious metals are late in the sequence.

The elements enriched in the pyritic, copper-zinc sulphide bodies are relatively uniform for all bodies, although some may be present at only slight concentrations. There are major enrichments of Cu, Ag, Zn, Cd, As, S, and Fe and minor enrichments of Pb, Au, (Hg), In, (Sn), Sb, (Bi), Se, and Te. (Those in brackets occur only in certain deposits.) The various metals exhibit an irregular zoning within individual deposits. This zoning bears no relationship whatever to what one might expect in original sedimentary processes (assuming an exhalative origin for these deposits). In some deposits the zoning appears to be related to sulphide replacement features or to structural adjustments within the deposits subsequent to the deposition of pyrite, pyrrhotite, and arsenopyrite.

Nearly all of the massive and disseminated pyritic, copper-zinc sulphide bodies have wall-rock alteration zones that envelop the lenses, disseminated zones, and stockworks. This alteration commonly exhibits fair to good bilateral symmetry. Silicification is usually pronounced, and there is often much sericitization,

chloritization, and pyritization. Carbonatization is not an important feature, but may be marked in the vicinity of some deposits (e.g. Flin Flon, Schist Lake, Manitoba; Mattabi, Ontario). The silicification is manifest in several ways — as an enveloping zone in which fine grained quartz is developed, as diffuse and irregular zones near the sulphide bodies where the rocks are pervaded by fine grained quartz, as enveloping zones where rounded nodules of fine grained quartz and carbonate are characteristic, and as enveloping zones in which a great profusion of quartz veins and stringers are present. The silicification seems best explained as an exchange-replacement process. As sulphur and other constituents replaced the silicates, silica was expelled from the environment (the sites of the sulphide lenses), migrated laterally or upward where it induced silicification of the rocks or was precipitated in wide-spread quartz veins and stringers. The replacement process is complicated and not readily expressed in the form of equations. However, for a simple iron silicate the following schematic equation shows what probably takes place:



The water liberated in the process is probably manifest in chloritization and sericitization. With respect to the latter there is often an enrichment in potassium and a consistent increase in the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio as the sulphide bodies are approached (Boyle, 1974).

Determination of the exact age of the pyritic, copper-zinc sulphide bodies with respect to the deposition of the enclosing volcanics and sediments, the intrusion of gabbro and diorite sills and dykes, the formation of porphyries, and granitization and metamorphic events is difficult, yet critical, in discussions concerning the origin of the deposits. For some orebodies there is no problem; these unequivocally cut the volcanic flows and sills at high angles and are related to fractures initiated by folding or faulting of the greenstone belts. A good example of this type of orebody is the Opemiska massive copper sulphide deposit, Chibougamou, Quebec (Derry and Folinsbee, 1957). For other orebodies, especially the stratiform type, there is much argument as to when they were formed. In certain high grade metamorphic terranes, especially in the Archean sedimentary belts, some of these stratiform bodies cut granite dykes, and others are younger than pegmatite dykes and sills, sulphides being abundantly developed in the highly altered granitic rocks. A typical example of this type of deposit is the former Sherritt Gordon orebodies in northern Manitoba (Farley, 1948), where the ore occurs in stratiform pegmatite sills injected along sedimentary and volcanic beds. Where the massive sulphide bodies are developed in breccia pipes the facts are often complicated. Most deposits cut and appear to offset or replace the earliest generation of gabbro and diorite dykes and sills but are themselves cut in places by later generations of dykes of similar composition and often by late quartz-feldspar dykes. At Flin Flon, the diorite sills within the ore zone are only partly altered

to schist and replaced by ore, the more massive parts remaining as horses" and "small dykes of feldspar porphyry cut the ore in the upper part of the mine" (Koffman *et al.*, 1948). However, Koo and Mossman (1975) observed that: "Several sills and dykes of metadiorite up to 30 metres thick cut the ores. Fine-grained chilled margins up to 1 metre wide developed in meta-diorite against massive ore, and commonly these contacts are sheared. The Boundary Gabbro also intersects the massive ore and effects of weak shearing are evident along the contacts. Minor veins of quartz, carbonates, sericite and/or sulfides occur in unsheared wall rocks and dikes around orebodies".

In the Rouyn-Noranda area interesting relationships with respect to dykes and orebodies are present. At the Normetal mine the massive sulphide bodies penetrate and alter massive porphyritic rhyolite which cuts sheared rhyolite agglomerates also replaced by sulphides. The sulphide bodies in turn are cut by a late diabase dyke (Brown, 1948). At the Aldermac mine Hawley (1948) observed: "The ore is clearly later than the quartz diorite-gabbro intrusives It is also later than the main porphyry stock, and from detailed underground studies is post-syenite-porphyry dykes". At the Horne Mine, the great massive sulphide bodies were formed as a consequence of a long period of complex mineralization stages, numbering at least three (Price, 1934, 1948). There has long been argument about the precise age of the Horne sulphides, some saying that they are older than the late diabase and others that they are younger. The argument is documented by Suffel (1935) and Wilson (1941). The writer's observations in the Rouyn-Noranda area suggest that the sulphide ores are at least in part younger than some of the early gabbro and diorite dykes because these are altered and mineralized in places. There are, however, some later dykes that seem to cut across the ores. With respect to the late diabase it appears that this rock cuts across the ores. There is no doubt, however, that there is late chalcopyrite in cross-faults in the diabase, but this is probably remobilized material as suggested many years ago by Brown (1948) who drew this inference from heating experiments by Professor Hawley. With respect to the granite in the Noranda area there is no doubt that some of the chalcopyrite, pyrite, and gold mineralization is later than this rock. At the Powell Rouyn mine and Don Rouyn prospect the shears and veins containing quartz, chalcopyrite, pyrite, and gold cut the Powell granite. Elsewhere, chalcopyrite in thin seams can also be seen cutting this granite. Finally, the relationships in the Chibougamau area are of particular interest. At the Campbell Chibougamau Mines, Malouf and Hinse (1957) state: "The dykes are a common feature throughout the anorthosite mass. They appear to be concentrated along the main shear zone, and comprise approximately 30 per cent of the rock in the area of the main workings. Dyke types identified to date include granite quartz-feldspar porphyry, feldspar porphyry, and diorite, in widths up to 40 feet. They strike subparallel to the shear, with dips between 55 and 70 degrees, north and

south. All are earlier than the final shearing and the ore, and they appear to have played a considerable part in ore localization".

Through the years I have had the opportunity to examine the dyke-sulphide ore relationships at some of the deposits mentioned above and at numerous others of various geological ages in different parts of the world. My observations indicate that most of the massive sulphide bodies in volcanic and sedimentary terranes are post-early gabbro, diorite, and quartz-feldspar dykes but commonly pre-late gabbro, diabase, and quartz-feldspar dykes. In places some of the massive parts of the orebodies are post-granite and pegmatite dykes or sills.

The age of the main masses of sulphides in the massive, copper-zinc orebodies with respect to the shearing, schisting, and brecciation of the zones in which they occur is often difficult to establish without detailed and prolonged observation. In many bodies particles of unreplaced schist occur in nearly massive ore whereas in others all degrees of replacement of schist fragments, breccia fragments, sheared rock, pieces of graphitic and cherty sedimentary rock, and blocks of all types of host rock can often be seen deep within the sulphide masses. In the Cuprus deposit in Manitoba for instance pieces of isolated graphitic tuff are caught deep within the massive sulphides (Cairns *et al.*, 1957); in the Kidd Creek deposit the writer observed isolated tabular pieces of graphitic schist strung out through the great sulphide lenses which are obviously unreplaced fragments of a once continuous bed. This is confirmed by Walker *et al.* (1975) who state: "The stratigraphic interval occupied by the massive sulphides is distinguished by the presence of discontinuous stratiform segments (which may represent a formerly continuous layer) of carbonaceous argillite and chert". All of these observations indicate that most of the bodies were formed during the period of shearing, schisting, and brecciation of the sites in which they occur. As mentioned previously some bodies show the effects of late shearing, schisting, or brecciation, but this is quite normal considering the tectonic environment in which most of these bodies were formed.

The data on the age of the massive sulphide bodies with respect to the Archean gold-quartz deposits are often inferential and equivocal since the two types of deposits do not often occur in cross-cutting relationships. The reasons for this interesting fact are not entirely clear. The principal reason may be structural, the massive sulphide bodies being formed in structures related to the early period of tectonism in greenstone and sedimentary belts and the gold-quartz deposits in structures related to the late periods of tectonic activity. At the Horne Mine in Quebec, Price (1934, 1948) found that the gold is late and may belong to a period of mineralization distinctly later than the pyrite-pyrrhotite-chalcopyrite stage. Space does not allow documentation of the data here, but the writer's observations suggest that there are at least two stages of gold mineralization in the massive sulphide bodies, one early and coeval

with the pyrite, arsenopyrite, and chalcopyrite and one later in the form of native gold and tellurides, commonly in small fractures often containing some quartz or carbonate. The last period may be related to the gold-quartz stage of mineralization in Archean belts which in most places is late, in part post-quartz-feldspar porphyry dykes, post-granite dykes, and post-granitic (Kenoran) stocks. With respect to the massive sulphide bodies and gold-quartz deposits it is interesting to note that the Au/Ag ratios of the two types of deposits are different. On a statistical basis the ratio for the sulphide ores is generally much less than 1, averaging about 0.025; in the gold-quartz deposits the ratio for the ores is generally much greater than 1, averaging about 3.6. This indicates that the general mobility of gold during the formation of the late stage gold-quartz mineralization has been considerably greater than that of silver, and *vice versa* during the earlier mineralization which led to the formation of the massive sulphide ores¹.

The origin of the Archean (and younger) massive pyritic, copper-zinc sulphide deposits, especially those in volcanic terranes, is the subject of much controversy. Some investigators see them as epigenetic deposits; others as essentially syngenetic (exhalite, synvolcanic) bodies. The list is legion of these who support the first hypothesis; likewise, many have supported the latter since about the turn of the century. More recently Oftedahl (1958) has reintroduced the exhalative sedimentary theory, and Ridler (1971), Sangster (1972), and Hutchinson (1973) have amplified it and given many examples of deposits throughout the world, which in their opinion are formed in this manner. As noted by Ridge (1974) the new exhalative theory was not greeted very enthusiastically at its birth or rather rebirth. It stirred up debates on many thorny subjects which were commented on by Kautsky (1958), Landergren (1958), Marmo (1958), and Kullerud *et al.* (1959). Most of the contentious points raised have not yet been satisfactorily answered by the exhalationists. As conceived by the syngeneticists the sulphides were laid down in a sedimentary manner as a result of exhalative volcanic processes, or as an alternative, the masses were deposited as a replacement of unconsolidated or slightly consolidated sediments. Later the deposits are supposed to have been metamorphosed and sheared or otherwise deformed, and the resulting textures in both the enclosing rocks and deposits are said to reflect these processes. Ignored or circumvented by circuitous reasoning is nearly a century of research on these

types of deposits, particularly that concerned with the timing of mineralization, structural localization of the bodies, discordant relationships, the fact that some occur in sedimentary terranes far from volcanic centres, the criteria of replacement, paragenesis of minerals, zoning of elements within individual bodies, wall-rock alteration phenomena, trace element distributions in the wall rocks, the evidence from hot spring and fumarole studies, the geochemistry of the metals entering aqueous environments, and a host of other troublesome facts, only a few of which can be mentioned.

Analogies between massive sulphide bodies and the metalliferous sediments of the Red Sea are often mentioned, but in reality there is no analogy. The Red Sea sediments contain only disseminated sulphide material in a matrix of siliceous, ferriferous, and carbonate oozes and muds. Their lithification might give deposits like the Kupferschiefer or White Pine Michigan copper deposits, not massive sulphide bodies. The source of the metals in the massive sulphide bodies is said to be fumaroles or submarine hot springs. But the literature and the writer's observations suggest that these phenomena are rather poor sources of the metals – sulphur and pyrite, yes – but the base metal sulphides and particularly silver and gold, no. There are no records of massive copper-zinc sulphide bodies being produced at the orifices of present-day fumaroles or hot springs, a circumstance that is difficult to ignore unless the doctrine of uniformitarianism is dismissed. Compilations based on the worldwide analyses of the water of hot springs and fumaroles, shows a general average of about 0.01 ppm Ag and 0.0003 ppm Au – hardly sufficient to produce the enormous amounts of silver in a deposit such as the Kidd Creek sulphide body at Timmins or the content of both gold and silver in deposits such as those at Noranda and Flin Flon. Another problem with submarine fumaroles and hot springs is identifying these phenomena in the rocks as mentioned in the section on iron formations.

Some of the massive pyritic, copper-zinc sulphide deposits have a stratiform aspect, but here again the details are often troublesome in proving a sedimentary origin. Many deposits, in detail, exhibit discordant relationships, and frequently tongues and the tails of the deposits run off across the strata. In Archean greenstone and sedimentary belts, and indeed in most eugeosynclines that have been mineralized regardless of age, there are usually two main periods of structural activity which yield specific types of structures. One period is early and is coincident with the folding of the volcanic and sedimentary rocks. During this period, zones of shearing, fracturing, and faulting occur mainly parallel to the bedding planes and grain of the country, particularly in tuffs, pyroclastics, and other weak or brittle beds such as quartz-feldspar porphyry flows. The other period of activity is later, the orientation of the forces being such that fractures, faults, and shear zones are formed across the strata and the grain of the country. The first period results in dilatant zones in which massive sulphide bodies and bedded veins are deposited; the later period gives rise to dilatant zones in which typical gold-quartz and

¹ Certain Archean gold-quartz deposits have Au/Ag ratios that are much less than 1. These contain abundant silver minerals. They are relatively rare in most greenstone and sedimentary terranes. A full documentation of the relationship of the Au/Ag ratios in Archean deposits is contained in Boyle (1979).

vein-like polymetallic deposits (commonly massive sulphides) are precipitated. As reiterated by the writer (Boyle, 1965) massive sulphide deposits are often "conformable" or "stratabound" because the structures (dilatant zones) in which they occur are conformable or stratabound. Their stratabound nature and morphology is, therefore, a result of tectonics and dilatancy and not the result of sedimentation processes or a modification thereof.

The relationships of the massive sulphide bodies to the various types of intrusive dykes and sills has been discussed above. In most cases it is apparent that the volcanic rocks and their associated sediments were in place and were intruded by various types of dykes and sills before the sulphide bodies were formed.

Most massive sulphide bodies in Archean rocks are marked by alteration zones, many of which envelop the ores and present a fair to good bilateral symmetry. Likewise, the trace element (Cu, Zn, Ag, Hg, etc.) distribution in the aureoles exhibits good bilateral symmetry in some deposits; in others the footwalls show the greatest enrichment; and in still others the hanging-wall exhibits this phenomena. Space does not permit a detailed discussion, but the interested reader should examine carefully the works by Nairis (1971) on the Rudtjebäcken deposit in the Skellefte district of northern Sweden; Nilsson (1968) on the Boliden deposit, Sweden; Sakrison (1966) on the host rocks of Lake Dufault mines, Quebec; Descarreaux (1973) on the Abitibi volcanic belt in Quebec; and Anderson and Creasey (1958) for some of the Jerome orebodies in Arizona. Aureoles of the type described in these papers do not occur in sedimentary deposits, at least not in the writer's experience.

Some investigators claim to have discovered soft sediment structures in the sulphide bodies. The evidence in the writer's opinion is equivocal. Structures such as slumps can as equally well be interpreted as due to intimate replacement or to post-deposition stress on the sulphides. Load features if they occur must be rare for the writer has not seen any of these in the many deposits that he has carefully examined. Graded bedding is rare, and where present it can best be interpreted as due to replacement of graded bedded greywackes. The writer has not seen intersulphide bedding by tuff, greywacke, etc. where one could say for certain that changes in the sedimentary processes had taken place. The so-called bedding or sedimentary banding in the sulphides is tenuous in most places and not easily followed for any distance. In many cases it merges into banded greywackes or tuffs and is obviously a replacement phenomena; in some deposits it is due to shear banding. The writer has not observed features such as rills and ripple marks in any of the sulphide deposits he has examined. Some bodies contain botryoidal (buckshot) pyrite, but the origin of this type of pyrite is highly controversial. The writer has seen it in vein deposits, where it is probably due to gel consolidation processes.

In recent years there have been a number of papers which purport to prove that the massive sulphide deposits have been metamorphosed, and that structures

such as kink folds, small drag folds, schistose appearance, etc. have been impressed upon them after deposition. Bertrand and Hutchinson (1973) and McBride (1974) attempted to show that this was the case at the Normetal mine, Northwestern Quebec, but Brown (1973) and Cabri *et al.* (1974) have disputed this. Numerous other papers could be quoted, but most deal with deposits of Phanerozoic age. As a comment on all papers that seek to show that the massive sulphide bodies have been metamorphosed, the writer finds the criteria often puzzling and certainly equivocal. So far as I am aware there are no criteria by which one can tell whether a sulphide mass has been metamorphosed or whether the fabric in the sulphide body represents replacement of a pre-existing fabric in the rocks. Worse still, it is not possible in my experience to distinguish between the effects of metamorphism on a sulphide body and those that obtain as a result of the concentration of the body in dilatant zones (sheared, dragfolded, schistose zones) while the metamorphic fabric was being impressed on the rocks. Since most massive sulphide bodies were probably deposited in dilatant zones during the period of maximum development of shearing, schistosity, etc., it is logical to expect that some bodies would carry a tectonic imprint somewhat similar to that of the enclosing rocks. Continued dragging, contortion, and shearing after the initial deposition of the sulphides may produce part of the fabric, but this is normal in a tectonic environment and does not in any way prove that the sulphide bodies are of syngenetic origin.

If the source of Cu, Zn, Pb, Ag, Au, etc. in the massive sulphide deposits is not exhalative whence did these metals derive? The answer is not simple, but there are some indications that most of the metals came from the greenstone and sedimentary piles and were concentrated in structurally induced dilatant zones as the result of diffusion during regional metamorphism and granitization processes. In support of this concept one only need refer to the enormous amounts of metals lost during the progressive granitization and metamorphism of greenstone and sedimentary piles (Table 6). It is suggested that these metals moved by diffusion in advance of the thermal front induced by granitization. Where suitable dilatant zones appeared during structural deformation, these provided low chemical potential sinks in which the various sulphides were deposited.

Carbonatization of volcanic piles as mentioned above may also have provided large amounts of a variety of elements (Table 7) which when set free during the process migrated laterally or vertically and were precipitated in available dilatant zones.

Massive and disseminated nickel-copper-cobalt sulphide deposits:

The massive and disseminated pyrrhotite-pyrite, nickel-copper-cobalt sulphide deposits have a restricted occurrence in Archean rocks. Many are essentially lenses, irregular bodies, and pipes of nearly massive

sulphides in shears, faults, breccia-zones and disrupted or sheared beds commonly in or near basic and ultrabasic flows, sills, dykes, and stocks. Others are irregular, disseminated sulphide bodies or zones generally in or near ultrabasic or basic sills and irregular masses. A few deposits of each type have a stratiform aspect. Their exact age is commonly difficult to ascertain especially those bodies in or near ultramafic and mafic rocks that occur at or near the joins of geological provinces (e. g. Thompson, Manitoba). Some of these deposits may be younger than Archean.

The sulphides composing the bodies are commonly present in massive aggregates or as disseminations and veinlets in altered, sheared, and fractured rock. Replacement features abound. The mineralogy is relatively simple comprising pyrrhotite, pentlandite, chalcopyrite, and pyrite with minor amounts of arsenopyrite, sperrylite, and a variety of other sulphides and arsenides. The principal elements concentrated include Cu, As, S, Ni, Co, Fe, and certain platinumoids. Nickel, copper and the platinumoids are the key elements in the genesis of these deposits. The wall-rock alteration effects are generally those of chloritization, serpentinization, and the development of talc, actinolite, and pyrite. Silicification and carbonatization, particularly the latter, are minor in most occurrences. Some orebodies exhibit remarkably little alteration of any kind. The features and setting of some of these deposits will serve to illustrate their general nature. More detailed accounts of the Canadian deposits may be found in the papers by Cameron *et al.* (1971) and Naldrett and Gasparrini (1971).

The nickel-copper-cobalt sulphide deposits at Lynn Lake, northern Manitoba comprise three types – massive sulphides, disseminated sulphides, and stockworks of sulphide stringers – all mainly in intensely fractured basic intrusives (gabbro, norite, diorite, peridotite, and quartz-hornblende diorite) that intrude the Archean Wasekwan volcanic series (Ruttan, 1957; Milligan, 1960). The principal sulphides are pyrrhotite, pentlandite, chalcopyrite, and pyrite, which replace all types of silicate minerals in the basic rocks. The alteration associated in part with the sulphides comprises mainly the development of actinolite, talc, and chlorite. The sulphides post-date minor granite, pegmatite, and feldspar porphyry dykes that cut the basic intrusives. These features have led Ruttan (*op. cit.*) and Milligan (*op. cit.*) to the conclusion that the Lynn Lake nickel ores were formed long after the consolidation of the basic-ultrabasic rocks with which they are associated. The Lynn Lake ores yield nickel, copper, cobalt, and minor amounts of gold and platinumoids.

The nickel deposits of the Thompson-Moak Lake Belt of Manitoba occur in the zone marking the boundary between the Superior and Churchill geological provinces of the Canadian Shield (Davies, 1960; Wilson and Brisbin, 1961; Zurbrigg, 1963). The folded country rocks are essentially gneiss and amphibolites with linear zones of metasediments (quartzites, greywacke, limestone, skarn, iron formation, etc.) and metavolcanics (greenstones) containing lenses and irregular bodies of altered peridotite. Granitic bodies intrude all of these rocks at

several places. The nickel orebodies are disseminations and stringers of sulphides in serpentinized peridotite and elongated, essentially stratiform, massive sulphide bodies and zones of sulphide stringers in drag-folded biotite schist, gneisses, and metasediments. The ores are composed mainly of pyrrhotite, pentlandite, and pyrite with minor amounts of chalcopyrite and marcasite and trace amounts of nickel arsenides. Replacement of the host rocks by these various minerals abound, but the alteration effects are not notable. They include the development of biotite and minor chloritization. The sulphides are post-pegmatite in age. The ores yield nickel, cobalt, and platinumoids; they are low in copper content.

The nickel deposits at Gordon Lake in northwestern Ontario are sulphide disseminations, stringers, and massive tabular bodies in shear zones in or near highly altered peridotites that seem to be part of the eastern extension of the Bird River Sill complex. The principal sulphides are pyrrhotite, pentlandite, chalcopyrite, and minor cobaltite. These cut pegmatites which in places intersect the altered peridotites. The ores yield nickel, cobalt, copper, and platinumoids.

The Cuniptau deposit near Goward, Ontario is in schistose zones that cut irregular serpentinized bodies which appear to be intrusive into Archean greenstones. The principal hypogene sulphides are pyrrhotite, chalcopyrite, pentlandite, pyrite, magnetite, sphalerite, marcasite, hematite, calaverite, sperrylite, and violarite, the last mainly of supergene origin (Sandefur, 1942). These minerals occur as disseminations, stringers, and irregular masses in the schistose zones which are marked by the development of serpentine, chlorite, talc, carbonates, and white micas. The ores yielded copper, nickel, platinum, gold, and silver.

The low grade nickeliferous Dumont ultramafic body, some 60 km northeast of Rouyn-Noranda, is a sill-like lens in greenstones (Eckstrand, 1975). Much of the sill is heavily serpentinized, and there are zones along the footwall in which talc and carbonates are extensively developed. The nickeliferous opaque minerals in the ultramafic body include magnetite, pentlandite, heazlewoodite, awaruite, and traces of millerite. These occur as finely disseminated grains spread throughout the serpentinite and as steeply dipping zones of disseminated intercumulus blebs mostly near the central part of the sill. Eckstrand (*op. cit.*) considers that the opaque nickel mineral assemblage was derived mainly as the result of serpentinization and talc-carbonate alteration of nickel silicates (olivine).

The Eastern Goldfields of Western Australia contain a number of recently discovered Archean nickel deposits in greenstone belts, particularly at Kambalda, Scotia, Nepean, Carr Boyd Rocks, Mount Windarra, Mount Clifford, Agnew, Mount Sir Samuel, and Mount Keith. Published descriptions and personal communications indicate to the writer that these deposits are essentially the same as most of those of Archean age in the Canadian Shield.

The Kambalda nickel deposits are associated with an Archean mafic and ultramafic complex in a greenstone and sulphide-rich sedimentary assemblage

(Woodall and Travis, 1969; Naldrett and Arndt, 1975). The zones of nickel-iron sulphide mineralization are located in or near the lower part of the ultramafic bodies (flows). Younger sodic granites and porphyritic sodic rhyolite dykes and sills intrude the greenstone and sedimentary rocks, ultramafic complex, and the sulphide ores. The principal sulphides are pyrrhotite, pentlandite, violarite, chalcopyrite, and pyrite. These occur in stringer zones, as massive aggregates, banded in places, and as disseminations. Iron, nickel, copper, and cobalt are the principal elements concentrated in the orebodies (Ewers *et al.*, 1972). The ultramafic complex exhibits a considerable degree of serpentinization and development of talc-carbonate.

The nickel deposits of the Carr Boyd Rocks complex in Western Australia are associated with a small layered ultramafic to mafic intrusive complex of Archean age in greenstones and associated sediments (Purvis *et al.*, 1972). The hypogene sulphide ore bodies comprise disseminated pyrrhotite, pentlandite, pyrite, and chalcopyrite in breccia pipes of bronzite pegmatoid that cross-cut the rocks of the complex. All of the rocks are extensively altered to serpentine-tremolite-actinolite-talc-chlorite rocks. The principal elements concentrated in the deposits are iron, nickel, cobalt, copper, and sulphur.

The origin of nickel sulphide deposits such as those just described has been variously interpreted. Many geologists have advocated magmatic processes among which crystal settling has appealed to most. Others have considered that magmatic hydrothermal activity has given rise to the deposits, and still others have suggested that alteration (serpentinization) is the agent mainly responsible for the concentration of the sulphides.

Some of the disseminated and massive sulphides zones in the basal members of certain mafic and ultramafic sills and irregular bodies may owe their origin to magmatic processes, but it is doubtful that economic concentrations form in this manner. Similarly, hydrothermal processes related to granitic intrusion seem incapable of producing these nickeliferous orebodies. If they do it is especially difficult to comprehend why these nickel-cobalt orebodies are always in or near mafic or ultramafic rocks that were initially enriched in nickel, cobalt, and platinoids.

The writer's observations and a literature review of the Archean nickel-copper-cobalt sulphide bodies show that certain geological and geochemical parameters are usually present in locales where orebodies are present. These are:

(1) Presence of a greenstone complex which may have been the main source of Cu, Ag, Au, and S. These complexes are generally highly metamorphosed, often granitized, and commonly carbonatized.

(2) Presence of a sedimentary complex often greatly enriched in sulphur.

(3) Presence of mafic and ultramafic sills, stocks, and irregular bodies that are commonly enriched in nickel, cobalt, and platinoids.

(4) Extensive zones of alteration manifest in greenstones, sediments, and mafic and ultramafic rocks by hydration, carbonatization, chloritization, and the development of talc. Serpentinization, talcification, and carbonatization are especially marked in the mafic and ultramafic bodies or rocks.

(5) Development of dilation zones such as shears, faults, drag folds, breccia zones, etc. which are late events in the metamorphic and tectonic history of the Archean terrane in question. These dilation zones and their contained sulphides often cut late granite dykes, pegmatites, etc.

In the writer's opinion the last parameter effectively eliminates the possibility that the iron-nickel-cobalt sulphides were derived by magmatic processes associated with the crystallization of the mafic-ultramafic complexes.

The various parameters discussed above suggest that most of the Archean nickel-cobalt-copper sulphide deposits are the result of diffusion processes promoted by regional metamorphism and tectonic dilation processes. It seems nearly certain that the nickel, cobalt, and platinoids were derived from the mafic and ultramafic rocks largely as the result of serpentinization, talcification, chloritization, and carbonatization. During these processes the ferride elements and platinoids were released from various silicates, oxides, and sulphides and migrated into local dilation zones marked by shearing, faulting, brecciation, etc. Similar processes operating on the greenstones and sediments yielded gold, silver, and most of the sulphur. Tables 6 and 7 indicate the enormous amounts of constituents released during the various metamorphic processes mentioned above. In the case of the nickeliferous orebodies the conjunction of diffusion currents, one from the mafic-ultramafic rocks carrying nickel, cobalt, and platinoids and the other from greenstone and sediments enriched in sulphur, copper, silver, and gold, in the late dilatant zones, has given rise to the sulphide orebodies, some bearing the precious metals.

Disseminated and stockwork Copper-Molybdenum deposits in quartz-feldspar porphyries and granitic rocks

Many of the quartz-feldspar porphyries that occur in Archean greenstone belts and associated sedimentary belts are slightly enriched in copper, molybdenum, gold, and other metals. Many of these bodies are intrusive dykes or stocks; others are flows; and still others have a replacement origin as suggested in the first section of this paper.

In the Yellowknife area some of these porphyries are enriched in copper and molybdenum (Jolliffe, 1938; Boyle, 1961) (Table 5). These porphyries carry considerable amounts of pyrite and pyrrhotite and minor amounts of chalcopyrite and molybdenite (3R type) in places. These minerals appear to be original constituents of the porphyries, although in some bodies

there is a general enrichment of all of the various sulphides in quartz veinlets and in sheared parts of the porphyry masses.

In the McIntyre mine at Timmins, Ontario, the Pearl Lake quartz-feldspar porphyry is extensively sheared and highly altered as a result mainly of sericitization and carbonatization. Parts are also replaced by anhydrite and gypsum, two minerals that also occur in the gold-quartz veins of this mine (Langford and Hancox, 1936).

Pyrite is particularly common throughout the altered Pearl Lake porphyry and is locally abundant in zones in the McIntyre mine. In one of these zones chalcopyrite and bornite occur in veinlets and disseminations in schistose rock and along innumerable slips in sufficient quantity to constitute ore grade material (Griffis, 1962; Carter, 1967). There are in addition small amounts of hematite, magnetite, tetrahedrite, tennantite, molybdenite, native silver, native gold, and scheelite. Analyses done at the Geological Survey also show the ores to be relatively rich in bismuth (up to 275 ppm), but no bismuth minerals were seen. To the writer all of these sulphides, sulphosalts, gold, etc. appear to have been introduced, or what seems more probable rearranged within the immediate rock sequences. In this respect it is interesting to note that a number of the basic flows in contact with the porphyry are relatively rich in copper. One which is amygdaloidal contains, according to W. Fink and O. F. Carter (pers. comm.), up to 0.5 per cent Cu.

There are some facts about the McIntyre disseminated copper-molybdenum orebody that are of interest. According to the writer's observations and analyses and published accounts of metals won from the various orebodies in the McIntyre mine, silver is more abundant in the disseminated copper-molybdenum orebody than in the gold-quartz deposits. In the copper orebody the Au/Ag ratio is about 0.14 whereas in the gold-quartz deposits the ratio is about 5 in sympathy with the general overall ratio (7) in the Porcupine gold belt.

The reasons for these two, quite different ratios is uncertain, but they evidently reflect differences in the mobility of silver and gold during mineralization processes. This suggests two separate mineralization periods, one gold-rich and the other highly argentiferous. In this respect it is of interest to note that a number of the deposits in the Porcupine gold belt are highly argentiferous. On the eastern extension some of the orebodies of the Ross mine have an unusual Au/Ag ratio (<1), and there are two mineralization stages (Jones, 1948). The first is a blue quartz with pyrite, chalcopyrite, sphalerite, galena, and gold, and the second comprises quartz-dolomite veins containing pyrite, sphalerite, galena, gold, tennantite, chalcopyrite, and native silver. The writer has also observed nickel-cobalt arsenides in the second stage of mineralization. On the western extension of the belt the Kidd Creek massive sulphide deposit is especially rich in native silver which appears to be very late in the paragenetic sequence. All of this evidence together with the fact that the silver-rich deposits are also accompanied by enrichments of arsenic, antimony, bismuth, and mercury

suggest a mineralization epoch which may be related in some manner to that at Cobalt, Ontario. Admittedly this is speculative, but the thought should be kept in mind when prospecting in the Porcupine gold belt.

In Archean greenstone and sedimentary belts numerous types of porphyries and granitic stocks exhibit weak impregnations with copper, molybdenum, tungsten, gold, and silver minerals. A few examples will suffice to illustrate this point. In the Setting Net Lake area of Northwestern Ontario, Ayers *et al.* (1973) and Wolfe (1974) have described an extensive zone of molybdenum-copper dissemination in a small (5.7 km²) epizonal pluton of equigranular to porphyritic granodiorite-quartz monzonite composition that intrudes Archean greenstones and metasediments. Narrow quartz veins fill joints in the pluton over a considerable volume and carry small amounts of molybdenite, pyrite, and chalcopyrite. These three minerals also occur as minor disseminations in the granodiorite-quartz monzonite rock. The average grade of a part of the mineralized zone is given as 0.06 per cent MoS₂ with minor copper. The alteration associated with the mineralization is sericitization and albitization of plagioclase, chloritization of biotite, and introduction of pyrite. The auriferous orebodies in porphyritic syenite in both the Young-Davidson and Matachewan Consolidated mines at Matachewan, Ontario were weakly mineralized with disseminated pyrite, chalcopyrite, galena, molybdenite, and scheelite over large volumes of rock (North and Allen, 1948; Derry *et al.*, 1948). The La Corne and the Indian Molybdenum deposits in Preissac township, Abitibi county, Quebec are extensive stockworks of quartz veins containing muscovite and feldspars in granite and granodiorite (Norman, 1948a, 1948b; Vokes, 1963). In these stockworks molybdenite and minor amounts of bismuthinite occur both in the quartz and as disseminations in the granitic rock. There are only scattered grains of pyrite, chalcopyrite, bismuthinite, bismuth, fluorite, beryl, and scheelite in these deposits. Finally, in many of the Archean belts containing massive sulphides there are often shattered zones or stockworks in the granitic stocks that are weakly mineralized with chalcopyrite and molybdenite and occasionally with bismuthinite, gold, etc. An example of this is the Powell granite northwest of Rouyn-Noranda. In many places this rock contains shears and small faults containing quartz, pyrite, chalcopyrite, gold and in a few places molybdenite as well. In fact, the Powell Rouyn gold mine is developed in this granite, and its ores contain up to 5 per cent combined pyrite and chalcopyrite (McMurchy, 1948). In places there are seams of nearly solid chalcopyrite in this granite.

The origin of all of these various disseminated and stockwork copper-molybdenum deposits is speculative. There is some evidence that many of the quartz-feldspar porphyries contained an initial complement of the metals, and that these were concentrated into dilatant zones or shoots marked by extensive fracturing, shearing, or brecciation. Some of the granitic bodies, however, appear to have been poor sources of the metals. In this case the volcanic and sedimentary piles into which the stocks were intruded probably supplied the metal,

concentration taking place in dilatant zones in the granitic bodies marked by shearing, fracturing, and brecciation.

Chromite Deposits

The Archean chromite deposits and occurrences are restricted entirely to ultramafic-mafic dykes, sills, flows, and irregular bodies. Four types of occurrences are common: dense chromite bands; disseminated chromite in irregular bands and layers; disseminated chromite in irregular altered zones; and stringers of chromite in irregular altered zones and layers. The principal mineral in all of these occurrences is chromite which is associated with various pyroxenes, amphiboles, chlorite, talc, serpentine, magnetite, carbonates, and minor sulphides (mainly pyrite and pyrrhotite but occasionally also nickel sulphides or arsenides such as rammelsbergite).

The chromite bands, layers, and disseminations occur in various parts of the ultramafic-mafic bodies. In some places they occur at or near the base of the sills. At others, e.g. Bird River, Manitoba, the chromite bands occur near the centres of the composite sills (Bateman, 1943). In the irregular ultramafic-mafic bodies the chromite may be disseminated through various parts of the altered bodies or in segregated bodies in the form of irregular and vein-like masses commonly near the contacts of the ultramafic-mafic bosses and irregular bodies as at Obonga Lake, Ontario (Graham, 1930).

The chromite deposits of Southern Rhodesia in the neighbourhood of Selukwe occur in serpentine, talc schist, and chlorite schist (altered basic-ultrabasic bodies) in the Basement (Archean) Complex. The deposits are irregular, lenticular, ovoid, and vein-like bodies of massive and disseminated chromite in silicified serpentine, talc schist, and carbonated talc schist. Similar deposits occur in the Mashaba, Berlingue, and Gwanda districts (Pelletier, 1964).

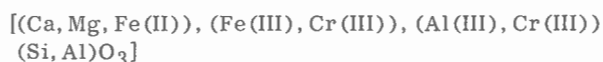
The Great Dyke of Southern Rhodesia, which extends for some 332 miles, cuts mainly Archean granite. Its age is uncertain, but some geologists think it may be late Archean (2.5 billion years). According to Worst (1964) the dyke consists of four igneous complexes that exhibit a marked layering and rhythmically repeated zoning of component rock types. Gabbroic rocks overlie the uppermost pyroxenite in each complex. Numerous stratiform seams of chromite ranging in thickness from an inch to eighteen inches run for many miles through individual complexes. They usually occur at the base of a zone consisting of dunite and harzburgite followed upwards by pyroxenite. The chromite occurs in relatively massive form and as close-packed disseminations. The upper seams of the complexes (chemical grade chromite) contain chromite intimately admixed with olivine and pyroxene; the lower seams (metallurgical grade chromite) have serpentine hanging walls and footwalls. Some of the hanging-wall serpentinites have abundant disseminated chromite. Worst (1964) considered that the chromite seams in the Great Dyke were formed by magmatic segregation. De Kun (1965), on the other

hand, outlined a complex history for the dyke during which extensive serpentinization took place.

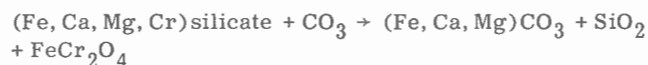
In India numerous deposits and occurrences of chromite occur in the Basement (Archean) schists and gneisses. The deposits in the Singhbhum District of Bihar occur in altered peridotites in Dharwarian slates, shales, and quartzites (Mahadevan, 1929; Krishnan, 1953). The chromite occurs as segregations and in vein-like bodies. Elsewhere in the Archean of India there are similar deposits in highly altered ultrabasic rocks in Mysore and Madras.

A few of the chromite bands and segregations seen by the writer in Archean ultrabasic-basic sills and irregular masses lie near the basal parts of the bodies and appear to represent magmatic segregations attendant upon the crystallization of the ultramafic rocks. By far the largest number of Archean chromite occurrences, however, lie in or near zones of alteration in the ultramafic-mafic rocks particularly in or near zones of serpentinization, talcification, chloritization, and carbonatization. These chromite occurrences were evidently derived by metamorphic processes.

Numerous silicates, on their crystallization from magmas, incorporate considerable amounts of chromium in their lattice (up to 2 per cent in some pyroxenes). The substitution of chromium for iron and aluminum in such silicates occurs as shown below for a hypothetical pyroxene.



When silicates such as this are hydrated or carbonated the resultant products cannot accommodate equivalent concentrations of chromium in their lattices. Consequently the element is liberated and mobile (Tables 6 and 7), crystallizing in appropriate sites as chromite. Iron may follow a similar course concentrating as magnetite. The reactions to produce segregations and bands of chromite and magnetite in this manner are complex and not readily set down in appropriate stoichiometric equations. Schematically, however, they may be represented as follows:



Alteration processes appear to endow chromium and iron with considerable mobility since one commonly finds veinlets and segregations of chromite or magnetite some distance (tens to hundreds of feet) from the main foci of alteration.

Asbestos Deposits

Most of the Archean ultramafic flows, sills, and irregular bodies are highly serpentinized and commonly contain some asbestos fibre (chrysotile). Only in a

few places, however, is the fibre in sufficient quantity to constitute asbestos orebodies. One good example of this is the Munro mine in Munro Township, Ontario described by Hendry (1951) and Satterly (1952). The Munro asbestos orebodies occur in a differentiated mafic to ultramafic composite sill-like body which can be traced for about three miles. The sill lies in a sequence of medium to basic volcanic rocks some of which contain ultramafic members with spinifex texture (Pyke *et al.*, 1973; Fleet and MacRae, 1975). The ultramafic members of the composite sill are highly serpentinized and intersected by innumerable reticulating veinlets of chrysotile asbestos. Where the latter are sufficiently developed over large volumes of rock they constitute orebodies. On the southeast border of the largest orebody and in places flanking it at depth there are extensive zones of carbonatization in which the serpentinites and volcanics are nearly completely altered to talc-carbonate schist. Such carbonatized zones are also widespread in other parts of the area affecting large volumes of both the basic volcanics and their associated sediments.

Chrysotile asbestos deposits and occurrences are common in certain parts of the southern part of the African Shield. Anhaeusser (1974) grouped these into three varieties in order of decreasing age: (1) layered complexes associated with basaltic and perioditic komatiite extrusives, and forming part of the Lower Ultramafic Unit of southern African greenstone belts, (2) layered ultramafic bodies associated with the intermediate to acid volcanic rocks that constitute part of the Mafic-to-Felsic Unit of greenstone belts and, (3) ultramafic intrusive bodies that post-date the greenstone belts, but which are still affected by Archean tectonic disturbances that arise from the emplacement of granites.

The deposits and occurrences in the layered ultramafic complexes of the Barberton Mountain Land in South Africa (Groups 1 and 2 above) include the Stolzburg ultramafic body, the Koedoe ultramafic body, occurrences in the Jamestown Schist Belt, the Havelock and Msauli asbestos deposits, the Kalkkloof ultramafic body and the Rosentium ultramafic body. Most of these asbestos deposits and occurrences are complex and irregular stockworks of fibre in highly serpentinized parts of the layered complexes, mainly in the dunite, peridotite, or harzburgite layers and zones (Van Biljon, 1964 and others; see the bibliography in Anhaeusser, 1974). Carbonated talc and serpentine rocks occur in the immediate vicinity of most of the occurrences and deposits.

In Rhodesia, most of the asbestos occurrences are in the layered Mashaba igneous complex, the Shabani ultramafic body, and the Filabusi ultramafic complexes (Groups 1 and 2 above). The Shabanie asbestos deposits, the largest in Africa, are irregular stockworks and fibre zones in a sheet-like mass of serpentinized dunite completely surrounded by granite gneiss. Talc and talc-carbonate rocks are common in the footwalls of the deposits. Laubscher (1964) considered the Shabanie deposits to have been derived as a result of the action of hydrothermal solutions enriched in CO₂. These altered the dunite resulting in excess magnesium and

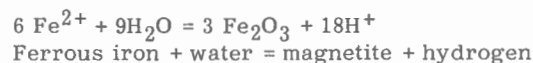
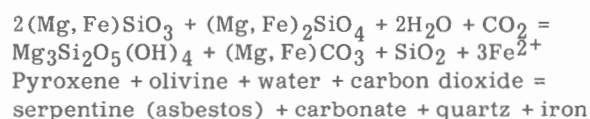
silica going into solution. The asbestos fibre grew from these solutions in available fractures.

Asbestos occurs in the Great Dyke of Rhodesia at numerous points (Anhaeusser, 1974). Most of the occurrences are in highly disturbed and broken zones in the vicinity of faults that have displaced the dyke laterally. At the Ethel asbestos mine the chrysotile fibre occurs in near-vertical seams concentrated in parallel, east-west trending zones on the southern side of a fault with a displacement of more than 300 metres. The wall rocks are mainly serpentine developed from harzburgite or dunite. Some brucite is intimately mixed with the fibre.

The Archean asbestos deposits and occurrences seen by the writer have a number of features in common: All of the asbestos-bearing ultramafic bodies are extensively hydrated (serpentinized) and generally highly fractured, the latter being related to regional faults mostly formed late in the tectonic history of the area. Carbonatization of basic lavas, associated sediments, and of the mafic-ultramafic sills and irregular bodies in places is usually marked near the asbestos bodies. These features suggest that hydration and carbonatization play a large part in the formation of the asbestos bodies.

Hydration and carbonatization of magnesium silicates such as olivine and pyroxene yield mobile Mg, Fe, and SiO₂ during the alteration processes. Where extensive dilation of the ultramafic bodies occurs these constituents are drawn into the fractures and small faults where the Mg, SiO₂, and OH (from water) combine as chrysotile; the iron is generally combined with oxygen as magnetite or hematite which commonly line the borders of the fractures or occur as central septa between the asbestos fibres.

Detailed equations cannot be written for the reactions that produce asbestos, but generalized reactions such as the following may be representative:



Other Industrial Minerals

A number of industrial minerals including feldspar, mica, and graphite are won from pegmatite and pegmatite-like bodies in Archean rocks in various parts of the world. The important mica pegmatites of the Nellore and Bihar belts in India (Ray, 1952) are apparently in Archean host rocks, but the pegmatites are evidently younger and probably of Proterozoic age (Pichamuthu, 1967).

Occurrences of talc have a relatively widespread distribution in Archean rocks being developed extensively in shear zones in magnesian volcanics and in alteration (mainly carbonated) zones in various types of ultramafic rocks of both intrusive and extrusive

origin. The origin of talc is essentially the same as that discussed for asbestos with the exception that there has been relatively little migration of the components of the mineral during alteration processes. Occurrences and deposits of talc are known in South Africa, Canada, India, and elsewhere.

Corundum and kyanite are developed in high grade Archean metamorphic terranes especially in rocks that were originally enriched in alumina such as certain sediments, aluminous volcanics, and certain aluminous ultramafic rocks. Deposits of crystal corundum and boulder corundum occur extensively in the Archean rocks of Rhodesia. According to Morrison (1972) and Anhaeusser (1974) the crystal corundum deposits owe their origin to: (1) the metamorphism of aluminous sedimentary rocks, (2) the desilication of pegmatites intrusive into hornblende and tremolite schists, (3) the metasomatism of amphibolites, biotite schists, serpentinites, and fuchsite mica schists during granitization, (4) the effects of granulite facies metamorphism on ultramafic rocks, on anorthosites, and on biotite schist relics in leuco-paragneisses. Morrison (op. cit.) noted that the boulder corundum deposits possessed the following features: (1) most deposits occur near greenstone-granite contacts or near intrusive mafic complexes or dykes, all of which provided a source of heat for the development of the corundum, (2) the corundum deposits form part of the lithological sequence and show no cross-cutting relationships with the country rocks, (3) the corundum commonly occurs as lenses within aluminous mica schists containing one or more of andalusite, chiastolite, sillimanite, and kyanite. Fuchsite, sericite, rutile, diaspore, and margarite frequently accompany the corundum, (4) the deposits occur with wall rocks that include ultramafic rocks (talc schists, serpentinites), banded iron formation, phyllites, and argillaceous metasediments (mafic tuffs), aluminous micaceous schists and hornblende schists or gneisses. He concluded that the boulder corundum deposits were formed as a result of the metamorphism of alumina-rich sediments (possibly bauxites).

Magnesite occurs mainly as an alteration product of ultramafic rocks in certain Archean terranes, in South Africa, Rhodesia, Canada, and elsewhere. Few of the deposits are of commercial importance.

Aggregate materials are obtained from Archean terranes in many parts of the world, as are also building materials such as granite, basalt, and slate.

Pegmatites

Granitic pegmatites are particularly common in some Archean terranes, most occurring in the high-grade metamorphic zones of the greywacke-slate sequences near their contacts with granitic bodies that have an intrusive aspect in places but were probably derived mainly by granitization processes. A few pegmatites occur in greenstone belts, mainly in the highly amphibolitized and granitized zones near their contacts with granodiorite and granite.

Most of the granite pegmatites are simple, being composed essentially of quartz, feldspars, and mica, often with tourmaline and small amounts of apatite, magnetite, and pyrite. Others are complex and often zoned, containing quartz, feldspars, micas, and one or more of spodumene, amblygonite, pollucite, beryl, tantalite-columbite, wadginitite, cassiterite, molybdenite, scheelite, wolframite, bismuth, bismuthinite, tourmaline, and many other rare minerals. The elements concentrated, in addition to the normal gangue elements, include one or more of: Li, Rb, Cs, Be, B, Sc, Y, La, rare earths, Sn, Ti, Zr, Hf, P, (As), (Sb), Bi, Nb, Ta, (S), Mo, W, F, Mn, and Fe. Those in brackets are generally local or rare.

Stanniferous pegmatites and aplites are relatively common in Archean terranes, particularly in Kenorane age granites and in their associated high-grade metamorphic rocks. In Canada such pegmatites occur mainly in the Slave and Superior provinces of the Canadian Shield, specifically in the region east of Yellowknife (Yellowknife-Beaulieu River district) and in eastern Manitoba (Red Sucker Lake and Bernic Lake districts). Most of these stanniferous pegmatites carry cassiterite as the main tin mineral; they are lithium-rich and generally contain abundant lithium minerals such as amblygonite, spodumene, and Li-mica. Further details are given by Mulligan (1975). In the African Shield, similar types of stanniferous pegmatites are widespread. Those in Swaziland are described by Davies (1964). Lithium minerals appear to be relatively rare or uncommon in these pegmatites. Cassiterite is the main tin mineral; it is closely associated with magnetite with which it is often intergrown.

Few of the bedrock stanniferous pegmatites and aplites are economic, but zones of these bodies commonly yield eluvial and alluvial deposits as in Swaziland (Davies, 1964) and in various other places in Africa including Nigeria, Zaire, Rwanda, etc. (Sainsbury, 1969). The age of many of the stanniferous granites, pegmatites, and aplites in the Precambrian of Africa appears to be in some doubt. The granites commonly intrude Archean rocks, but they may actually be of early Paleozoic age.

The origin of pegmatites has generally been attributed to magmatic processes, specifically to residual extracts heavily charged with mineralizers such as H₂O, F, P, and B. Some investigators have, however, considered pegmatites to be derived by metamorphic secretion processes, among them T. Sterry Hunt who advocated such an origin more than a century ago. Such an origin seems to be applicable to most Archean pegmatites that occur in metasedimentary terranes. Other granitic pegmatites, those that cut their granitic host rocks, seem to have been derived by diffusion of their constituents from the granitic rocks that were at relatively high temperatures but fully crystallized and consolidated.

In the Yellowknife area support for the metamorphic derivation of pegmatites from the country rocks was found (Table 8). Rocks that are enriched in lithium

Table 8

Average lithium and boron contents of rocks of the Yellowknife District, Northwest Territories

Rock types	Boron content ppm	Lithium content ppm	Remarks
<u>Greenstone belt</u>			
Meta-andesite, meta-basalt, and dacite	<5	25	Pegmatites poor in boron and lithium
Interflow sediments (slate, graphitic schist, greywacke, chert)	200	12	
Quartz-feldspar porphyry	5	5	
Granodiorite and granite (Western granodiorite)	5	24	
Pegmatites and aplites associated with granodiorite	<5	<1-10	
<u>Sedimentary area</u>			
Greywacke, slate, phyllite, and quartz-mica schist	35	64	Pegmatites greatly enriched in boron and lithium
Granite (Prosperous Lake granite)	5	45	
Pegmatites associated with granite	1,000	70-3,000	

and boron such as the greywacke-slate sequence and the derived granites contain pegmatites also enriched in these elements. On the other hand, rocks such as the greenstones and derived granodiorite that are poor in lithium and boron are, likewise, devoid of pegmatites containing these elements. Research on other typical pegmatitic elements is continuing.

SUMMARY AND CONCLUSIONS

The principal types of mineral deposits in Archean greenstone and sedimentary belts include iron deposits in iron formations, manganese deposits, gold-quartz veins and lodes, arsenic and antimony deposits, tungsten deposits, massive and disseminated iron-copper-zinc and nickel-copper-cobalt sulphide bodies, disseminated copper-molybdenum deposits, chromite deposits, chrysotile asbestos deposits, and pegmatites.

The Archean iron formations are sedimentary bodies, their volatile components (CO₂ and S) originating it is thought, from extensive degassing of volcanic flows in a submarine environment. Their principal constituents, silica and iron, were probably derived by submarine leaching of ignimbrites and tuffs aided by the solubilizing action of CO₂, H₂SO₄, and HCl. The manganese in certain Archean manganese deposits may have had a similar origin in some belts, but many of the economic deposits in India appear to be chemical sediments derived by normal weathering processes. The gold-quartz, arsenic and antimony deposits, tungsten deposits, massive and disseminated sulphide

bodies, chromite and asbestos deposits, and pegmatites were derived by various mechanisms involving metamorphic secretion processes.

Most of the elements of the Periodic Table are enriched many times above their average terrestrial abundance (Clarke) in one or more of the various types of Archean deposits (Fig. 3). Some, however, have a very low enrichment factor being present only in certain pegmatites. These elements include U, Th, Ra, Zr, Hf, Sc, Y, and the various rare earths. The halides (F, Cl, Br, and I) also fall into this category, although fluorine is enriched in certain deposits especially pegmatites.

The elements greatly enriched in Archean deposits commonly in commercially exploitable amounts include the following:

Group I:	Li, Rb, Cs, Cu, Ag, Au
Group II:	Be, Zn, (Cd)
Group III:	(Ga), (In), (Tl), Sc(?), Y(?), Ce(?), Th(?)
Group IV:	Si, (Ge), (Sn), (Pb), Ti(?), Zr(?)
Group V:	As, Sb, (Bi), Nb, Ta
Group VI:	S, (Se), (Te), Cr, Mo, W
Group VII:	Mn
Group VIII:	Fe, (Co), Ni, (platinoids)

Those marked with a (?) are only rarely encountered in commercial amounts; those in brackets are generally byproducts of the mining and smelting of other types of ores.

ELEMENT ENRICHED	MINERALIZATION								
	SULPHIDE ¹ SCHISTS	IRON AND MANGANESE FORMATIONS	CHROMITE DEPOSITS	ASBESTOS DEPOSITS	MASSIVE SULPHIDE (Cu, Zn) DEPOSITS	MASSIVE SULPHIDE (Fe, Ni, Co) DEPOSITS	PEGMATITES	DISSEMINATED Cu-Mo DEPOSITS	GOLD-QUARTZ ² DEPOSITS
Group I H, (H ₂ O) Li Na K Rb Cs Cu Ag Au		.....							.....
Group II Be Mg Ca Sr Ba Zn Cd Hg		.....		.....					.....
Group III B Al Ga In Tl Sc Tr ³ Th U	.....	.....			.....		.....		.....
Group IV C, (CO ₂) Si, (SiO ₂) Ge Sn Pb Ti Zr	.....	.....	.....	.....	.....	.....	.....		.....
Group V P As Sb Bi V Nb Ta	.....	.....	.....		.....	.....	.....	.....	.....
Group VI S Se Te Cr Mo W	.....	.....	.....	.....	.....	.....	.....	.....	.....
Group VII F Mn Re		.....	.....				.....	.....	.....
Group VIII Fe Co Ni Pts ⁴	.....	.....	.....		.....	.....	.....	.....	.....
	EARLY ARCHEAN				TIME →				LATE ARCHEAN (KENORAN)
Notes:	1. Sulphide schists include sulphide facies of Algoma-type iron formations				— Enrichment at the percentage level				
	2. Gold-quartz deposits include certain arsenic and antimony deposits				- - - Enrichment at the fractional percentage level (0.01-1.0)				
	3. Tr=rare earths: Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu				..... Enrichment at the trace (<1-100 ppm) level				
	4. Pts=platinoids: Ru, Rh, Pd, Os, Ir, Pt				Enrichments include those in both the deposits and their alteration zones				

GSC

Figure 3. Elemental enrichments during the various phases of Archean mineralization.

The Archean is notably lacking in or contains only small (generally uneconomic) deposits of the following types:

- Evaporites and salines (Na, K, Mg, Ca, B, SO₄, N, F, Cl, Br, and I)
- Sedimentary phosphate deposits
- Barium and strontium deposits
- Mercury deposits
- Fossil bauxite and laterite deposits
- Uranium and thorium deposits
- Carbonatites (Nb, Ta, Zr, Ba, Sr, Cu, etc.)

- Hydrocarbon deposits
- Tin deposits
- Lead deposits
- Zirconium deposits

At our present state of knowledge we can only speculate on the reasons for the omission of many types of deposits in the Archean, especially those of epigenetic origin.

It seems obvious that the omission of certain types of deposits from the Archean is closely related to the

low degree of biochemical activity at that time. To this we can probably assign the lack of sedimentary phosphate, limestone, dolomite, and hydrocarbon deposits. The lack of fossil bauxite and laterite deposits is probably due to the climatic and weathering conditions which prevailed in Archean time. Glacial weathering and subsequent sedimentation such as are indicated by Archean (Timiskaming-type) sediments are not inimical to the formation of bauxites and laterites. Similarly, these particular types of weathering, abundance of running water, and cold conditions are not conducive to the formation of evaporites and salines.

The reasons for the omission of mercury, tin, lead, uranium, and carbonatite deposits in the Archean are not at all clear. Mercury occurs in many of the gold and sulphide deposits of Archean age, but only in S. Africa does the element reach sufficient concentrations to form an ore, and even there the deposits are small. The deposits of tin in the Archean are, likewise, small and not generally of economic interest unless deeply weathered, and the tin minerals concentrated in eluvial and alluvial placers. Some tin is won as a byproduct of the mining of sulphide deposits and pegmatites, but the amounts are small. Lead is, likewise, mainly a byproduct of Archean sulphide deposits. If we exclude the Witwatersrand deposits, which may be doubtfully of Archean age, we note a great scarcity of uranium deposits of Archean vintage. It is of interest to note, however, that uranium deposits are commonly deposited in Archean terranes as in the Goldfields area of Saskatchewan and in the Singhbhum district of India, but the first mentioned are of Proterozoic age (Robinson, 1955) and the second probably also of Proterozoic age (Pichamuthu, 1967).

Mercury is a highly volatile element and one could argue that the metamorphic and ore forming temperatures during Archean time were too high to permit deposition of mercury minerals. Such does not seem to be the case, however, judging from the work of Cameron and Jonasson (1972) who discounted any significant loss of mercury during metamorphism. Furthermore, some Archean sulphide-rich graphitic sediments are relatively rich in mercury (up to 50 ppm) (Boyle and Dass, 1971), and mercuriferous minerals such as tellurides, tetrahedrite, and sphalerite are relatively common in small amounts in most Archean gold deposits. The problem of the lack of mercury deposits appears to be neither one of provenance nor of metamorphic grade. Some other unknown factor is obviously involved. The scarcity of lead deposits of Archean age may be a function of the abundance of lead at the time. Perhaps radioactive decay processes had not proceeded long enough to provide an ample source of the element. To prove this, however, we need more data on the abundance relationships of uranium, thorium, and primordial lead in the proto-earth. The paucity of uranium deposits of Archean age is inexplicable given our present state of knowledge about the geochemistry of this radioelement. Similarly the absence of carbonatites seems paradoxical considering the relative nearness to the mantle at the time and the great quantity of carbon dioxide which appears to have been available.

All of these omissions are problems to which those interested in metallogenesis should address themselves since their solution is important in understanding the metallogenetic history of the earth.

ACKNOWLEDGMENTS

Numerous geologists throughout the world have provided me with various samples from the types of Archean deposits discussed above. To them I am most grateful. My colleagues Drs. G. A. Gross, R. H. Ridler, and J. B. Henderson provided many of the samples of Archean iron formations from which Table 2 was compiled. Dr. R. G. Garrett kindly read the manuscript and offered many valuable suggestions for improvement. This does not on any account imply that he is in agreement with the views presented.

REFERENCES IN THE TEXT

- Anhaeusser, C. R.
1974: The nature of chrysotile asbestos occurrences in southern Africa -- a review; Univ. Witwatersrand, Johannesburg, Econ. Geol. Res. Unit, Inf. Circ. 90, 28 p.
- Anderson, C. A. and Creasey, S. C.
1958: Geology and ore deposits of the Jerome area, Yavapai County, Arizona; U. S. Geol. Surv., Prof. Paper 308, 185 p.
- Armstrong, H. S.
1960: Marbles in the "Archean" of the Southern Canadian Shield; Int. Geol. Cong., Report 21st Session, Norden, Proc. Sec. 9, Pt. IX, p. 7-20.
- Ayers, L. D., Wolfe, W. J., and Averill, S. A.
1973: The Early Precambrian Setting Net Lake porphyry molybdenum deposit; Abst., Can. Inst. Min. Met., Ann. Mtg. Vancouver, Can. Inst. Min. Met. Bull., v. 66, no. 731, p. 48.
- Bateman, J. D.
1943: Bird River chromite deposits, Manitoba; Can. Inst. Min. Met., Trans. v. 46, p. 154-183.
- Bertrand, C. and Hutchinson, R. W.
1973: Metamorphism at the Normetal mine, Northwestern Quebec; Can. Inst. Min. Met. Bull., v. 66, no. 740, p. 68-76.
- Boyle, R. W.
1955: The geochemistry and origin of the gold-bearing quartz veins and lenses of the Yellowknife greenstone belt; Econ. Geol., v. 50, no. 1, p. 51-66.
1961: The geology, geochemistry, and origin of the gold deposits of the Yellowknife district; Geol. Surv. Can., Mem. 310, 193 p.

- Boyle, R. W. (cont.)
- 1963: Diffusion in vein genesis; in Symposium — Problems of Postmagmatic Ore Deposition, v. 1, Prague, p. 377-383.
- 1965: Origin of the Bathurst-Newcastle sulfide deposits, New Brunswick; *Econ. Geol.*, v. 60, p. 1529-1532.
- 1968: Fahlbands, sulfide schists, and ore deposition; *Econ. Geol.*, v. 63, no. 7, p. 835-838.
- 1970: The source of metals and gangue elements in hydrothermal deposits; in Problems of hydrothermal ore deposition, Editors Z. Pouba and M. Stempok, *Int. Union Geol. Sci.*, ser. A, no. 2, Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, p. 3-6. (Also *Mineral. Deposita*, 1968, v. 3, no. 2, p. 174-177.)
- 1974: The use of major elemental ratios in detailed geochemical prospecting utilizing primary halos; *J. Geochem. Explor.*, v. 3, p. 345-369.
- 1979: Boyle, R. W. and Davies, J. L.
1973: Banded iron formations; *Geochim. Cosmochim. Acta.*, v. 37, no. 5, p. 1389.
- Boyle, R. W. and Dass, A. S.
1971: The origin of the native silver veins at Cobalt, Ontario; *Can. Mineral.*, v. 11, pt. 1, p. 414-417.
- Brown, W. L.
1948: Normetal mine; in *Structural geology of Canadian ore deposits*, v. 1, *Can. Inst. Min. Met.*, Montreal, p. 683-692.
- 1973: Discussion: Metamorphism at the Normetal mine, Northwestern Quebec; *Can. Inst. Min. Met. Bull.*, v. 66, no. 740, p. 76.
- Cabri, L. J., Maclean, W. H., and Scott, S. D.
1974: Comments on "Metamorphism at the Normetal mine, Northwestern Quebec"; *Can. Inst. Min. Met. Bull.*, v. 67, no. 746, p. 158-159.
- Cairns, R. B., et al.
1957: Cuprus mine; in *Structural geology of Canadian ore deposits*, v. 2, *Can. Inst. Min. Met.*, Montreal, p. 253-258.
- Cameron, E. M., Siddeley, G., and Durham, C. C.
1971: Distribution of ore elements in rocks for evaluating ore potential; nickel, copper, cobalt, and sulphur in ultramafic rocks of the Canadian Shield; in *Geochemical Exploration*, Editors R. W. Boyle and J. I. McGerrigle; *Can. Inst. Min. Met., Spec. vol. 11*, p. 298-313.
- 1979: The geochemistry of gold and its deposits; *Geol. Surv. Can., Bull.* 280, 584 p.
- Cameron, E. M. and Jonasson, I. R.
1972: Mercury in Precambrian shales of the Canadian Shield; *Geochim. Cosmochim. Acta*, v. 36, p. 985-1005.
- Carter, O. F.
1967: A geological summary of the McIntyre mine; Private report McIntyre Mines, 10 p.
- Clark, L. A.
1965: Geology and geothermometry of the Marbridge nickel deposit, Malartic, Quebec; *Econ. Geol.*, v. 60, p. 792-811.
- Davidson, S. and Banfield, A. F.
1944: Geology of the Beattie gold mine, Duparquet, Quebec; *Econ. Geol.*, v. 39, p. 535-556.
- Davies, D. N.
1964: The tin deposits of Swaziland; in *The geology of some ore deposits in Southern Africa*, v. 2, Editor, S. H. Haughton, *Geol. Soc. S. Afr.*, p. 535-541.
- Davies, J. F.
1960: Geology of the Thompson-Moak Lake District, Manitoba; *Can. Min. J.*, v. 81, no. 4, p. 101-104.
- De Kun, N.
1965: The mineral resources of Africa; Elsevier Publishing Co., Amsterdam, 740 p.
- Derry, D. R. and Folinsbee, J. C.
1957: Opemiska copper mine; in *Structural geology of Canadian ore deposits*, v. 2; *Can. Inst. Min. Met.*, Montreal, p. 430-441.
- Derry, D. R., Hopper, C. H., and McGowan, H. S.
1948: Matachewan Consolidated mine; in *Structural geology of Canadian ore deposits*, v. 1, p. 638-643; *Can. Inst. Min. Met.*, Montreal.
- Descarreaux, J.
1973: A petrochemical study of the Abitibi volcanic belt and its bearing on the occurrences of massive sulphide ores; *Can. Inst. Min. Met. Bull.*, v. 66, no. 730, p. 61-69.
- Duquette, G.
1966: General geology and asbestos mineralization in the Chibougamau district; *Can. Min. J.*, v. 87, no. 4, p. 70-76.
- Eckstrand, O. R.
1975: The Dumont serpentinite: a model for control of nickeliferous opaque mineral assemblages by alteration reactions in ultramafic rocks; *Econ. Geol.*, v. 70, p. 183-201.

- Evans, J. E. L.
1944: Porphyry of the Porcupine district, Ontario; Geol. Soc. Amer. Bull., v. 55, pt. 2, p. 1115-1141.
- Ewers, W. E., Hudson, D. K., and Davis, C. E. S.
1972: An interpretive study of a nickel-iron sulfide ore intersection, Lunnon Shoot, Kambalda, Western Australia; Econ. Geol., v. 67, p. 1075-1092.
- Farley, W. J.
1948: Sherritt Gordon mine; in Structural geology of Canadian ore deposits, v. 1, p. 292-295; Can. Inst. Min. Met., Montreal.
- Fleet, M. E. and MacRae, N. D.
1975: A spinifex rock from Munro Township, Ontario; Can. J. Earth Sci., v. 12, p. 928-939.
- Ginzburg, F. L. and Sheidina, L. D.
1974: State of silicic acid in nitric acid solutions; Soviet Radiochemistry, v. 15, no. 3, p. 411-415. (Trans. Consultants Bureau, New York.)
- Goodwin, A. M.
1973: Archean iron-formations and tectonic basins of the Canadian Shield; Econ. Geol., v. 68, no. 7, p. 915-933.
- Graham, A. R.
1930: Obonga Lake chromite area, District of Thunder Bay; Ont. Dep. Mines, 39th Ann. Rep., pt. 2, p. 51-60.
- Griffis, A. T.
1962: A geological study of the McIntyre mine; Can. Inst. Min. Met. Bull., v. 55, no. 598, p. 76-83.
- Gross, G. A.
1965: Geology of iron deposits of Canada, v. 1, Geol. Surv. Can., Econ. Geol. Rep. 22, 181 p.
- Gustafson, J. K.
1945: The Porcupine porphyries; Econ. Geol., v. 40, p. 148-152.
- Hawley, J. E.
1948: The Aldermac copper deposit; in Structural geology of Canadian ore deposits, v. 1, p. 719-730; Can. Inst. Min. Met., Montreal.
- Henderson, J. B.
1975a: Sedimentological studies of the Yellowknife Supergroup in the Slave Structural province; in Report of Activities, Part A, Geol. Surv. Can., Paper 75-1, pt. A, p. 325-330.
- Henderson, J. B. (cont.)
1975b: Archean stromatolites in the northern Slave Province, Northwest Territories, Canada; Can. J. Earth Sci., v. 12, p. 1619-1630.
- Henderson, J. F. and Brown, I. C.
1966: Geology and structure of the Yellowknife greenstone belt, District of Mackenzie; Geol. Surv. Can., Bull. 141, 87 p.
- Hendry, N. W.
1951: Chrysotile asbestos in Munro and Beatty Townships, Ontario; Can. Inst. Min. Met., Trans., v. 54, p. 28-35.
- Holmes, T. C.
1944: Some porphyry-sediment contacts at the Dome mine, Ontario; Econ. Geol., v. 39, no. 2, p. 133-141.
- Hutchinson, R. W.
1973: Volcanogenic sulfide deposits and their metallogenic significance; Econ. Geol., v. 68, no. 8, p. 1223-1246.
- Iler, R. K.
1955: The colloid chemistry of silica and silicates; New York, Cornell Univ. Press, 324 p.
- Jacobson, R. R. E., Snelling, N. J., and Truswell, J. F.
1964: Age determinations in the geology of Nigeria, with special reference to the older and younger granites; Overseas Geology and Mineral Resources, v. 9, no. 2, p. 168-182.
- James, H. L. and Sims, P. K. (Editors)
1973: Precambrian iron-formations of the world; Econ. Geol., v. 68, no. 7, p. 913-1221.
- Jolliffe, A. W.
1938: Yellowknife Bay-Prosperous Lake area, Northwest Territories, Geol. Surv. Can., Paper 38-21, 41 p.
- Jones, W. A.
1948: Ross mine; in Structural geology of Canadian ore deposits, v. 1, p. 570-579; Can. Inst. Min. Met., Montreal.
- Kautsky, G.
1958: The theory of exhalative-sedimentary ores proposed by Chr. Oftedahl; Geol. Fören. Stockholm Förh., v. 80, no. 3, p. 283-287.
- Koffman, A. A., et al.
1948: Flin Flon mine; in Structural geology of Canadian ore deposits, v. 1, p. 295-301; Can. Inst. Min. Met., Montreal.

- Koo, J. and Mossman, D. J.
1975: Origin and metamorphism of the Flin Flon strata-bound Cu-Zn sulphide deposits, Saskatchewan and Manitoba; *Econ. Geol.*, v. 70, p. 48-62.
- Krishnan, M. S.
1953: Chromite; *Geol. Surv. India, Bull. No. 7*, 47 p.
- Kullerud, G., Vokes, F. M., and Barnes, H. L.
1959: On exhalative-sedimentary ores; *Geol. Fören. Stockholm Förh.*, v. 81, no. 1, p. 145-148.
- Landergrén, S.
1958: Comments to "A theory of exhalative-sedimentary ores"; *Geol. Fören. Stockholm Förh.*, v. 80, no. 3, p. 288-290.
- Langford, G. B. and Hancox, E. G.
1936: Hypogene anhydrite from McIntyre mine, Porcupine District, Ontario; *Econ. Geol.*, v. 31, p. 600-609.
- Laubscher, D. H.
1964: The occurrence and origin of chrysotile asbestos and associated rocks, Shabani, Southern Rhodesia; in *The geology of some ore deposits in Southern Africa*, v. 2, Editor S. H. Haughton, *Geol. Soc. S. Afr.*, p. 593-624.
- Li, K. C. and Wang, C. Y.
1947: Tungsten; Reinhold Pub. Corp. New York, 430 p.
- Little, H. W.
1959: Tungsten deposits of Canada; *Geol. Surv. Can., Econ. Geol. Ser. no. 17*, 251 p.
- MacLean, A.
1956: Geology of Lebel Township; *Ont. Dep. Mines, Bull. 150*, 63 p.
- Mahadevan, C.
1929: The chromite-bearing ultrabasic deposits of Singhbhum; *Econ. Geol.*, v. 24, p. 195-205.
- Malouf, S. E. and Hinse, R.
1957: Campbell Chibougamau mines; in *Structural geology of Canadian ore deposits*; v. 2, p. 441-449, *Can. Inst. Min. Met.*, Montreal.
- Marmo, V.
1958: On the theory of exhalative-sedimentary ores; *Geol. Fören. Stockholm Förh.*, v. 80, no. 3, p. 277-282.
- McBride, D. E.
1974: Metamorphism at the Normetal mine (discussion); *Can. Inst. Min. Met. Bull.*, v. 67, no. 744, p. 119.
- McMurphy, R. C.
1948: Powell Rouyn mine; in *Structural geology of Canadian ore deposits*; v. 1, p. 739-747, *Can. Inst. Min. Met.*, Montreal.
- Michard, G.
1975: Basalt-sea water interaction as a source of manganese. Preliminary thermodynamical study; *Compte rendus, Acad. Sci.*, v. 280, sec. D, no. 10, p. 1213-1216.
- Milligan, G. C.
1960: Geology of the Lynn Lake District, Manitoba Mines Branch, *Publ. 57-1*, 317 p.
- Mitcham, T. W.
1974: Origin of breccia pipes; *Econ. Geol.*, v. 69, p. 412-413.
- Moore, E. S.
1954: Porphyries of the Porcupine area, Ontario; *Roy. Soc. Can., Trans.*, v. 48, ser. 3, sec. 4, p. 41-57.
- Moore, E. S. and Maynard, J. E.
1929: Solution, transportation, and precipitation of iron and silica; *Econ. Geol.*, v. 24, no. 3, p. 272-303; no. 4, p. 365-402; and no. 5, p. 506-527.
- Morrison, E. R.
1972: Corundum in Rhodesia; *Rhodesia, Geol. Surv., Min. Res. Ser. 16*, 24 p.
- Muir, M. D. and Hall, D. O.
1974: Diverse microfossils in Precambrian Onverwacht group rocks of South Africa; *Nature*, v. 252, p. 376-378.
- Mulligan, R.
1975: Geology of Canadian tin occurrences; *Geol. Surv. Can., Econ. Geol. Rep. no. 28*, 155 p.
- Nairis, B.
1971: Endogene dispersion aureoles around the Rudtjebäcken sulphide ore in the Adak area, Northern Sweden; in *Geochemical Exploration*, Editors R. W. Boyle and J. I. McGerrigle, *Can. Inst. Min. Met. Spec. Vol. 11*, p. 357-374.
- Naldrett, A. J. and Gasparrini, E. L.
1971: Archean nickel sulphide deposits in Canada: their classification, geological setting, and genesis, with some suggestions as to exploration; in *Symposium on Archean rocks*, Editor J. D. Glover, *Geol. Soc. Aust. Spec. Pub. no. 3*, p. 201-226.

- Naldrett, A. J. and Arndt, N. T.
1975: Association of nickel sulphides with rocks of volcanic origin suggests new exploration targets; *Northern Miner*, v. 60, no. 51, p. 39-40.
- Nilsson, C. A.
1968: Wall rock alteration at the Boliden deposit, Sweden; *Econ. Geol.*, v. 63, p. 472-494.
- Norman, G. W. H.
1948a: La Corne molybdenite deposit; in *Structural geology of Canadian ore deposits*, v. 1, p. 850-852, *Can. Inst. Min. Met.*, Montreal.
1948b: Indian molybdenum deposit; in *Structural geology of Canadian ore deposits*, v. 1, p. 845-850, *Can. Inst. Min. Met.*, Montreal.
- North, H. H. and Allen, C. C.
1948: Young-Davidson mine; in *Structural geology of Canadian ore deposits*, v. 1, p. 633-637, *Can. Inst. Min. Met.*, Montreal.
- Oftedahl, C.
1958: A theory of exhalative-sedimentary ores; *Geol. Fören. Stockholm Förh.*, v. 80, pt. 1, no. 492, p. 1-19.
- Pelletier, R. A.
1964: Mineral resources of South-Central Africa, p. 158-161; Oxford Univ. Press, Cape Town.
- Pichamuthu, C. S.
1967: The Precambrian of India; in *The Precambrian*, v. 3, Editor, K. Rankama, Interscience Publishers, New York, p. 1-96.
- Price, P.
1934: The geology and ore deposits of the Horne mine, Noranda, Quebec; *Can. Inst. Min. Met.*, *Trans.*, v. 37, p. 108-140.
1948: Horne mine; in *Structural geology of Canadian ore deposits*, v. 1, p. 763-772, *Can. Inst. Min. Met.*, Montreal.
- Purvis, A. C., Nesbitt, R. W., and Hallberg, J. A.
1972: The geology of part of the Carr Boyd Rocks complex and its associated nickel mineralization, Western Australia, *Econ. Geol.*, v. 67, p. 1093-1113.
- Pyke, D. R.
1975: On the relationship of gold mineralization and ultramafic volcanic rocks in the Timmins area; *Ont. Div. Mines, Misc. Paper 62*, 23 p.
- Pyke, D. R., Naldrett, A. J., and Eckstrand, O. R.
1973: Archean ultramafic flows in Munro Township, Ontario; *Geol. Soc. Am. Bull.*, v. 84, p. 955-977.
- Ray, S.
1952: Symposium on India's mica industry; *Geol. Min. Met. Soc. India, Bull.* no. 11, 79 p.
- Reid, J. A.
1944: Replacement and igneous intrusion; *Econ. Geol.*, v. 39, p. 448-449.
- Ridge, J. D.
1974: Note on boiling of ascending ore fluids and the position of volcanic-exhalative deposits in the modified Lindgren classification; *Geology*, v. 2, no. 6, p. 287-288.
- Ridler, R. H.
1970: Relationship of mineralization to volcanic stratigraphy in the Kirkland-Larder Lakes area, Ontario; *Geol. Assoc. Can., Proc.* v. 21, p. 33-42.
1971: Analysis of Archean volcanic basins in the Canadian Shield using the exhalative concept; *Can. Inst. Min. Met., Bull.*, v. 64, no. 714, p. 20 (abst.).
1972: Volcanic stratigraphy of the Kirkland Lake Area; p. 33-52 in *Precambrian volcanism of the Noranda-Kirkland Lake-Timmins-Michipicoten and Mamainse Point areas, Quebec and Ontario*, 24th Intl. Geol. Cong., *Field Excursion Guidebook*, 93 p.
1973: Exhalite concept a new tool for exploration; *Northern Miner*, Annual Review Issue, Nov., v. 59, no. 37, p. 59-61.
- Robinson, H. S.
1923: Geology of the Pearl Lake area, Porcupine district, Ontario; *Econ. Geol.*, v. 18, no. 8, p. 753-771.
- Robinson, S. C.
1955: Mineralogy of uranium deposits, Goldfields, Saskatchewan; *Geol. Surv. Can., Bull.* 31, 128 p.
- Roy, S.
1966: Syngenetic manganese formations of India; *Jadavpur Univ., Calcutta*, 219 p.
- Ruttan, G. D.
1955: Geology of Lynn Lake; *Can. Inst. Min. Met., Bull.*, v. 48, no. 518, p. 339-348.
1957: Lynn Lake mine; in *Structural geology of Canadian ore deposits*, v. 2, p. 275-291, *Can. Inst. Min. Met.*, Montreal.
- Sahli, E. W.
1961: Antimony in the Murchison Range of the north-eastern Transvaal; 7th Comm. *Min. Met. Cong., Trans.*, v. 1, p. 181-199.

- Sainsbury, C. L.
1969: Tin resources of the world; U. S. Geol. Surv. Bull. 1301, 55 p.
- Sakrison, H. C.
1966: Chemical studies of the host rocks of the Lake Dufault mine, Quebec; unpubl. Ph.D. thesis, McGill Univ., Montreal, 138 p.
- Sandefur, B. T.
1942: The geology and paragenesis of the nickel ores of the Cuniptau mine, Goward, Nipissing district, Ontario; Econ. Geol., v. 37, p. 173-187.
- Sangster, D. F.
1972: Precambrian volcanogenic massive sulphide deposits in Canada; a review; Geol. Surv. Can., Paper 72-22, 44 p.
- Satterly, J.
1952: Geology of Munro Township; 60th Ann. Rep. Ont. Dep. Mines, v. 60, pt. 8, 60 p.
- Suffel, G. G.
1935: Relations of later gabbro to sulphides at the Horne mine, Noranda, Quebec, Econ. Geol., v. 30, p. 905-915.
- UNESCO
1973: Genesis of Precambrian iron and manganese deposits; Proc. Kiev Symp. August 1970; Pub. UNESCO, Paris, 382 p.
- Van Biljon, W. J.
1964: The chrysotile deposits of the Eastern Transvaal and Swaziland; in The geology of some ore deposits in Southern Africa, v. 2, Editor, S. H. Haughton, Geol. Soc. S. Afr., p. 625-669.
- Walker, R. R., Matulich, A., Amos, A. C., Watkins, J. J., and Mannard, G. W.
1975: The geology of the Kidd Creek mine; Econ. Geol., v. 70, p. 80-89.
- Wanless, R. K., Boyle, R. W., and Lowdon, J. A.
1960: Sulphur isotope investigation of the gold-quartz deposits of the Yellowknife district; Econ. Geol., v. 55, no. 8, p. 1591-1621.
- Whitman, A. R.
1927: A synthetic porphyry at Porcupine; J. Geol., v. 35, no. 5, p. 404-420.
- Wilson, H. D. B. and Brisbin, W. C.
1961: Regional structure of the Thompson-Moak Lake nickel belt, Can. Inst. Min. Met., Bull., v. 54, no. 595, p. 815-822.
- Wilson, M. E.
1941: Noranda district, Quebec; Geol. Surv. Can., Mem. 229, 148 p.
- Wolfe, W. J.
1974: Geochemical and biogeochemical exploration research near Early Precambrian porphyry-type molybdenum-copper mineralization, Northwestern Ontario, Canada; J. Geochem. Explor., v. 3, no. 1, p. 25-41.
- Woodall, R. and Travis, G. A.
1969: The Kambalda nickel deposits, Western Australia; 9th Comm. Min. Met. Cong. Proc., v. 2, p. 517-533.
- Worst, B. G.
1964: Chromite in the Great Dyke of Southern Rhodesia; in The geology of some ore deposits in Southern Africa, Editor, S. H. Haughton, Geol. Soc. S. Afr., p. 209-224.
- Vokes, F. M.
1963: Molybdenum deposits of Canada; Geol. Surv. Can., Econ. Geol. Rep. no. 20, 332 p.
- Zurbrigg, H. F.
1963: Thompson mine geology; Can. Inst. Min. Met., Bull., v. 56, no. 614, p. 451-460.

SELECTED GENERAL REFERENCES

- Anhaeusser, C. R.
1972: The evolution of the early Precambrian crust of southern Africa; Univ. Witwatersrand, Johannesburg, Econ. Geol. Res. Unit, Inf. Circ. 70, 31 p.
- 1974: Archean metallogeny in southern Africa; Univ. Witwatersrand, Johannesburg, Econ. Geol. Res. Unit, Inf. Circ. 91, 38 p.
- Anhaeusser, C. R., Roering, C., Viljoen, M. J., and Viljoen, R. P.
1968: The Barberton Mountain Land: A model of the elements and evolution of an Archean fold belt; Geol. Soc. S. Afr., Trans., Anex. v. 71, p. 225-254.
- Anhaeusser, C. R., Mason, R., Viljoen, M. J., and Viljoen, R. P.
1969: A reappraisal of some aspects of Precambrian Shield geology; Geol. Soc. Am., Bull., v. 80, no. 11, p. 2175-2200.
- Anhaeusser, C. R. and Button, A.
1974: Review of Southern Africa stratiform ore deposits. Their position in time and space; Univ. Witwatersrand, Johannesburg, Econ. Geol. Res. Unit, Inf. Circ. 85, p. 1-48 (Chem. Abst. v. 81, 172937z).
- Baer, A. J. (Editor)
1970: Symposium on basins and geosynclines of the Canadian Shield; Geol. Surv. Can., Paper 70-40, 265 p.

- Baragar, W. R. A.
 1966: Geochemistry of the Yellowknife volcanic rocks; *Can. J. Earth Sci.*, v. 3, p. 9-30.
 1968: Major-element geochemistry of the Noranda volcanic belt, Quebec-Ontario; *Can. J. Earth Sci.*, v. 5, p. 773-790.
- Baragar, W. R. A., Goodwin, A. M., and Souther, J. G.
 1966: Volcanism and mineral deposits; in *Contributions to geological exploration in Canada*, Editor, S. E. Jenness, *Geol. Surv. Can.*, Paper 66-42, p. 8-14.
- Cameron, E. M.
 1974: Sulphur in Archean volcanic rocks of the Canadian Shield; *Geol. Surv. Can.*, Paper 74-18, 9 p.
 1975: Geochemical methods of exploration for massive sulphide mineralization in the Canadian Shield; *Proc. 5th Int. Geochem. Expl. Symp.*, Vancouver, Canada, p. 21-49.
- Cornwall, H. R.
 1966: Nickel deposits of North America; *U. S. Geol. Surv.*, Bull. 1223, 62 p.
- De Geoffroy, J. and Wu, S. M.
 1970: A statistical study of ore occurrences in the greenstone belts of the Canadian Shield; *Econ. Geol.*, v. 65, p. 496-504.
- Dimroth, E.
 1975: Carbon and sulfur in Precambrian sedimentary rocks: Evidence for atmospheric oxygen; *Prog. Geol. Soc. Am.*, *Geol. Assoc. Can.*, etc., Waterloo, Ontario, p. 747.
- Doe, B. R. and Smith, D. K. (Editors)
 1972: *Studies in mineralogy and Precambrian geology*; *Geol. Soc. Am.*, Mem. 135, 348 p.
- Douglas, R. J. W. (Editor)
 1970: *Geology and economic minerals of Canada*; *Econ. Geol. Report*, no. 1, 5th ed., 838 p.
- Glover, J. E. (Editor)
 1971: *Symposium on Archean rocks*; *Geol. Soc. Aust.*, Spec. Pub. no. 3, 469 p.
- Goodwin, A. M.
 1966: The relationship of mineralization to Precambrian stratigraphy in certain mining areas of Ontario and Quebec; *Geol. Assoc. Can.*, Spec. Paper no. 3, 144 p.
- Green, D. H.
 1975: Genesis of Archean peridotitic magmas and constraints on Archean geothermal gradients and tectonics; *Geology*, v. 3, no. 1, p. 15-18.
- Hallberg, J. A.
 1972: Geochemistry of Archean volcanic belts in the Eastern Goldfields region of Western Australia; *J. Petrol.*, v. 13, p. 45-56.
- Hofmann, H. J.
 1971: Precambrian fossils, pseudofossils, and problematica in Canada; *Geol. Surv. Can.*, Bull. 189, 146 p.
- Holman, R. H. C.
 1963: A regional geochemical reconnaissance of bedrock in the Red Lake - Lansdowne House area of Ontario, Canada; in eight papers on regional geochemistry in Canada; *Geol. Surv. Can.*, Paper 63-23, p. 28-39.
- International Geological Congress
 1960: Pre Cambrian stratigraphy and correlations: Report 21st Session, Norden, Proc. Sec. 9, pt. IX, Editors A. Simonen and J. A. O. Kouvo, 206 p.
 1964: Archean and Precambrian geology: Report 22nd Session, India, Proc. Sec. 10, Editors M. S. Subramanyam and A. K. Saha, 581 p.
 1968: Geology of Precambrian; Report 23rd Session, Czechoslovakia, Proc. Sec. 4, Editor, B. Hejtman, 298 p.
 1972: Precambrian Geology; Report 24th Session, Canada, Proc. Sec. 1, Editors A. M. Goodwin and H. R. Wynne-Edwards, 379 p.
- Kretschmar, U. and Kretschmar, D.
 1975: Geology and ultramafic flows of the Malartic Group, N. W. Quebec; *Prog. Geol. Soc. Am.*, *Geol. Assoc. Can.*, etc., Waterloo, Ontario, p. 801-802.
- Naldrett, A. J.
 1966: The role of sulphurization in the genesis of iron-nickel sulphide deposits of the Porcupine district, Ontario; *Can. Inst. Min. Met.*, Bull., v. 59, p. 489-497.
 1973: Nickel sulphide deposits - Their classification and genesis, with special emphasis on deposits of volcanic association; *Can. Inst. Min. Met.*, Trans., v. 76, p. 183-201.
- Naqvi, S. M., Rao, V. D., Satyanarayana, K., and Hussain, S. M.
 1974: Geochemistry of post-Dharwar basic dikes and the Precambrian crustal evolution of peninsular India; *Geol. Mag.*, v. 11, no. 3, p. 229-236.
- Pichamuthu, C. S.
 1974: On the banded iron formations of Precambrian age in India; *J. Geol. Soc. India*, v. 15, p. 1-30.

- Pyke, D. R. and Middleton, R. S.
 1971: Distribution and characteristics of the sulphide ores of the Timmins area, *Can. Inst. Min. Met., Bull.*, v. 64, no. 710, p. 55-66.
- Rankama, K. (Editor)
 1963- The Precambrian, Vols. 1, 2, 3, and 4;
 1970: Interscience Publishers, New York.
- Sullivan, C. J.
 1959: The origin of massive sulphide ores; *Can. Inst. Min. Met., Bull.*, v. 52, p. 613-619.
- Sutton, J. and Windley, B. F.
 1974: The Precambrian; *Sci. Prog.*, Oxford, v. 61, p. 401-420.
- Tomich, S. A.
 1974: A new look at Kalgoorlie Golden Mile geology; *Aust. Inst. Min. Met., Proc.*, no. 251, Sept., p. 27-35.
- Viljoen, R. P., Saager, R., and Viljoen, M. J.
 1970: Some thoughts on the origin and processes responsible for the concentration of gold in the Early Precambrian of Southern Africa; *Mineral. Deposita (Berl)*, v. 5, p. 164-180.
- Watson, J. V.
 1973a: Effect of reworking on high-grade gneiss complexes; *R. Soc. London, Phil. Trans. A*, v. 273, p. 443-455.
 1973b: Influence of crustal evolution on ore deposition; *Inst. Min. Met. Trans.*, v. 82, sec. B, p. 107-113.
- Wilson, H. D. B. (Editor)
 1969: Symposium: Magmatic ore deposits; *Econ. Geol. Publ. Co. Monograph 4*, 366 p.
- Wilson, H. D. B., Andrews, P., Moxham, R. L., and Ramlal, K.
 1965: Archean volcanism in the Canadian Shield; *Can. J. Earth Sci.*, v. 2, p. 161-175.