Boyle 7.20

Economic Geology
Vol. 54, 1959, pp. 1506–1524

THE GEOCHEMISTRY, ORIGIN, AND ROLE OF CARBON DIOXIDE, WATER, SULFUR, AND BORON IN THE YELLOWKNIFE GOLD DEPOSITS NORTHWEST TERRITORIES, CANADA[1]

R. W. BOYLE

CONTENTS

ABSTRACT

The gold deposits of the Yellowknife district occur in two distinct geological settings. The principal economic deposits occur in quartz-carbonate lenses in extensive chlorite schist zones (shear zones) cutting greenstone (amphibolite) rocks. The other deposits, of less economic importance, occur in quartz lenses in meta-sedimentary rocks.

The deposits in the greenstones represent concentrations of silica, carbon dioxide, water, sulfur, arsenic, antimony, gold, and other metallic elements. Those in the sediments represent concentrations of silica, sulfur, boron, gold, and other metallic elements.

For the deposits in the greenstones chemical evidence is presented to show that, under the influence of a strong thermal gradient, some of the carbon dioxide, water, sulfur, gold, silver, and other metallic elements in the original volcanic rocks was mobilized and migrated into the extensive shear zone systems. In the shear zones the chemical equilibrium was severely displaced, water and carbon dioxide reacted with the amphibolite rock producing extensive widths of chlorite and chlorite-carbonate schist, and silica, sulfur, gold, and numerous other elements present in the rock were mobilized. These mobilized constituents, together with those added by diffusion from the country rocks, migrated into dilatant zones, principally at shear zone junctions and flexures. In these sites they were precipitated as quartz, carbonates, sulfides, and gold.

A similar process has operated to form the gold-quartz lenses in the meta-sediments. In these rocks silica, boron, sulfur, and various metallic elements were mobilized during the metamorphism of the sediments, and these migrated into and were precipitated in dilatant zones in faults, fractures, and drag folds in the rocks.

---

[1] Published by permission of the Director, Geological Survey of Canada, Department of Mines and Technical Surveys, Ottawa, Canada.

in such a way as to avoid chemical contamination or damage to the lattice structure. If temperatures above about 300° C are used, it will be necessary to modify the apparatus so as to ensure that the radiation counting equipment is not damaged by overheating.

The main feature of the tracer method is that a definite characteristic of the solution, closely related to solubility, can be measured without having to withdraw a sample and without having to alter the temperature or pressure in any way that might break the continuity of the experiment or introduce inaccuracies. This feature makes it possible to know when equilibrium between solid and liquid has been reached and so to establish a series of points on an equilibrium curve merely by changing temperature or pressure. In any study of this kind, much information on the rates of solution could be obtained.

The writer believes that the method can be used for studying a wide variety of solid-aqueous systems at any pressure and at any reasonable temperature assumed for hydrothermal processes.

ACKNOWLEDGMENTS

The writer acknowledges that the original suggestion for using a radioactive tracer came from Dr. C. A. Winkler of the Chemistry Department, McGill University. Dr. L. Yaffe of the Radiochemistry Department gave valuable advice and assistance and very kindly read the manuscript. The writer is indebted to Dr. V. A. Saull who directed the thesis. He gave much encouragement and advice and many of his suggestions for improving the manuscript were adopted. Financial support for the project, which formed the subject of the writer's M.Sc. thesis, was provided by the Geological Survey of Canada.

DEPARTMENT OF GEOLOGICAL SCIENCES,
McGILL UNIVERSITY,
MONTREAL, QUEBEC,
Dec. 23, 1958

REFERENCES

1. Frederickson, A. F., and Cox, J. E., Jr., 1954, Mechanism of solution of quartz in pure water at elevated temperatures and pressures: Am. Mineralogist, v. 39, p. 886.
2. Friedlander, G., and Kennedy, J. W., 1949, Nuclear and radiochemistry: New York, John Wiley and Sons Ltd.
3. Gibson, R. E., 1938, The effect of pressure on the solubility of solids in liquids: Am. Jour. Sci., v. 236, p. 49.
4. Lewis, G. N., and Randall, M., 1923, Thermodynamics: New York, McGraw-Hill Book Co., p. 184.
5. Schiff, H. I., Chemistry Department, McGill University, Montreal: Personal communication.
6. Soret, M. C., 1881, Sur l' etat d' equilibre que prend, au point de vue de sa concentration, une dissolution saline primitivement homogène dont deux parties sont portées a des températures différentes: Ann. Chim. et Phys. (5)., v. 22, p. 293.
7. Tuttle, O. F., 1945, Two pressure vessels for silicate waters studies: Geol. Soc. America Bull., v. 60, pp. 1727–1729.
8. Verhoogen, J., 1938, Thermodynamic calculation of the solubility of some important sulphides, up to 800° C: ECON. GEOL., v. 33, p. 34 and p. 777.

INTRODUCTION

THIS paper summarizes part of a research project carried out by the writer on the geochemistry and origin of the gold deposits of the Yellowknife district. A previous paper in this journal (4) outlined the geochemistry and suggested an origin of the major gold-bearing quartz veins in the greenstone belt of the district. The present paper adds further data on the geochemistry of the volatiles, offers an explanation for their present distribution, and discusses their role in the mineralization processes. A synthesis, summarizing the writer's views on the origin of the gold deposits, is given at the end of the paper.

It should perhaps be pointed out that another part of the project has dealt with the distribution and geochemistry of gold, silver, arsenic, antimony, copper, lead, and zinc in both the deposits and their host rocks. The results of this investigation are much too detailed to be described here, and the interested reader is referred to the writer's memoir (5) which will be published in the near future. Briefly the results indicate that the metals noted above are present in sufficient amounts in both the greenstones and sediments to provide the concentrations in the deposits. It has also been ascertained that the metals such as gold, silver, and zinc follow sulfur closely in their geochemistry, and hence statements made about the migration of sulfur in this paper also apply to these metals.

GENERAL GEOLOGY

The general geology of the Yellowknife district was described first by Stockwell and Kidd (19, 20) and later, in more detail, by Jolliffe (14, 15, 16, 17). More recently a description of the geology and a structural analysis of the principal ore-bearing shear zones of the greenstone belt was published by Henderson and Brown (12, 13). The geology of the orebodies of the Con-Rycon and Giant Mines was published by Campbell (7), Dadson and Bateman (10), Dadson (8, 9), Bateman (1), Brown and Dadson (6), and Boyle (2, 3). These authors have covered the geology of the district and gold deposits in considerable detail, and the brief description that follows gives a summary of the most important features and provides a background for discussing the part that the volatiles have played in the formation of the gold deposits.

The consolidated rocks within the area are Precambrian in age (Fig. 1). The oldest rocks are greenstones consisting of a succession of massive and pillowed andesite and basalt flows with interbedded dacite flows, tuffs, and agglomerates (Division A, Yellowknife Group). These rocks contain numerous gabbro and diorite sills and are cut by dikes of similar composition. Quartz-feldspar porphyry dikes and masses cut the greenstones throughout the district, but are found in greatest profusion in the northern part of the belt, particularly in the area east and southeast of Ryan Lake. The greenstones are overlain by a thick series of greywacke, argillite, slate, quartzite, and their metamorphic equivalents (Division B, Yellowknife Group).

Three large granitic masses occur within the district. One flanks the

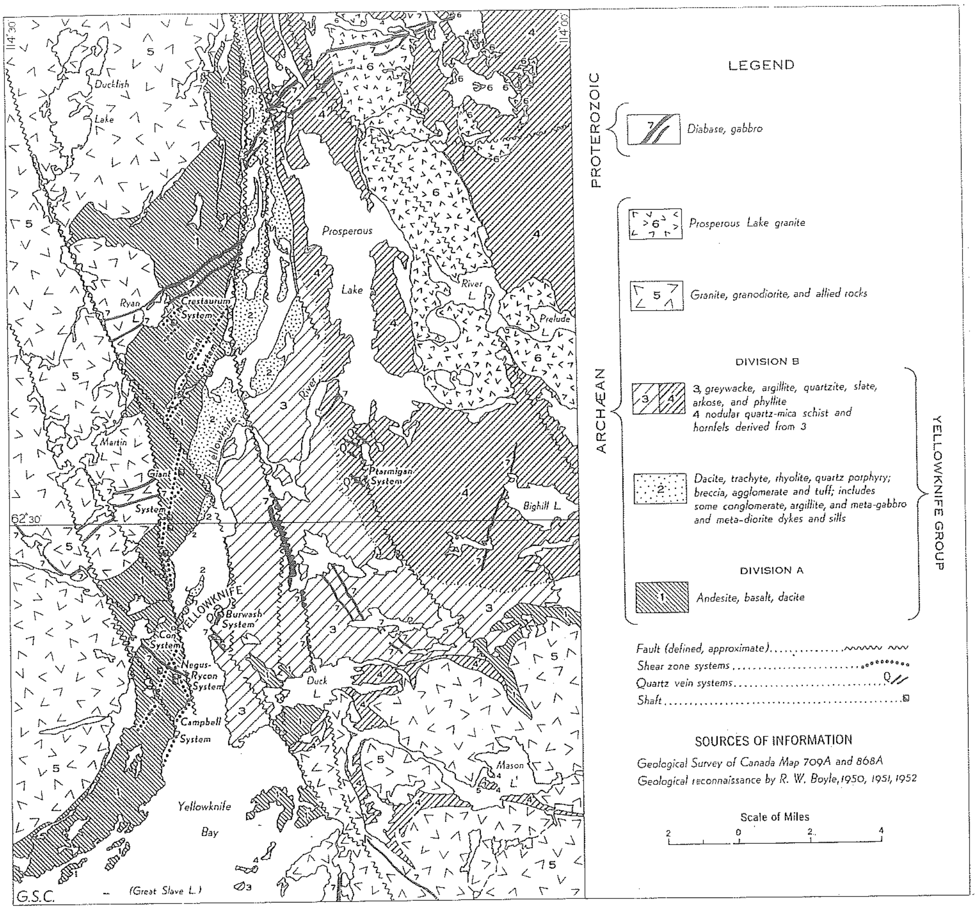


FIG. 1. Map showing general geology of Yellowknife District, Northwest Territories.

greenstone belt on the west, and another forms a large mass south of the sedimentary area. The third granitic mass, known as the Prosperous Lake granite, occurs east of Prosperous Lake. Field and chemical evidence suggest that the western granitic mass originated by granitization of a great series of sedimentary rocks lying stratigraphically below the greenstones. The Prosperous Lake granite and southeastern granitic mass were probably derived by granitization of parts of the Yellowknife sediments.

The greenstones have been extensively altered by regional metamorphism. The metamorphic facies (Fig. 2) are distinctly related to the granodiorite-greenstone contact and comprise a contact amphibolite facies, an intermediate epidote amphibolite facies, and a poorly developed greenschist facies.

Two metamorphic facies are clearly defined in the sediments and are related to the Prosperous Lake and southeastern granitic masses (Fig. 1).

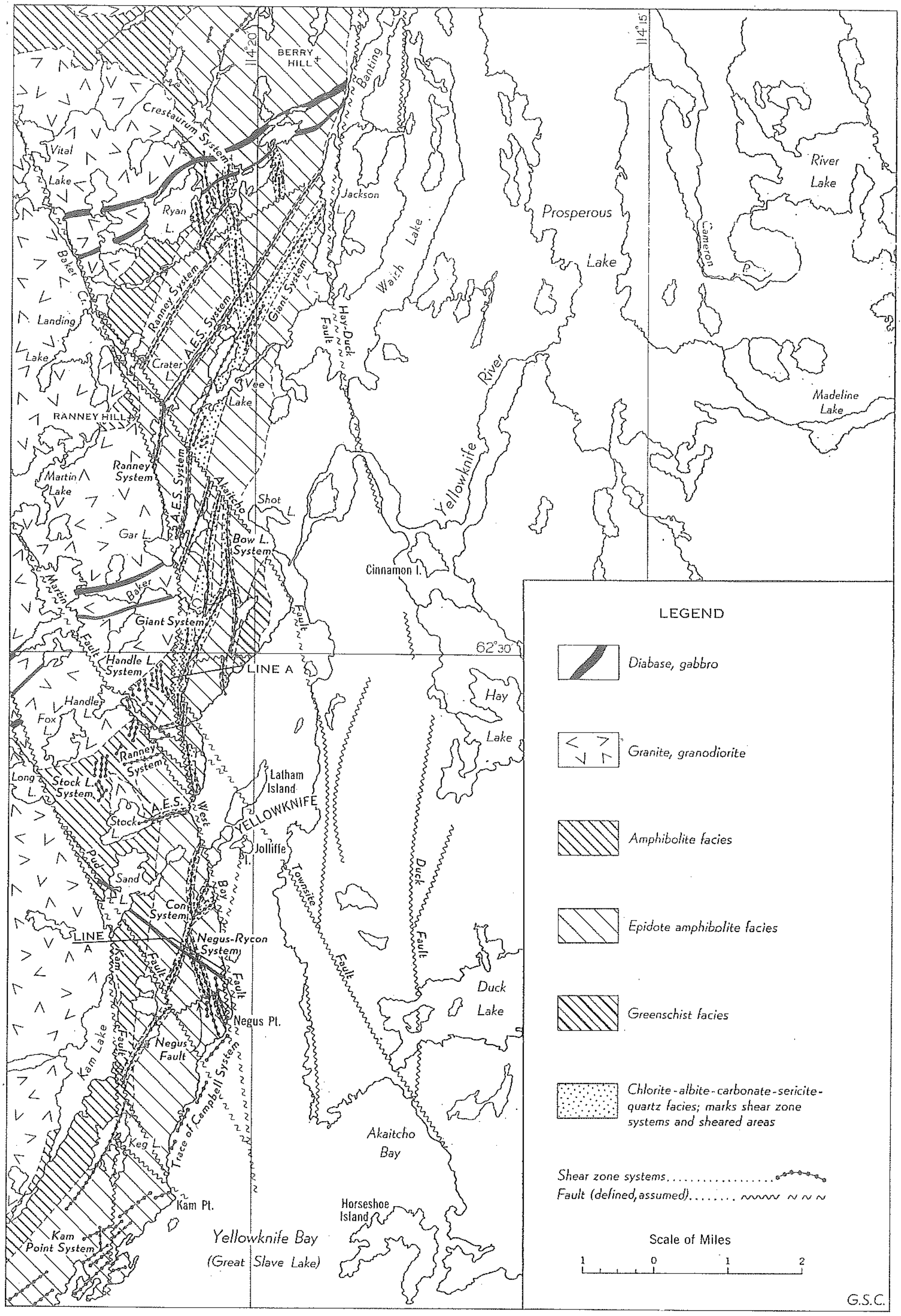


FIG. 2. Map showing metamorphic facies and shear zone systems, Yellowknife greenstone belt, Northwest Territories.

Next to these granitic masses a zone of nodular quartz-mica schist and hornfels containing garnet, andalusite, staurolite, and cordierite is present. This facies grades sharply into relatively unaltered greywacke, argillite, arkose. and slate.

Pegmatites, containing quartz, feldspar, mica, and locally typical pegmatite minerals such as tourmaline, beryl, and spodumene, are abundant in the Prosperous Lake granite and the quartz-mica schist and hornfels facies of the Yellowknife sediments.

Diabase dikes and basic sills are the youngest consolidated rocks in the district. These have a gabbroic to ultrabasic composition and are relatively unaltered except where cut by late faults.

The greenstone rocks of the district are folded into a broad northeasterly-plunging asymmetrical syncline. The northwest limb (greenstone belt) consists of a simple homoclinal succession of volcanic flows that dip and face southeast. The southeast limb is overturned and is in part folded into a subsidiary anticline. The sediments of the Yellowknife group are complexly folded into tight isoclinal folds which in turn have been cross-folded.

Two ages of shear zones occur in the greenstone belt (Fig. 2) : (a) early shear zones that parallel the lava flows in strike and dip and contain a few small high-grade gold-quartz lenses, e.g., Ranney system, and, (b) shear zones that transect the lava flows and contain the large economic gold-quartz veins and lenses of the district, e.g., Con system. The Giant-Campbell shear zone system is the major ore-bearing system in the district and probably formed along a major thrust fault zone. The smaller but productive Con and Negus-Rycon systems are subsidiaries of this large system.

In the shear zone systems the principal ore controls are shear zone junctions and flexures and drag-folded parts of the large schist zones. The deposits are veins, lenses, and complex bodies of quartz that are generally marked by an adjacent carbonate-sericite-pyrite-arsenopyrite alteration halo. This halo grades imperceptibly into the chlorite-carbonate or chlorite schist of the shear zones.

In the sediments of the Yellowknife group gold-quartz veins and lenses are developed in small faults, drag folds, saddle reefs, ruptured and sheared axes of isoclinal folds, and other structures, all formed during the complex folding of the sedimentary rocks. Most of these veins and lenses have no well-developed alteration zones, but a few are marked by a narrow zone of tourmalinized rock. Structurally these veins and lenses are isolated bodies, unconnected to any system of fractures or faults along which hydrothermal solutions could have travelled.

Some of the gold-quartz lenses in the greenstones cut the last phase of granite dikes, from which it can be assumed that the deposits were formed after the emplacement and consolidation of the granitic mass flanking the greenstone belt. The lenses also cut the quartz-feldspar porphyry dikes and masses, thus ruling out the possibility that these bodies were the source of hydrothermal solutions from which the lenses were derived. In the sedimentary area the quartz lenses and veins appear to be contemporaneous with the metamorphism of the sediments and the formation of the Prosperous Lake granite.

Post-diabase faults and fractures cut all rocks in the district. In these faults quartz-hematite lenses and "giant quartz veins" are localized at or near junctions and flexures. Silicification, sericitization, and chloritization are the principal alteration effects in the rocks adjacent to the quartz bodies.

In the greenstones the principal minerals in the epigenetic deposits of the shear zones are quartz, carbonates, sericite, pyrite, arsenopyrite, stibnite, chalcopyrite, sphalerite, pyrrhotite, various sulphosalts, galena, scheelite, gold, and aurostibite. Two or more generations of quartz, carbonates, sulfides and gold are generally present in the complex orebodies. In the sediments the gold-quartz veins and lenses contain essentially quartz, with small amounts of pyrite, sphalerite, galena, tourmaline, and gold. Two or more generations of gold and quartz may be present in the veins.

The characteristic minerals in the late faults are quartz and hematite with small amounts of carbonates and chalcopyrite. Only traces of gold are found in the mineralized parts of the late faults.

GEOCHEMISTRY OF THE VOLATILES

A knowledge of the chemistry of the volatiles particularly water, carbon dioxide, sulfur, and boron is essential in any discussion of the origin of ore deposits. On the one hand are hydrothermalists who think that volatiles such as water and carbon dioxide are the transporting media for the ore and gangue elements. On the other are those who hold that the elements are concentrated by diffusion processes and that the volatiles act principally as catalysts and activating agents. It was with both these concepts in mind that the chemistry of water, carbon dioxide, sulfur, and boron, was traced in detail in the metamorphic facies, shear zones, and gold deposits.

All analyses for the volatiles were made on fresh material from outcrops and mine workings. Composite samples from the various facies were employed for the most part, but samples on traverses across the metamorphic facies were used to trace the migration of water, carbon dioxide, and sulfur, e.g., Line A, Fig. 2.

Water, Carbon Dioxide, and Sulfur.—In the rocks, in their present state, most of the water is bound in amphiboles, chlorite, and the mica minerals. Small amounts also occur along grain boundaries and in liquid inclusions in all minerals. Carbon dioxide is fixed mainly in the carbonates, but small amounts are present in apatite and other minerals, along grain boundaries, and in liquid inclusions. Sulfur is held principally in the sulfides with only small amounts in apatite and in the sulfates of liquid inclusions. Table 1 records the contents of water, carbon dioxide, and sulfur, in the metamorphic facies, shear zones, and quartz lenses of the greenstone belt and sedimentary area. Figure 3 gives a graphical representation of the generalized analytical results from the greenstone belt. Attention is called to the following features:

In the greenstone belt the contents of water, carbon dioxide, and sulfur increase toward the lower grade facies, i.e., outwards from the granodiorite. In the sedimentary area water is the only volatile that shows any significant change across the metamorphic facies. As in the greenstone belt there is an increase in the content toward the lower grade facies.

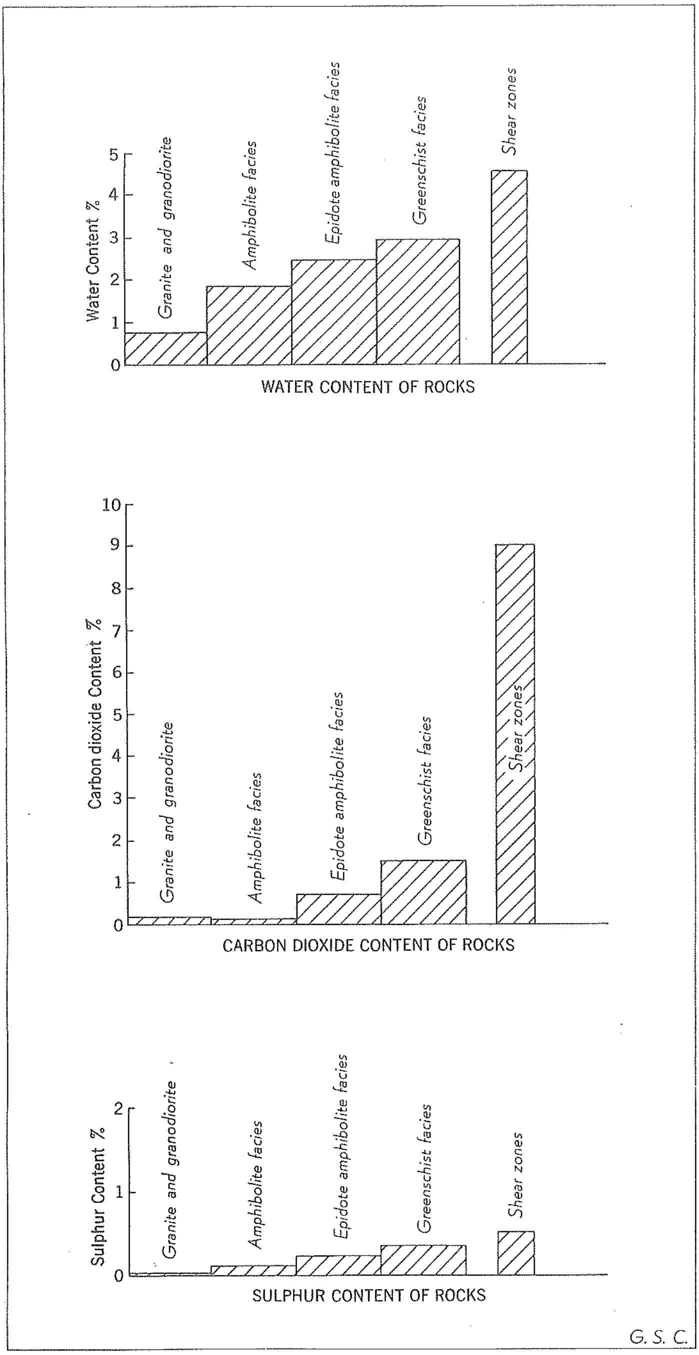


FIG. 3. Water, carbon-dioxide, and sulfur content of granitic rocks, metamorphic facies, and shear zones, Yellowknife greenstone belt, Northwest Territories.

TABLE 1

CONTENT OF VOLATILES (H_2O, CO_2, S) IN ROCKS OF THE YELLOWKNIFE DISTRICT

Description of rock and facies	H_2O (total), %	CO_2, %	S, %	Remarks
Greenstone Belt				
Western granodiorite	0.75	0.14	0.03	Average values calculated from analyses of composite samples
Amphibolite facies	1.84	0.09	0.09	Average values calculated from analyses of composite samples
Epidote amphibolite facies	2.47	0.68	0.20	Average values calculated from analyses of composite samples
Greenschist facies	3.00	1.28	0.20	Average values calculated from analyses of composite samples
Tuffs and other sediments	1.56	5.55	1.45	Analysis of composite sample of graphitic tuff
Chlorite-carbonate schist in shear zones	5.33	8.03	0.12	Composite sample
Carbonate-sericite schist in shear zones	1.26	15.57	3.26	Composite sample
Quartz-carbonate lenses and veins	0.50	4.00	2.30	Contents variable; approximations only
Sedimentary Area				
Prosperous Lake granite	0.43	0.18	Trace	Average values calculated from analyses of composite samples
Knotted quartz-mica schist and hornfels	2.38	0.12	0.13	Average values calculated from analyses of composite samples
Relatively unaltered slate, phyllite, greywacke, and argillite	3.35	0.07	0.12	Average values calculated from analyses of composite samples
Pegmatites	0.50	0.10	Trace	Average values calculated from analyses of composite samples
Quartz veins	0.50	0.10	0.50	Contents variable; approximations only

Analyses by J. A. Maxwell, R. J. C. Fabry, S. Courville, and R. W. Boyle.

The shear zones cutting the greenstones show a marked enrichment in water, carbon dioxide, and sulfur, and the quartz-carbonate bodies in the shear zones are enriched in carbon dioxide and sulfur. The pegmatites cutting the sediments exhibit no enrichment in the volatiles nor are they surrounded by hydrous or carbonated zones. The quartz veins in the sediments are likewise not enriched in water or carbon dioxide, but locally they may have higher than average amounts of sulfur.

The profiles of water, carbon dioxide, and sulfur are instructive in determining the trend of migration of these compounds and their probable source. Ideally the profiles along traverse lines rise toward the lower grade facies and simulate diffusion profiles (Fig. 4 (a)). They are best explained by the mobilization of volatiles initially present in the rock followed by diffusion away from a high temperature zone, i.e., diffusion down a thermal gradient. If the granitic rocks were the source of the volatiles the profiles should simulate the one shown in Figure 4 (*b*). That is, the greatest concentration of volatiles should exist in the rocks adjacent to the source, and the content of volatiles should decrease with distance from the source.

It might be argued, however, that when the granitic rocks produced the volatiles (i.e., during their last stages of crystallization) the adjacent greenstone rocks were so highly heated that the volatiles were carried well out of the contact zones. Here one must carefully note certain phase relationships between the granitic rocks and the amphibolite facies of the greenstones. Muscovite and chlorite are present in the last phases of the western granitic mass. These minerals are also present in the greenschist facies and in the shear zones where the volatile content is high. From thermodynamic considerations it follows that since muscovite and chlorite were stable minerals when the granite formed they would also have been stable in the adjacent amphibolite facies if the necessary amount of water had been available. Muscovite and chlorite are, however, not prevalent minerals in the amphibolite facies and the inference is, therefore, clear that large amounts of water and carbon dioxide were not given off by the granite and added to the adjacent amphibolite zone. If the volatiles had migrated in quantity into the greenstone rocks adjacent to the granite, extensive carbonated, sericitized, and chloritized zones would have been developed, and large concentrations of sulfides could be expected.

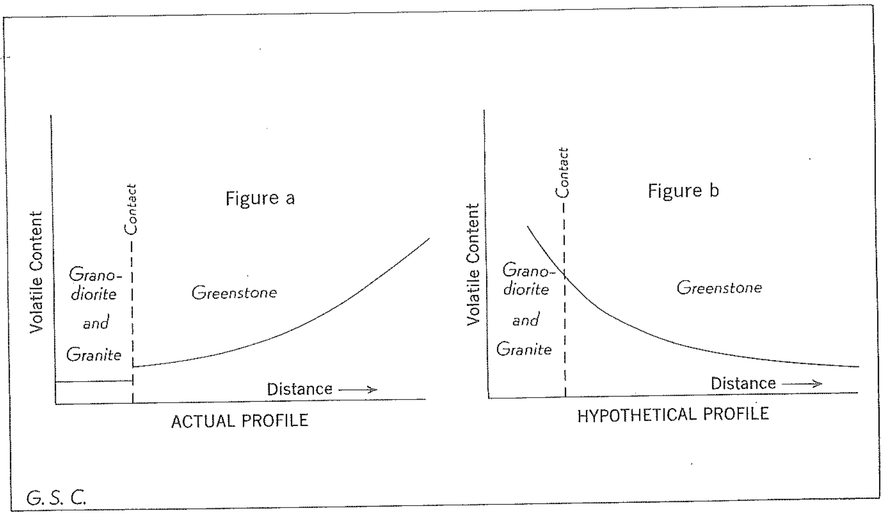
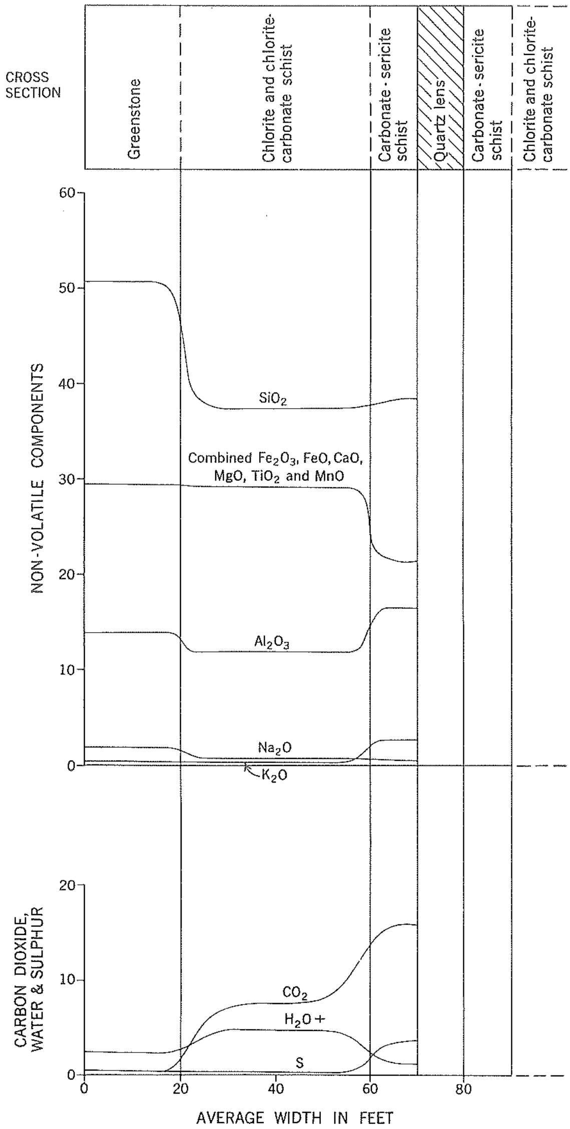


FIG. 4. Comparison of actual and hypothetical profiles of volatile contents of greenstone rocks.

In the sedimentary rocks similar features are present. There are no hydrated, carbonated, or sulfurized zones adjacent to the Prosperous Lake granite. On the contrary, the rocks in the knotted quartz-mica schist zone adjacent to the granite are dehydrated having lost more than one percent of their water when compared with the average water content of a normal sedimentary series of shale, argillite, and greywacke.[2]

[2] The average water content of a normal sedimentary series of shale, argillite, and greywacke, as compiled from various sources, lies close to 3.5%. R. A. Daly (Igneous rocks and the depths of the earth, McGraw-Hill Book Company, New York, 1933, p. 478), gives 1.64% H_2O as an average for sandstones and 5.02% H_2O for shales.



G.S.C.

FIG. 5. Chemical changes produced by alteration of greenstone. Composite samples from all shear zones.

Space does not permit a detailed discussion of the role of carbon dioxide, water, and sulfur in the formation of the shear zones and gold-quartz bodies in the greenstone belt. For this the interested reader is referred to a previous paper by the writer (4). Only the more important features are described here.

Table 2 records analyses of composite samples of greenstone, chlorite-carbonate schist, and carbonate-sericite schist, and Figure 5 gives a graphical representation of the chemical changes that have taken place during the formation of gold-quartz lenses in the shear zones. The main points of interest are the consistent increase in carbon dioxide and the marked decrease in silica as the quartz bodies are approached. Water is enriched in the chlorite and chlorite-carbonate phase and is lower in content in the sericite phase. Sulfur shows a slight decrease in the chlorite-carbonate schist and a marked enrichment in the carbonate-sericite phase. Potash is enriched in the carbonate-sericite phase, and the soda content is decreased in both the chlorite-carbonate and carbonate-sericite phases. Iron, magnesium, calcium, and manganese show individual trends, but the total content of their combined oxides decreases in all phases of alteration. Alumina exhibits a slight decrease in the chlorite-carbonate phase and a substantial gain in the carbonate-sericite phase.

These changes in the chemical constituents represent a trend toward equilibrium in the shear zones. As carbon dioxide, water, and sulfur diffused into and through the shear zones, the feldspars and cafemic minerals were attacked, chlorite, carbonates, sericite, and sulfides were formed at their expense, and large quantities of silica were released. These introductions and subsequent reactions were promoted principally by the dilatancy of the shear zones. Where structural movement along the shear zones created low pressure zones the physiochemical equilibrium was re-established by the lateral and upward migration of silica into these zones where this constituent was precipated as quartz to form the quartz bodies. Similar equilibrium adjustments have lead to the rearrangement of the cafemic oxides, soda, potash, alumina, and other constituents within the shear zones.

Boron.—The results of a spectrographic investigation of the boron content of the various rock types at Yellowknife, together with average analyses of similar unmetamorphosed rock types are given in Table 3. The following points are evident.

The sedimentary rocks contain much higher contents of boron than the basic volcanic and dike rocks, a feature that is also shown by the average boron contents of similar unmetamorphosed rocks. Hence, one can conclude that the differences in the boron contents of the Yellowknife rocks were inherited when the rocks were formed and are not the result of later additions from magmatic solutions. It should also be pointed out that there is no noticeable enrichment of boron in the high-grade facies of either the greenstone belt or sedimentary area, a feature that further indicates that the granites did not supply the boron. Similar conclusions were reached by Goldschmidt (11) as a result of his research on boron in rocks.

The shear zones and quartz veins in the greenstone rocks (average boron content, < 10 ppm), are markedly low in boron, whereas the quartz veins and pegmatites in the knotted schist aureole (average boron content, 70 ppm) of the Prosperous Lake granite are enriched in boron. The pegmatites in the Prosperous Lake granite (average boron content, 170 ppm) carry significant concentrations of boron held in tourmaline whereas those present in

TABLE 2

Chemical Changes Produced by Alteration of Greenstone, Composite Samples of All Shear Zone Systems

	A-76, %	A-251, %	Adjusted, %	Gains and losses in constituents	Percentage gains and losses	A-250, %	Adjusted, %	Gains and losses in constituents compared with A-76	Percentage gains and losses
SiO_2	50.45	40.36	37.12	−13.33	− 26.42	38.19	38.30	−12.15	− 24.08
Al_2O_3	13.96	12.87	11.84	− 2.12	− 15.19	16.26	16.31	+ 2.35	+ 16.83
Fe_2O_3	2.00	1.06	0.97	− 1.03	− 51.50	0.38	0.38	− 1.62	− 81.00
FeO	9.61	12.00	11.04	+ 1.43	+ 14.88	3.49	3.50	− 6.11	− 63.58
CaO	10.23	8.94	8.22	− 2.01	− 19.65	11.02	11.05	+ 0.82	+ 8.02
MgO	6.53	8.43	7.75	+ 1.22	+ 18.68	5.77	5.79	− 0.74	− 11.33
Na_2O	1.85	0.90	0.83	− 1.02	− 55.14	0.29	0.29	− 1.56	− 84.32
K_2O	0.39	0.41	0.38	− 0.01	− 2.56	2.82	2.83	+ 2.44	+ 622.64
H_2O+	2.36	5.20	4.78	+ 2.42	+102.54	1.16	1.16	− 1.20	− 50.85
H_2O-	0.11	0.13	0.12	+ 0.01	+ 9.09	0.10	0.10	− 0.01	− 9.09
TiO_2	1.02	1.05	0.97	− 0.05	− 4.90	0.82	0.82	− 0.20	− 19.61
P_2O_5	0.13	0.11	0.10	− 0.03	− 23.08	0.21	0.21	+ 0.08	+ 61.54
MnO	0.21	0.22	0.20	− 0.01	− 4.76	0.17	0.17	− 0.04	− 19.05
CO_2	0.68	8.03	7.39	+ 6.71	+986.76	15.57	15.62	+14.94	+2,197.06
S	0.22	0.12	0.11	− 0.11	− 50.00	3.26	3.27	+ 3.05	+1,386.36
Cl	0.02	0.00	0.00	− 0.02	−100.00	0.01	0.01	− 0.01	− 50.00
Cr_2O_3	0.03	0.03	0.03	0.00	0.00	0.00	0.00	− 0.03	− 100.00
C	0.04	0.12	0.11	+ 0.07	+175.00	0.04	0.04	0.00	0.00
As_2O_3						1.50	1.50		
Total	99.84	99.98				101.06			
Less 0 = S, Cl	0.10	0.05				1.22			
Net total	99.74	99.93				99.84			
Specific gravity	2.99	2.75				3.00			
Analyst	J. A. Maxwell	S. Courville				S. Courville			

Notes:

1. A-76—Composite sample of epidote amphibolite facies (greenstone).
2. A-251—Composite sample of chlorite-carbonate schist of shear zones.
3. A-250—Composite sample of carbonate-sericite schist of shear zones.
4. Adjusted % = percentages of A-251 and A-250 multiplied by the factors 2.75/2.99 and 3.00/2.99, respectively, to reduce to a common volume.

TABLE 3

BORON CONTENT OF THE ROCKS OF THE YELLOWKNIFE DISTRICT COMPARED WITH GEOCHEMICAL AVERAGES OF SIMILAR UNMETAMORPHOSED ROCK TYPES

Yellowknife District, rock types, facies, etc.	B, (ppm) (1)	Similar rock types (2)	Geochemical average B, (ppm)
Greenstone belt			
Western granodiorite, composite	20–40	Granites	0.9–3
Amphibolite facies	<10	Basalts and gabbros	1.6–3
Epidote amphibolite facies	<10		
Greenschist facies	<10		
Meta-diorite and gabbro dikes	<10		
Shear zones	<10		
Tuffs	10–100		
Sedimentary area			
Prosperous Lake granite and pegmatites, composite	200–600		
Prosperous Lake granite	40–300	Granites	0.9–3
Pegmatites	1,000–2,000		
Knotted quartz-mica schist and hornfels	40–100	Shales	310
Relatively unaltered argillite, graywacke, slate, etc.	50–100	Quartzites	9–31
Quartz-feldspar porphyry	20–60		
Diabase dikes	<10	Basalts and gabbros	1.6–3

Notes:

(1) Analyses by spectrographic laboratory, Geological Survey of Canada.

(2) Data from Rankama, K., and Sahama Th. G.—Geochemistry, University of Chicago Press, 1949.

the western granodiorite (average boron content 30 ppm) contain little or no tourmaline. From the foregoing it is clear that where quartz bodies and pegmatites cut rocks containing an ample supply of boron they are enriched in this element, and the obvious inference is that the host rocks have provided the boron. If the boron were derived from magmatic hydrothermal solutions it is most difficult to account for these differential concentrations on any physiochemical basis.

Discussion.—There is no need to call upon granitic differentiation processes for any of the volatiles in the rocks, shear zones, quartz bodies, or pegmatites, in the Yellowknife district. On the contrary the facts suggest that initially sufficient quantities of the volatiles were normal components of the country rocks.

Considering the greenstones it is logical to assume that prior to metamorphic reconstitution they would contain one-half of one percent water (average for basalts). Sulfur and carbon dioxide would likewise be initial constituents. Many of the greenstones are amygdalar indicating a considerable initial volcanic gas content (H_2O, HCl, CO_2, H_2S, SO_2 etc.). The boron content would be low judging from the geochemical averages of basic rocks. Furthermore, it should be borne in mind that the greenstones were laid down on the ocean floor as suggested by the presence of pillows and interbedded tuffs. During their deposition, consolidation, and cooling they would absorb and trap sea water containing various other volatiles. As a grand total, therefore, it can be logically assumed that the initial concentration of volatiles in the greenstones would be sufficient to produce any of the metamorphic effects in the rocks and the alteration of the shear zones.

As for the sediments it is well known that shales, argillites, etc., contain an abundance of water both in their constituent minerals and in interstices. Sulfur and carbon dioxide are also normal original constituents of sediments and are commonly present in considerable concentrations. Boron would be initially present in the tourmaline of the resistates and also as adsorbed ions.

On quantitative grounds some may question the postulate that the host rocks were the source of the sulfur and metallic elements in the deposits. There seems to be little justification for this criticism when one considers the facts on the provenance of these elements. In Table 4 are given total amounts of S, As, Sb, Cu, Zn, Au, and Ag in the rock of the Giant-Campbell system prior to shearing and the amounts of these elements in the deposits. The ratio of concentration is also given as a percentage. For calculation the dimensions of the system were taken as follows: length—10 miles, average width—500 feet, depth—3 miles. The contents of the elements in this amount of rock, as averaged from spectrographic and chemical analyses of unsheared greenstone rocks, were taken as follows: S—1,500 ppm, As—12 ppm, Sb—1 ppm, Cu—50 ppm, Zn—50 ppm, Au—0.01 ppm and Ag—1 ppm. The amount of ore in the system was assumed to be 6 million tons, twice the amount mined and in known reserves. The tenor of this ore, as averaged from the analyses of the ores in the greenstone belt, was taken as follows: S—2.34%, As—1.35%, Sb—0.15%, Cu—0.07%, Zn—0.28%, Au—0.654 ounce/ton, and Ag—0.139 ounce/ton.

The author is fully aware that many factors enter into calculations such as those given in Table 4. However, he feels that while the figures are not exact they at least give the order of magnitude. It is apparent from these figures that all sulfur, arsenic, antimony, and other chalcophile elements could have been derived solely from the sheared rock of the shear zone. When one considers the probable contribution of gold, silver, and the sulfide con-

TABLE 4

CONTENTS OF CHALCOPHILE ELEMENTS IN SHEAR ZONES AND DEPOSITS OF THE GIANT-CAMPBELL SYSTEM

Element	Total content in shear system prior to shearing and alteration (millions of tons)	Total content in deposits (millions of tons)	Ratio of concentration, %
S	62	0.14	0.226
As	0.5	0.081	16.2
Sb	0.04	0.009	22.5
Cu	2.0	0.004	0.20
Zn	2.0	0.017	0.85
Au	12.2 $\times 10^6$ (ozs.)	3.9 $\times 10^6$ (ozs.)	32.0
Ag	1,219 $\times 10^6$ (ozs.)	0.834 $\times 10^6$ (ozs.)	0.068

stituents to the shear zones during the metamorphism of the greenstone belt as a whole there is little need to call upon outside sources such as magmatic solutions to supply these elements. The same can also be said for deposits in the sediments.

The present distribution of the volatiles in the metamorphic facies and shear zones in the greenstones and in the metamorphic facies in the sediments is best explained by the mobilization, migration, and concentration of the volatiles initially present in the rocks. The migration of the volatiles has taken place under the influence of a thermal gradient, and equilibrium among the components of the rocks in the presence of differing concentrations of volatiles has been attained by the formation of characteristic mineral phases that enable one to map the metamorphic facies. In the shear zones equilibrium has been established by the migration of silica into dilatant zones to form the quartz bodies and by the rearrangement of numerous other constituents. Similar chemical adjustments during metamorphism have given rise to the quartz lenses in the sedimentary rocks.

In the country rocks and shear zones the effects of the volatiles are manifest over great distances, and alteration of the rocks and minerals has taken place in the minutest detail. Such pervasive chemical effects can hardly be attributed to the action of solutions percolating along fractures. Rather, diffusion processes seem more capable of producing such extensive alteration effects and giving the characteristic profiles across the shear zones and metamorphic facies. Considering the deep seated conditions under which the gold-quartz lenses were formed one is led to the conclusion that ionic or gaseous diffusion along grain boundaries and other discontinuities in the minerals and rocks was the effective mechanism by which both the volatiles and metals migrated.

If one accepts the migration of elements in rocks by diffusion, water no longer plays its classical role as a transporting agent in the hydrodynamical sense. Instead this volatile acts mainly as a catalyst and activating agent which promotes the mobilization and migration of many constituents. The writer is of the opinion that large volumes of flowing water are unnecessary for the formation of veins and lodes of the deep-seated Yellowknife type. A more adequate explanation of the role of water would seem to be that this volatile formed a pervasive gaseous medium through which the various ions migrated. This view can be supported by the recent researches of Morey (18) who has shown that numerous oxides, including silica, are relatively soluble in gaseous water, and by the observations of many chemists that ions migrate readily through a gaseous water medium.

In the writer's view the role of water in the formation of the Yellowknife deposits has been, therefore, largely that of a catalyst. In addition this volatile in consort with carbon dioxide and sulfur has acted as an activating agent in liberating large amounts of silica that was delivered to dilatant zones in the shear zones of the greenstones. In this role the three volatiles have also bound many elements forming the characteristic minerals of the shear zones and alteration halos.

SYNTHESIS OF MINERALIZATION PROCESSES

The role of the volatiles and the origin of the gold-quartz deposits at Yellowknife can best be illustrated by the following historical synthesis of the mineralization of the greenstone belt and sedimentary rocks. Figure 6 is a schematic representation of the synthesis as it applies to the greenstone belt.

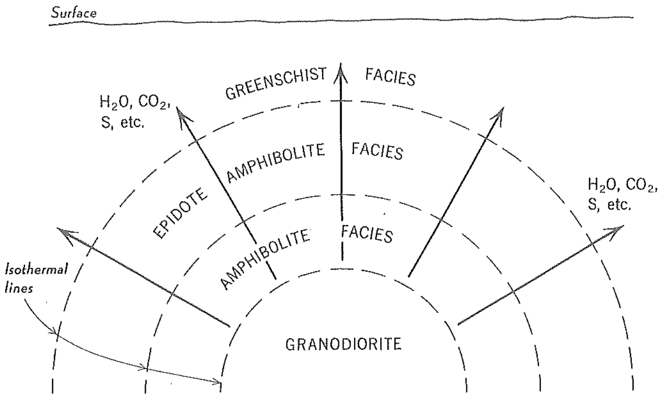
In early Precambrian time a thick series of marine sediments was laid down followed by extensive extrusions of lava flows that now form the greenstone belt. This was followed by further deposition of marine sediments (Yellowknife group).

A period of great orogeny followed during which the competent lavas were folded into a broad syncline, and the less competent sediments were complexly folded. Near the end of the orogenic period the sediments lying below the greenstones were granitized to form the western granitic mass. Large zones of the sediments lying above the greenstones (Yellowknife group) were also granitized to form the Prosperous Lake and southeastern granitic masses.

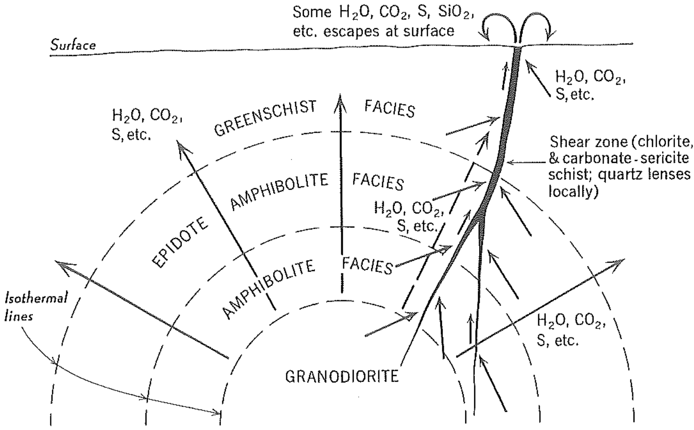
During these orogenic processes a strong temperature gradient existed outward from the foci of granitization leading to the formation of the zone facies of metamorphism in the greenstone belt and sedimentary rocks. At this time much water, carbon dioxide, sulfur, and some of the chalcophile elements including gold and silver, were mobilized in the greenstone belt and migrated toward the cooler parts, that is, down the temperature gradient at right angles to the isothermal lines as shown by the vectors in Figure 6 (a). If there had been no structural breaks in the rocks the result would have been a simple metamorphic halo about a granitized centre.

However, in the greenstone belt a great system of shear zones was formed near the end of the orogeny, after the consolidation of the granitic bodies. As a consequence the migration vectors were radically changed by the dilatancy of the shear zones as shown in Figure 6 (b). The shear zones literally sucked the mobile carbon dioxide, water, sulfur, and other elements from the country rocks and funnelleled them toward the surface. Because of the great extent and depth of the shear zones the effects of dilatancy were undoubtedly felt over a great volume of the country rocks, and mobile elements were probably contributed from points thousands of feet horizontally and vertically from the shear zone systems. Extensive structures that impose such marked dilatant effects on the country rocks may be termed "first degree dilatant zones."

During the formation of the large shear zones carbon dioxide, water, and sulfur reached a high concentration along them. As a consequence the chemical equilibrium was strongly displaced, and chloritization, carbonatization, and pyritization, of an enormous tonnage of volcanic rock too place. This led to the liberation of silica, potassium, calcium, iron, etc., and in addition gold, silver and other metallic elements present in the rock affected by alteration. These liberated compounds and elements, together with those added to the shear zones by diffusion from the host rocks, migrated laterally and vertically to "second degree" low pressure dilatant zones at shear zone junctions and other structural locales where contorted zones or openings were



(a) Formation of metamorphic facies



(b) Formation of mineralized shear zones

Note: Arrows indicate direction of migration of H_2O, CO_2, S, As, and other elements

G.S.C.

FIG. 6. Schematic diagrams to illustrate the formation of metamorphic facies and mineralized shear zones in the greenstone belt.

formed. In these sites, secondary reactions promoted by low pressure and lower chemical potential resulted in the precipitation of quartz, carbonates, pyrite, arsenopyrite, and gold, forming quartz-sulphide-gold lenses with adjacent alteration halos.

In the sedimentary rocks the quartz lenses and their contained sulfides and gold were concentrated by similar processes. During severe structural deformation of the rocks many dilatant zones appeared in drag-folded parts of the beds, along faults, and along sheared axes of anticlines and synclines. To restore the chemical equilibrium within the rocks silica, sulfur, boron, and various metallic elements migrated into these zones where they were precipitated, forming the gold-quartz-sulfide veins and lenses. The mobilization and migration of the compounds and elements forming the gangue and ore minerals were promoted principally by the high temperature and stress that prevailed during the metamorphic processes.

In late Precambrian time all rocks were extensively faulted, and this was followed by deposition of quartz and hematite at certain favorable sites in the late faults. The agents of regional metamorphism were not active at this time and only the highly mobile compound, water, played a major part in the limited mineralization. The water attacked the various minerals in the fault breccia and adjacent wall rocks reducing them to chlorite and sericite. Silica was liberated together with iron and a few other elements. The silica and iron migrated into dilatant zones along the faults where they were precipitated as quartz and hematite. The presence of hematite emphasizes the high oxidation potential present when the mineral was formed. If carbon dioxide and sulfur had been mobilized, as was the case during the formation of the shear zones, extensive bodies of carbonates and sulfides would have been formed in the late faults.

CONCLUSIONS

The detailed research on the origin of the gold-quartz deposits of the Yellowknife district suggests the following:

1. The volatiles and other constituents of the deposits were derived by lateral and vertical secretion from the series of rocks in which they occur.
2. The energy necessary to mobilize various elements and concentrate them in deposits was in part inherent in the metamorphic processes and in part due to dilatancy resulting from structural deformation.

Geological Survey of Canada,
Ottawa,
Jan. 22, 1959

REFERENCES

1. Bateman, J. D., 1952, Some geological features at Giant Yellowknife: Proc. Geol. Assoc. Canada, v. 5, p. 95–107.
2. Boyle, R. W., 1954, The shear zone systems of the Yellowknife greenstone belt: Canadian Min. Jour., v. 75, p. 59–64 and p. 69–75.
3. ——, 1954, The structural localization of the gold orebodies of the Yellowknife greenstone belt: Canadian Min. Jour. v. 75, p. 71–77.
4. ——, 1955, The geochemistry and origin of the gold bearing quartz veins and lenses of the Yellowknife greenstone belt: Econ. Geol., v. 50, p. 51–66.
5. ——, 19—, The geology, geochemistry, and origin of the gold deposits of the Yellowknife district, Northwest Territories: Geol. Surv. Canada, Memoir (in press).
6. Brown, C. E. G., and Dadson, A. S., 1953, Geology of the Giant Yellowknife Mine: Canadian Inst. Min. Metallurgy Trans., v. 56, p. 69–86.
7. Campbell, N., 1949, The Con-Rycon Mine, Yellowknife, N.W.T.: Canadian Inst. Min. Metallurgy Bull., v. 42, no. 446, p. 288–292.
8. Dadson, A. S., 1949, The Giant Yellowknife Gold Mine, Yellowknife, N.W.T.: Report, Giant Yellowknife Gold Mines, Ltd., March 30, 1949.

9. ——, 1949, The Giant Yellowknife: Western Miner, v. 22, no. 10, p. 82–90.
10. Dadson, A. S., and Bateman, J. D., 1948, Giant Yellowknife Mine: in Structural geology of Canadian ore deposits, Canadian Inst. Min. Metallurgy Jubilee Volume, p. 273–283.
11. Goldschmidt, V. M., 1954, Geochemistry: Oxford, p. 288–289.
12. Henderson, J. F., and Brown, I. C., 1950, Structure of the Yellowknife greenstone belt, Northwest Territories; Canadian Inst. Min. Metallurgy Trans., v. 53, p. 415–422.
13. ——, and ——, 1952, The Yellowknife greenstone belt: Canada Geol. Survey, Paper 52-28.
14. Jolliffe, A. W., 1938, Yellowknife Bay-Prosperous Lake area, Northwest Territories: Canada Geol. Survey, Paper 38-21.
15. ——, 1942, Yellowknife Bay, District of Mackenzie, Northwest Territories: Canada Geol. Survey, Map 709A.
16. ——, 1946, Prosperous Lake, District of Mackenzie, Northwest Territories: Canada Geol. Survey, Map 868A.
17. Jolliffe, F. (A. W.), 1936, Yellowknife River Area, Northwest Territories: Canada Geol. Survey, Paper 36-5.
18. Morey, G. W., 1957, The solubility of solids in gases: Econ. Geol., v. 52, p. 225–251.
19. Stockwell, C. H., 1933, Great Slave Lake-Coppermine River Area, Northwest Territories: Canada Geol. Survey, Sum. Rept. 1932, pt. C., p. 37–63.
20. Stockwell, C. H., and Kidd, D. F., 1932, Metalliferous mineral possibilities of the mainland part of the North West (sic) Territories: Canada Geol. Survey, Sum. Rept. 1931, pt. C, p. 70–85.