GEOLOGICAL
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CANADA

DEPARTMENT OF MINES
AND TECHNICAL SURVEYS

MEMOIR 310

THE GEOLOGY, GEOCHEMISTRY, AND ORIGIN OF THE GOLD DEPOSITS OF THE YELLOWKNIFE DISTRICT

R. W. Boyle

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PREFACE

Lack of detailed data on which to base theories for the origin of mineral deposits is a serious deficiency of geological knowledge, but recent developments have provided rapid and more accurate methods of obtaining and interpreting such data. New geochemical tools and techniques have now made it possible to make accurate quantitative studies on the distribution of chemical elements associated with the formation of a mineral deposit and such a study formed the basis for this report.

The gold deposits of the Yellowknife district range from simple to complex both structurally and mineralogically and are well exposed both on surface and underground. The author describes the gold deposits and their wall-rocks, and presents the results of detailed geochemical studies. He concludes that sufficient amounts of all the materials necessary for the formation of the gold deposits were present in the country rocks and suggests a process whereby the elements could have been transported to form the deposits.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, May 27, 1959

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THE GEOLOGY, GEOCHEMISTRY, AND ORIGIN OF THE GOLD DEPOSITS OF THE YELLOWKNIFE DISTRICT

Abstract

The geology and mineralogy of the gold-quartz deposits of the Yellowknife district are described together with an exhaustive study of the geochemistry of the country rocks and alteration zones and the geochemistry and origin of the ore and gangue minerals, and underground waters. The deposits occur as quartz lenses in extensive chlorite schist zones (shear zones) cutting Precambrian greenstones, and as quartz lenses developed along structures in highly folded and contorted Precambrian sedimentary rocks. Those in the greenstones represent concentrations of silica, carbon dioxide, sulphur, arsenic, antimony, gold, silver and numerous other metallic elements. Those in the sediments are mainly concentrations of silica, sulphur, boron, iron, lead, zinc, gold and silver.

Chemical evidence is presented to show that during metamorphism some of the carbon dioxide, water, sulphur, arsenic, gold, silver and other metallic elements in the greenstones were mobilized and migrated by diffusion into the shear-zone systems. In the shear zones, water and carbon dioxide reacted with the amphibolite rock producing extensive widths of chlorite and chlorite-carbonate-sericite schist. Silica, iron, potassium and other elements and compounds were mobilized and migrated into dilatant zones in the shear zones where they were precipitated to form the mineralized gold-quartz lenses and veins.

In the sediments, silica, boron, sulphur and various metallic elements were mobilized during metamorphism and migrated into, and were precipitated in, dilatant zones in faults, fractures, and drag-folds.

Résumé

Le présent mémoire traite de la géologie et de la minéralogie des gîtes de quartz aurifère de la région de Yellowknife. On y trouve aussi une étude pousée de la géochimie des terrains encaissants et des zones d'altération, de la géochimie et de l'origine du minerai et des minéraux de gangue, ainsi que des eaux souterraines. Les gîtes se présentent sous forme de lentilles de quartz au sein de zones étendues de schiste chloriteux (zones de cisaillement) qui coupent des roches vertes précambriennes, et sous forme de lentilles de quartz qui se forment le long des structures dans des roches sédimentaires précambriennes fortement plissées et déformées. Dans ces roches vertes, on trouve des concentrations de silice, d'anhydride carbonique, de soufre, d'arsenic, d'antimoine, d'or, d'argent et de plusieurs autres éléments métalliques. Les dépôts sédimentaires renferment surtout des concentrations de silice, de soufre, de bore, de fer, de plomb, de zinc, d'or et d'argent.

Il est démontré, à l'aide de preuves chimiques que, au cours du métamorphisme, une certaine partie de l'anhydride carbonique, de l'eau, du soufre, de l'arsenic, de l'or, de l'argent et des autres éléments métalliques présents dans les roches vertes a été mise en mouvement et a émigré par diffusion vers les formations des zones de cisaillement. Au sein de ces zones, l'eau et l'anhydride carbonique ont réagi au contact de la roche à amphibolite, produisant de larges formations de chlorite et de schiste à chlorite, à carbonate et à séricite. La silice, le fer, le potassium ainsi que d'autres éléments et composés se sont mis en mouvement et ont émigré vers les zones en dilatation au sein des zones de cisaillement, ou ils ont précipité sous forme de lentilles et de filons de quartz aurifère minéralisé.

Dans les dépôts sédimentaires, la silice, le bore, le soufre et divers éléments métalliques se sont mis en mouvement au cours du métamorphisme pour émigrer, en se précipitant, dans des zones en dilatation au sein de failles, de fractures et de plis d'entraînement.

Chapter I

INTRODUCTION

The first part of this memoir deals with the geology and mineralogy of the gold-quartz deposits of the Yellowknife district, Northwest Territories. The second part is concerned with the geochemistry of the country rocks and alteration zones and the geochemistry and origin of quartz, carbonate minerals, sulphides, gold, silver, and underground waters.

At present there are two producing gold mines in the district, the Con-Rycon mine of the Consolidated Mining and Smelting Company, Limited, and the Giant mine owned and operated by Giant Yellowknife Gold Mines Limited. Two former producers, the Ptarmigan mine and the Negus mine, suspended operations in 1942 and 1952 respectively. Two promising prospects held by Akaitcho Yellowknife Gold Mines Limited and Crestaurum Mines Limited remain at the development stage.

Orebodies of the Giant, Con-Rycon, and Negus mines have provided the largest part of the gold production of the Northwest Territories. The orebodies of the Con-Rycon and Negus mines were found in 1935 and 1936 respectively. The Con mine came into production in 1938, and the Negus in 1939. The main orebodies of the Giant mine were discovered in 1944, and production commenced in 1948. Complete histories of these three mines are given by Lord (1951)[1].

The gold-quartz deposits of Yellowknife occur in two distinct geological settings. The orebodies of the Giant, Con-Rycon, and Negus mines occur in quartz lenses in extensive chlorite schist zones (shear zones) cutting greenstones. The orebodies of the Ptarmigan mine and similar deposits occur in quartz lenses developed along faults, in drag-folds, and other structures in highly folded and contorted sedimentary rocks.

The deposits in the greenstones represent concentrations of silica, carbon dioxide, sulphur, arsenic, antimony, gold, silver and numerous other metallic elements. Those in the sediments are mainly concentrations of silica, sulphur, boron, iron, lead, zinc, gold and silver.

For the deposits in the greenstones chemical evidence is presented to show that, under the influence of a strong thermal gradient during the metamorphism of the greenstone belt, some of the carbon dioxide, water, sulphur, arsenic, gold, silver and other metallic elements in the original volcanic rocks was mobilized and migrated by diffusion into the shear-zone systems. In the shear zones the chemical equilibrium was strongly displaced, water and carbon dioxide reacted with the amphibolite rock producing extensive widths of chlorite and chlorite-carbonate-sericite schist, and silica, iron, potassium and other elements were

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[1] Dates, or names and dates in parentheses refer to publications in the Bibliography.

mobilized. These mobilized elements and compounds together with some of those added from the country rocks migrated into dilatant zones mainly at contorted shear-zone junctions and drag-folded parts of the shear zones. In these sites they were precipitated to form the mineralized gold-quartz lenses and veins.

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

Scope of Research

The research on the gold-quartz deposits consisted of both field and laboratory studies. Field work was done during the field seasons of 1950, 1951 and 1952 and constituted about one third of the research time. The remaining time was spent on detailed laboratory work in the geochemical laboratories of the Department of Geological Sciences, University of Toronto and later in the laboratories of the Geological Survey of Canada.

The field work consisted principally of mapping the extensive shear-zone systems in the greenstone belt and determining the structural factors that are responsible for localizing the gold-quartz lenses in the greenstone belt and sedimentary rocks. Field studies of the metamorphic facies were also carried out in both the greenstone and sedimentary belts.

During field work, samples of all rocks were systematically collected along selected traverses across the metamorphic facies. In addition, samples of granites, pegmatites, sedimentary rocks, greenstones, and diabase were collected for detailed geochemical work. Samples of all types of ores were collected for mineralogical and geochemical studies, and the alteration zones were sampled in all mines for thin-section work and detailed geochemical work.

The laboratory work consisted of thin- and polished-section studies, chemical analyses for both major and minor elements, and X-ray determinations of the complex minerals. Decrepitation studies and a sulphur isotope investigation were also carried out and are described elsewhere (Boyle, 1954c; Wanless, Boyle, and Lowdon, in press).

Acknowledgments

The author was ably assisted by G. Gillespie during the 1950 field season, by G. McVittie during the 1951 field season, and by R. Moxham during the 1952 field season. The enthusiastic cooperation of these three men is gratefully acknowledged.

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Many others aided the author by providing information and helping in many ways. Among these G. B. Langford, F. G. Smith, W. W. Moorhouse, R. Sproule, J. Whyard, C. E. Anderson, K. Kidder, S. Daigle, and the late W. Johnston deserve special thanks.

Mr. W. MacDonald, consulting geologist, Yellowknife, supplied valuable information on the gold deposits during their early stages of development.

Chapter II

TOPOGRAPHY, GENERAL GEOLOGY, AND STRUCTURE

The general geology of the Yellowknife district was described first by Stockwell and Kidd (1932) and by Stockwell (1933), and later in more detail, by Jolliffe (1936, 1938, 1942a, 1946). 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 (1950b, 1952b). These writers have covered the geology of the district in considerable detail. The brief description that follows summarizes the most important features and provides a background for the complex mineralization history of the district.

Topography and General Geology

The topography of the Yellowknife district is typical of the Precambrian Shield. Viewed from Berry Hill, the highest topographic feature within the district, the country is a peneplain strongly lineated by many valleys and rocky hills (*see* Plate I). With the exception of innumerable lakes and muskegs, almost continuous rock outcrop is present throughout the district. Large forest fires have removed the moss, lichen, and trees from the outcrops, and exceptional opportunities exist for the observation and study of the complex geological features.

The district was severely glaciated during Pleistocene time, and erratics, roches moutonnées, outwash sand and gravel plains, eskers, glacial lacustrine clays, and other glacial features are present in many areas. The sand plains afford excellent construction sites. The town of Yellowknife is built on the sand plain east of Sand Lake, and the airport occupies the broad sand plain south of Long Lake. Abandoned beaches occur locally throughout the area. These are at least 240 feet above Great Slave Lake in places and probably represent glacial material that has been reworked by wave action.

The district is in the region of permanently frozen ground, but the permafrost is patchy in its distribution. According to Bateman (1949) permafrost is absent beneath rock ridges or outcrop areas, but is generally present beneath deep overburden. He states that the depth of permafrost, in places down to 280 feet or more, is directly related to the thickness of the overburden and suggests that the permafrost may have originated in late glacial time and was preserved by the insulating cover of clay, sand, and muskeg.

Ice veins, filling cavities in late faults and fractures, have been observed in the permafrost zone down to depths of 250 feet or more. Some ice lenses present interesting mineralogical features and contain native gold (Boyle, 1951).

All consolidated rocks within the district are Precambrian in age. The table of formations (Table 1) follows the one suggested by Henderson and Brown

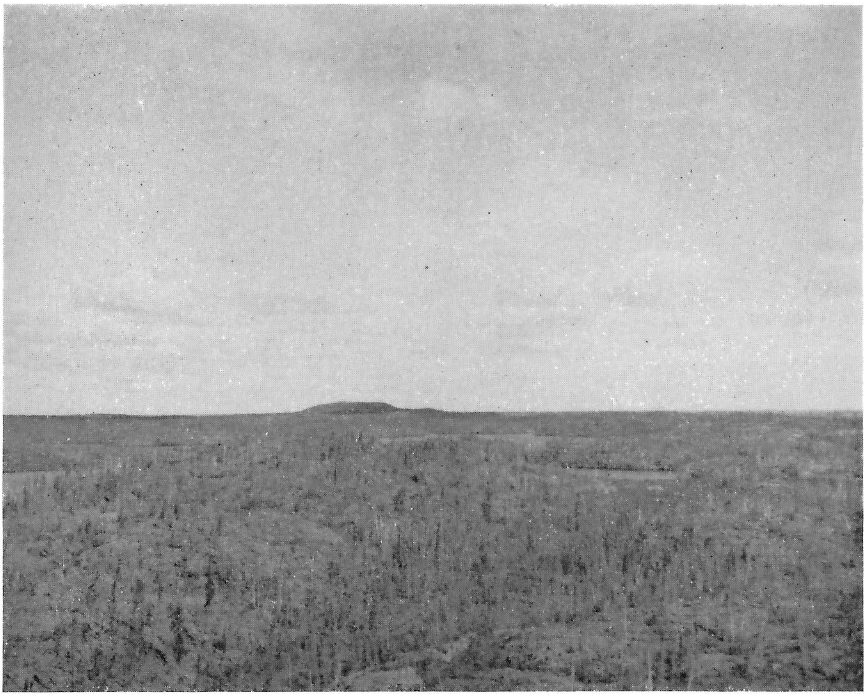

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Plate I. *View northwards toward Berry Hill (elevation 865 feet), Yellowknife district, Northwest Territories.*

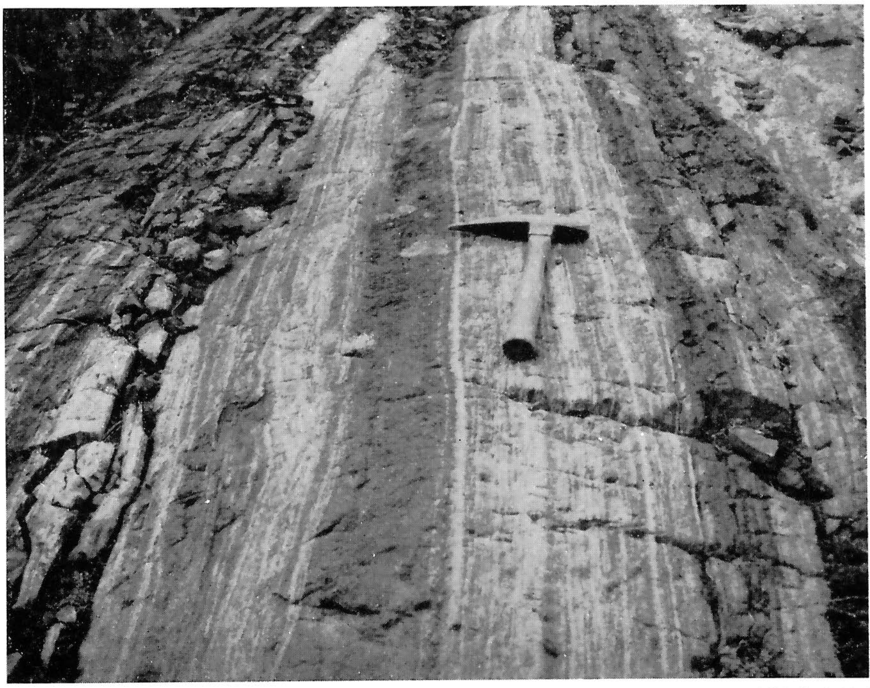

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Plate II. *Cherty tuffs, Joe Lake, Yellowknife greenstone belt.*

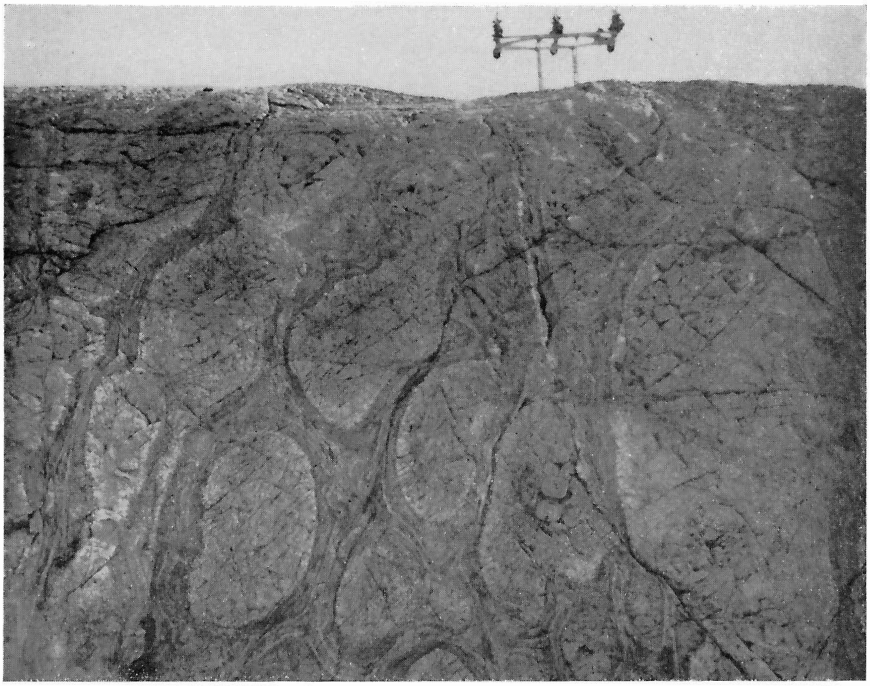

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Plate III. *Variolitic pillowed basalt, Yellowknife greenstone belt.*

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Plate IV. *Meta-gabbro dyke with an abundance of white-weathering zoisitized feldspar phenocrysts, Yellowknife greenstone belt.*

(1952b). The writer has added a few additional rock types that have a bearing on the mineralization of the district. The field relationships of the principal rock types are shown in Figure 1 (in pocket). Chemical analyses of the characteristic rock types are given in Chapter V.

The oldest rocks, Division A, Yellowknife group, are a succession of massive and pillowed andesite and basalt flows with interbedded dacite flows, tuffs (Plate II), and agglomerates. Some flows are pillowed and variolitic along strike for several miles and afford excellent horizon markers (Plate III).

The rocks of Division B comprise a thick series of sediments including greywacke, slate, quartzite, arkose, argillite, and phyllite. Near the base of the series, dacites, trachytes, agglomerates, and tuffs are interbedded with some conglomerate and greywacke. The contact relationships of these rocks with those of Division A are obscured for the most part by drift or lakes. In one

Table 1

Table of Formations

Age	Formation	Description	Remarks
Quaternary		Sand, gravel, clay	Principally glacial in origin.
		— Great Unconformity —	
Proterozoic		Diabase, gabbro	Dykes and sills of these rocks intrude all other consolidated rocks.
Archæan or Proterozoic		Prosperous Lake granite and associated pegmatites Granodiorite, granite, quartz-diorite, diorite, and aplite	Age relationships of Prosperous Lake granite and other granitic bodies uncertain. Folinsbee *et al.* (1956) consider all granitic bodies to be of a single Archæan age.
Archæan		Quartz-feldspar porphyry	Origin and age relationships to other granitic bodies uncertain.
		Meta-diorite and meta-gabbro dykes	Origin uncertain. These rocks cut the meta-gabbro sills and Division A below. They have not been observed cutting Division B.
		Meta-gabbro sills	
	Yellowknife group Division B	Greywacke, argillite, phyllite, quartzite, arkose, tuffs, conglomerate, and their metamorphic equivalents Dacite, trachyte, rhyolite, quartz porphyry, volcanic breccia, agglomerate, and tuff	Division B overlies Division A with apparent conformity.
	Division A	Basalt, andesite, dacite, cherty tuffs, tuffs, and agglomerates	
Proterozoic (?)	Unclassified	Conglomerate and quartzite	These rocks rest with angular unconformity on Division A of the Yellowknife group, but relations to Division B are unknown.

Figure 2
Yellowknife greenstone belt showing metamorphic facies, District of Mackenzie, Northwest Territories

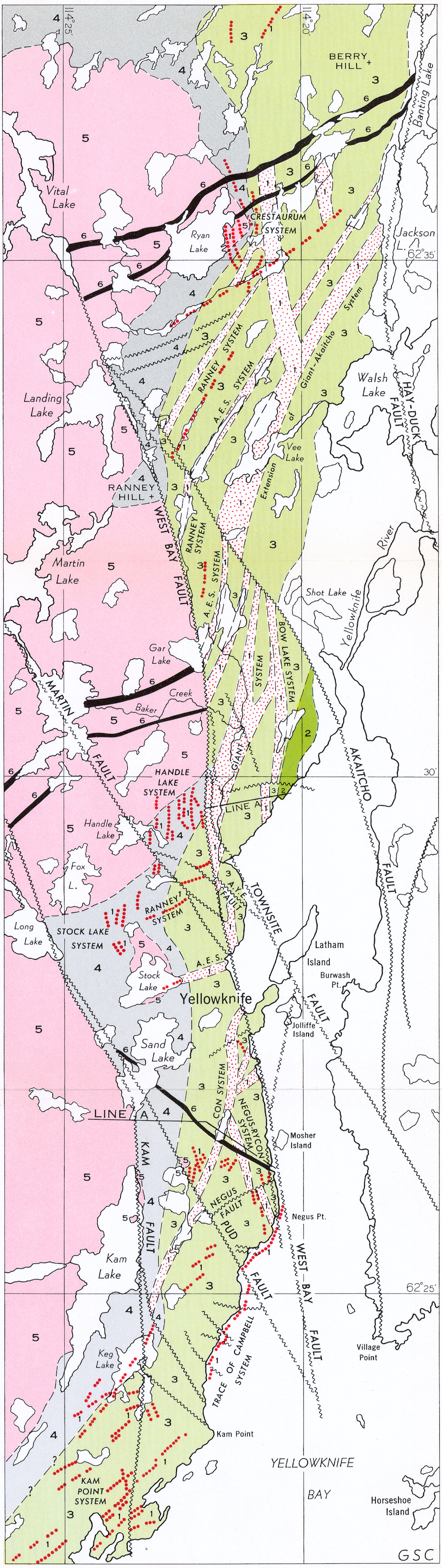
Scale of Miles
1 0 1

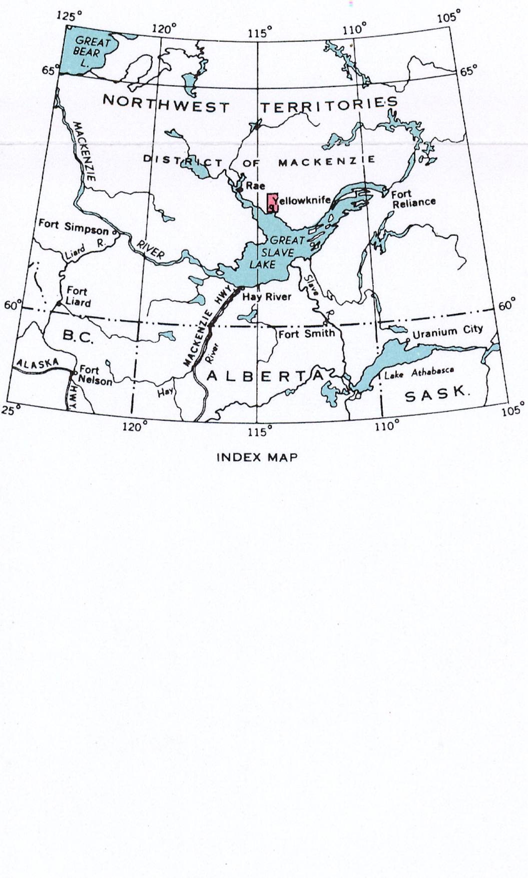
LEGEND

6	*Diabase, gabbro*
5	*Granite, granodiorite*
4	*Amphibolite facies*
3	*Epidote amphibolite facies*
2	*Greenschist facies*
1 ● 1	*Chlorite-albite-carbonate-sericite quartz facies; marks sheared areas and shear zone systems*

Fault (defined, approximate)......................

Sources of Information
Geological Survey of Canada, Maps 709A, and 868A
Geological Survey of Canada, papers 48-17, 49-26, 50-34, 52-24
Various mining company reports and maps
Geological investigation by R. W. Boyle, 1950, 1951, 1952





locality, however, contacts are good and no structural discordance is evident. It is probable, therefore, that Division B is conformable with Division A.

Division A, together with the meta-diorite and meta-gabbro dykes and quartz-feldspar porphyry bodies, is overlain in the vicinity of the Yellowknife River by a sequence of unclassified conglomerates and quartzites. Similar conglomerates also occur on Jolliffe Island and underlie the Sub Islands. The determination of the age relationship of these conglomerates and quartzites to Division B is complicated by faulting and a lack of good contacts, but lithological and structural relationships suggest that these sediments may be much younger than Division B. They have, therefore, been placed in an unclassified category, and their exact relationship remains a problem for the future.

The earliest intrusive rocks are gabbro and diorite sills and irregular masses. These are cut by swarms of diorite and gabbro dykes, some of which contain characteristic irregular white-weathering phenocrysts (Plate IV). Some of these characteristic dykes make excellent structural markers for determining relative movements along shear zones and faults.

Parts of three large granitic bodies occur within the area. Each body has distinctive contact and internal features that have a bearing on their respective origins.

Two of the granitic bodies with their related granite stocks, dykes, and aplites are similar. One of these flanks the western greenstone belt; the other forms a large mass south of the sedimentary area in the vicinity of Duck and Mason Lakes.

The contact features of the western granitic mass differ throughout its length. In some places, sharp contacts with the greenstone rocks were observed. In other places, especially around Stock and Ryan Lakes, the granitic mass is highly contaminated with xenoliths of volcanic rock.

In the western granitic mass, particularly in the contact zone, several phases of granitic material can be discerned. In general, the earliest phase is more basic than succeeding cutting generations. The first phase, that is the base rock which other generations cut, is a medium-grained, locally porphyritic, pink- to grey-weathering granodiorite or quartz diorite. It contains quartz, oligoclase, microcline, perthite, biotite (commonly altered to chlorite), and/or hornblende. Accessory minerals include, pyrite, magnetite, epidote, sphene, apatite, spinel, rarely tourmaline, zircon, and carbonate minerals. Succeeding phases contain more microcline and perthite, and rarely contain hornblende. Final phases are granite stocks and dykes, small pegmatites, and aplites which are restricted to the granitic mass and a narrow contact zone in the greenstones. These contain quartz, microcline, minor amounts of oligoclase, and some chloritized biotite. Accessory minerals include apatite, zircon, pyrite, and in places a little tourmaline. All granite dykes, pegmatites, and aplites have relatively sharp contacts with both granitic and greenstone rocks.

The southeastern granitic mass is extremely variable and contains such an abundance of inclusions of sedimentary and volcanic rock that the term migmatite is perhaps more appropriate for some areas. In places, however, relatively pure granodiorite and granite occur. In the vicinity of Wool Bay, a rock approaching diorite in composition is present. This rock has been derived from volcanic rocks because volcanic features can still be made out in many outcrops. As in the western mass several phases in the formation of the granitic body are evident. Early phases have a granodioritic, quartz-dioritic, or dioritic composition. In places porphyritic phases may occur. Late phases include granite and aplite dykes and masses.

The northeastern granitic body (Prosperous Lake granite) is composed of two distinct phases, an older granite phase and a younger granite-pegmatite phase. The granite is medium to coarse grained and contains clear quartz, microcline, oligoclase, honey-coloured muscovite, and pleochroic biotite. Accessory minerals include garnet, tourmaline, apatite, pyrite, and zircon. The pegmatites are coarse grained, have relatively sharp contacts with the granite, and contain slightly smoky quartz, microcline, cleavelandite, perthite, muscovite, black tourmaline and small amounts of garnet, ilmenite, and apatite.

The contacts of the Prosperous Lake granite with the sedimentary rocks are sharp in some places and gradational in others. A notable feature is the occurrence of numerous sedimentary inclusions in the granite mass proper especially within a belt along the eastern contact of the mass.

The knotted quartz-mica schists and hornfels adjacent to the Prosperous Lake granite are cut by many pegmatites. These pegmatites have sharp contacts with the schist in most places, and in a few places a tourmalinized zone is developed in the schist or hornfels. The characteristic minerals developed in these pegmatites include the usual pegmatitic minerals and locally, tourmaline, beryl, spodumene, amblygonite, lithiophilite, petalite, scheelite, molybdenite, tantalite-columbite, tapiolite, garnet, pyrite, arsenopyrite, apatite, cordierite, andalusite, and graphite. Tourmaline is the most abundant of the rare minerals.

White- to pink-weathering quartz-feldspar porphyries are common in some parts of the greenstone belt and occur as dykes and irregular stocks. One of these stocks outcrops on the northeastern shore of Pud Lake, and irregular isolated dyke-like bodies of porphyry occur in the underground workings of the Con, Negus, and Rycon mines. The porphyry dykes have sharp contacts with the greenstone rocks and generally contain irregular angular fragments of relatively unaltered volcanic rock. In the mines the porphyry dykes cut an early age of quartz lenses and are cut and offset by the ore-bearing shear zones. These porphyries contain quartz and sericitized, zoned, plagioclase phenocrysts in a groundmass of plagioclase, quartz, microcline, sericite, carbonates, and chloritized biotite. Accessory minerals include abundant pyrite and pyrrhotite and small amounts of apatite, zircon, rutile, epidote, and molybdenite.

Similar quartz-feldspar porphyries occur as irregular dyke-like masses and sinuous dykes in great profusion northeast of Vee Lake. Many of these rocks appear to cut an early stage of schistosity which is related to the Giant-Campbell shear-zone system, but are themselves sheared and highly altered to quartz-carbonate-sericite schists.

The rocks of Division A, their associated gabbro and diorite sills and dykes, and Division B, have been profoundly affected by the agents of regional metamorphism. The andesites, basalts, gabbro, and diorite rocks have undergone the characteristic alterations peculiar to greenstone rocks. In most areas, the metamorphic facies can be traced, but faults have complicated the ideal zoning arrangement.

The regional facies present in the western greenstone belt are distinctly related to the granodiorite-greenstone contact and comprise a contact amphibolite facies, an intermediate epidote amphibolite facies, and an outer greenschist facies. Isograd lines are nowhere sharp, and transition zones are the rule. Minor reversals in the index minerals are common, and the lower-grade facies are complicated by shear zones. Figure 2 illustrates the metamorphic zoning in the greenstone belt as compiled from data obtained from field mapping, thin-section studies, and chemical analyses. The map is only an attempt to present a generalization of a very complex situation, but it is felt that the outlines of the facies fit the majority of facts observed.

The amphibolite facies is the most distinctive in the field. The rocks are massive and original features such as pillows and amygdules are retained. They are coarse to medium grained and black or greenish black in colour. In thin sections, brown to green pleochroic hornblende possessing fair crystal outlines and cleavage, is distinctive. The plagioclase is in the andesine range and is generally clear and little altered. Epidote, quartz, magnetite and/or ilmenite, and sphene occur in small amounts. Carbonates and sulphides are low in amount. In tuffs, garnets are developed.

This facies grades imperceptibly to the intermediate epidote amphibolite facies. In this facies the rocks are relatively massive and retain their original features. In thin sections the amphibole is generally fibrous, light green, nonpleochroic, and possesses low interference colours. The plagioclase is in the albite-oligoclase range and is always crowded and intergrown with fibrous amphibole and epidote granules and patches. Epidote and zoisite or clinozoisite are characteristically developed and usually occur as granules and patches often showing anomalous blue interference colours. Quartz, magnetite, leucoxene, and small amounts of carbonate minerals and chlorite are generally present. Pyrite and pyrrhotite are minor accessory minerals.

The epidote amphibolite facies grades imperceptibly into the greenschist facies which is the most difficult one to outline. An attempt is made on the map, but the differentiation is not good. The greenschist facies is marked by rocks which contain an abundance of green chlorite with anomalous olive and blue interference colours, epidote, and other epidote-family minerals. The plagioclase is commonly albite but is so highly altered and filled with chlorite and carbonate minerals that

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Plate V. *Knotted quartz-mica schists, Prosperous Lake, Northwest Territories.*

good determinations are seldom possible. Carbonates and quartz are abundant and form patches and ramifying areas throughout much of the rock. Leucoxene and sulphides are everywhere present as accessory minerals. The rocks show only traces of a schistosity, and original features such as pillows are present in many outcrops.

Locally, a fourth facies which the author has called the chlorite-albite-carbonate-quartz facies is superimposed upon the three regional facies. The rocks in this facies mark the shear zones of several extensive systems and are highly schistose and severely contorted. The character of this facies is discussed at length in the chapters to follow.

The rocks of Division B, conglomerate, greywackes, etc., have been altered over wide belts to quartz-mica schists, hornfels, and knotted quartz-mica schists. Most of the knots contain segregations of quartz, biotite, and carbonaceous matter that have been transformed into crystals of andalusite, garnet, staurolite, and cordierite where a higher degree of metamorphism has prevailed (Plate V). Zoning arrangements about the Prosperous Lake and Southeastern granite masses include an inner zone of knotted quartz-mica schist and hornfels that grades relatively sharply through a narrow zone of quartz-mica schist into an outer zone of relatively unaltered sediments (*see* Figure 1, in pocket). The writer did not carry out a detailed petrographic investigation of these rocks since they have been adequately described by Jolliffe (1938) and Folinsbee (1942) for the Yellowknife-Beaulieu area, and by Henderson (1943), Henderson and Jolliffe (1939), Denton (1940), Fortier (1947), and Boyle (1949) for the Gordon Lake and Ross Lake areas. The reader is referred to these accounts for details.

The youngest consolidated rocks in the area are diabase dykes and sills and a composite peridotite-gabbro intrusive sheet.

The diabase dykes and sills are relatively unaffected by metamorphism except where cut by late faults. They have a pronounced ophitic texture, are fresh on broken surfaces, and contain zoned plagioclase and augite, olivine, some quartz, ilmenite and/or titaniferous magnetite, rarely biotite, and minor amounts of apatite, pyrite, and pyrrhotite. The plagioclase ranges from bytownite (An_{75}) to oligoclase (An_{25}) and in many thin sections shows an alteration to epidote and white mica. The pyroxene according to Wilson (1949) is augite which generally shows an alteration to hornblende or actinolite, chlorite, clinozoisite, and chrysotile. The olivine occurs in rounded grains, usually contains ilmenite or magnetite, and in nearly all cases is partly altered to serpentine. The quartz is generally clear and commonly occurs as a micropegmatitic intergrowth in interstices. Ilmenite and titaniferous magnetite occur in amounts up to 10 per cent of the rock. Pyrite and pyrrhotite are present as small grains and irregular patches throughout the rock.

The diabase dykes weather a characteristic brown colour and are readily distinguished from earlier dyke rocks. They occur in three well-defined sets that trend northwest, east-northeast, and northeast, respectively. Two or more ages are present, but Wilson (1949) concludes that there are no major petrographic differences between the sets of dykes, and that they may all have come from a similar magma.

The composite peridotite-gabbro intrusive sheet dips gently to the east and outcrops from a point on the Yellowknife River southward to the north shore of Duck Lake (*see* Figure 1, in pocket). Beyond the latter point the sheet outcrops on an island in Duck Lake and is then probably cut off by the Akaitcho fault. The probable southern extension is found on the shore of Willow Lake from where it trends southwest through the granitic area and the various islands west of Wool Bay.

The rocks making up the sheet are massive and jointed and vary in their mineral composition. The common minerals include pyroxene, basic plagioclase, olivine, serpentine, quartz, biotite, ilmenite, pyrrhotite, pyrite, and chalcopyrite. In a few places streaks and patches of the three sulphides mentioned above occur over widths of 4 inches near the base of the intrusive.

In nearly all areas the diabase dykes and peridotite-gabbro sills were intruded before extensive late faulting took place. In one or two places, however, late dykes were intruded after the early periods of movement along the late faults. Such an instance is noted by Riley (1946) in the Walsh Lake area where a late diorite dyke was intruded along the Walsh fault for a distance of 3 miles.

Structure

Folding

According to Jolliffe (1942a) the volcanic rocks of Division A lie in a northeasterly plunging syncline bordered on either limb by younger granitic masses and greatly modified by folding and late faulting. The synclinal axis lies up the centre of Yellowknife Bay to Burwash Point on the eastern mainland. The syncline is asymmetric. The northwest limb (greenstone belt) consists of a simple homoclinal succession that dips and faces southeast. The southeast limb is overturned and is in part folded into a subsidiary anticline. In addition, it is complicated by crossfolding. The axis of the subsidiary anticline, now disrupted by late faulting, passes through the three areas of volcanic rocks that border the southeastern granitic mass. As a result of crossfolding, this subsidiary axis plunges to the southwest on Horseshoe Island, to the east in the volcanics south of Duck Lake, and to the west in the volcanic assemblages southwest of Creek Lake.

The rocks of Division B are highly folded and contorted throughout their extent. Tight isoclinal folding predominates, and severe crossfolding, resulting in canoe-shaped synclines, domes, and irregular S-shaped folds, is evident in most areas. The strong development of primary features such as grain gradation and bedding in the sediments has facilitated the determination of the attitudes of the complex structures developed.

Faulting and Fracturing

The fault and fracture pattern is extremely intricate. To orient the reader, it is briefly summarized here. A detailed description is given in the next chapter.

Two major periods of faulting and fracturing have taken place within the district; the first period is distinctly pre-diabase dyke intrusion, the second period is distinctly post-diabase. The types of structures developed during these periods are different and are easily recognized in the field.

Within the greenstone belt an early period of faulting produced two types of shear zones, and in the sedimentary belt severe folding and faulting has given rise to ruptured axes of synclines and anticlines, sheared and fractured beds and bedding planes, and complicated drag-folds within weak argillitic and slaty beds. A few early faults and shear zones are present in the sedimentary rocks, but these structures are nowhere nearly as abundant as in the greenstones.

Post-diabase faults cut greenstones and sediments and all granitic rocks. These structures are widespread in their occurrence and are marked by strong lineaments which are distinctive both on the ground and on air photographs in many parts of the Northwest Territories.

Chapter III

THE SHEAR-ZONE SYSTEMS, FAULTS, AND FRACTURES, AND THEIR ROLE IN THE STRUCTURAL CONTROL OF MINERALIZATION

In the following, descriptions are given of the various structures which have localized mineralization in the Yellowknife district, namely pre-diabase fractures and shear zones in the greenstone belt, pre-diabase fractures and faults peculiar to the sedimentary rocks of the district, and post-diabase faults which cut all rock types. As a guide to the reader in following the complex descriptive details, Tables 2 and 3 give age relationships of the faults, fractures, and shear zones.

Pre-diabase Fractures and Shear Zones in the Greenstone Belt

For description purposes, the pre-diabase fractures and shear zones that cut the greenstones can be classified according to their structural characteristics and relative age as follows:

1. Early pre-shear-zone fractures
2. Shear zones
    - (*a*) shear zones that parallel the lava flows in strike and dip
    - (*b*) shear zones that transect the lava flows
3. Pre-diabase fractures that cut the shear zones.

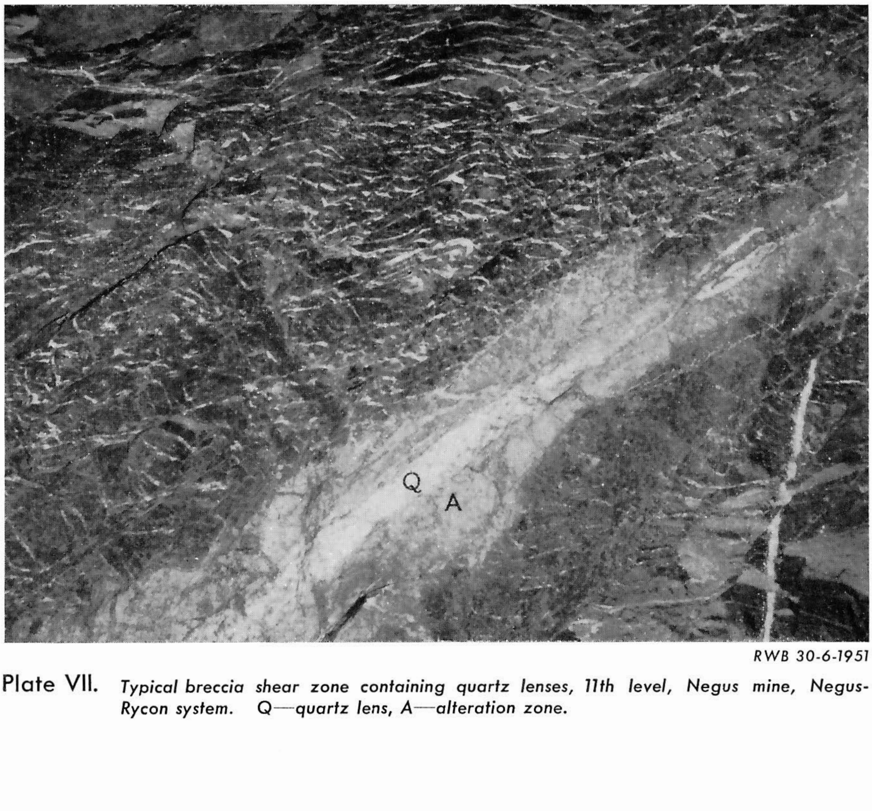
Table 2

Age Relationships of Faults, Fractures, and Shear Zones in the Greenstone Belt

Structure (oldest first)	Notes on age relationships
Fractures (non ore-bearing)	
Parallel shear zones (ore-bearing)	Age relative to the transecting type not clearly defined in many places
Transecting shear zones (ore-bearing)	
Fractures (non ore-bearing)	Prevalent in ore zones; cut ore shoots and their alteration zones
Post-diabase faults (non ore-bearing)	
Slips and minor faults in country rocks and ore-bodies (non ore-bearing)	Probably same age as late post-diabase faults; some appear to be younger

RWB 24-6-1951

Plate VI. *Early quartz-filled fracture, Yellowknife greenstone belt.*



RWB 30-6-1951

Plate VII. *Typical breccia shear zone containing quartz lenses, 11th level, Negus mine, Negus-Rycon system. Q—quartz lens, A—alteration zone.*

RWB 1-6-1951

Plate VIII. *Typical schist zone containing quartz lenses, 13th level, Negus mine, Campbell system.*

Early Pre-shear-zone Fractures

The pre-shear-zone fractures are abundant in the greenstone rocks and relatively rare in the granitic masses. They are conspicuous since they enclose lenses of white and greyish quartz containing a few grains of feldspar and pyrite in some places.

These fractures are clean-cut cracks and exhibit little or no brecciation. The contacts of the quartz with the wall-rocks are knife-sharp, and replacement features or alteration zones are absent (Plate VI). The quartz lenses are elongated and vary in width from 1 inch to a maximum of 3 feet, with lengths seldom exceeding 50 feet. Adjacent to and within the western granitic mass the fractures and their contained quartz lenses have irregular strikes and dips and have a random distribution; those occurring in the greenstones proper have a more definite structural pattern, and strikes of S20°E to S40°E and steep dips are general. Many of the fractures and quartz lenses are *en echelon,* and it is unusual to find two quartz lenses on the strike of the same fracture. In general, the fractures on the extensions of the quartz lenses are single cracks which if traced, terminate within a few feet.

In the western granitic mass and its contact zone in the greenstones the fractures and quartz lenses show no preferred structural environment, but in areas farther from the granitic mass they are concentrated in massive flows and meta-gabbro and meta-diorite dykes.

Their localization in most dykes and massive flows appears to have resulted from the action of tensional forces acting on the dykes during the early folding of the greenstones.

The age relationships of the early fractures are not readily determined in most areas because of the restricted length of the fractures and quartz lenses and the paucity of cutting relationships with other structural elements. In the granitic mass and its contact zone some of the quartz lenses in the fractures cut both the granodiorite and small quartz-feldspar segregations. Other quartz lenses occur simply as segregations in the granodiorite. In one good exposure in greenstone rocks south of Handle Lake, an aplite dyke cuts one of the quartz lenses, and not far away a diabase dyke cuts a similar lens. Another quartz lens in a distinct fracture north of Yellowknife townsite is cut and offset by a late post-diabase fault. The only underground relationships observed were on the third and sixth levels of the Negus mine. On the third level a quartz-feldspar porphyry dyke cuts an early quartz lens which has knife-sharp contacts and no wall-rock alteration zones. The porphyry dyke in turn is sheared, and offset by an ore-bearing shear zone, and in this case it is positive that the shear zones are younger than some fractures containing quartz lenses. Similar relationships exist on the sixth level where an ore-bearing shear zone clearly offsets an early vertical quartz lens with knife-sharp contacts and no accompanying alteration zones.

Shear Zones

The shear zones of the greenstone belt fall into two structural categories: those that parallel the volcanic flows and tuff beds in strike and dip; and those that transect the volcanic flows in both strike and dip. With the exception of one marginal deposit the first type contains only small uneconomic gold orebodies. The second type have localized the major economic gold-bearing quartz bodies of the Yellowknife greenstone belt.

In the field the shear zones have been traced by detailed mapping of their outcrops, by plotting available diamond-drilling data, and by mapping the shear zones in the workings of the various mines. Figure 3 (in pocket) shows the geographical location and structural relationships of the various shear-zone systems.

Internal Nature of the Shear Zones

The greenstone belt is characterized by shear zones which have two distinct types of internal features. These two types are best described by the terms *breccia shear zone* and *schist zone*. Gradations from one type to the other are common in many of the systems to be described.

The breccia shear zones (Plate VII) are marked by a zone of rock broken into spindle-shaped fragments that are locally cemented by carbonate minerals. The fragments are rarely greater than 6 inches in any dimension, and most are about the size of brazil nuts which they simulate in shape.

The fragments in the ideal breccia shear zones are massive to slightly schistose in character and rarely exhibit the marked schistosity or extreme alteration of the rock composing the schist zones. Where quartz lenses occur in this type of shear zone a buff-coloured, dense, dyke-like alteration zone is present in which the outlines of the original breccia fragments can often be discerned upon close examination.

The schist zones (Plate VIII) are marked by linear zones of highly schistose rock which cleaves along an infinite number of parallel planes owing to the extreme lineation and parallel orientation of chlorite and sericite. The zones are especially common in the ore localities of the Con and Negus-Rycon systems and are the principal feature of the Giant-Campbell shear-zone system. The shear zones which parallel the volcanic flows are also predominantly of a schistose nature. In most cases the dips, and in some cases the strikes, of the schist planes intersect the walls of the shear zones at a small angle (*see* Figure 14, p. 28).

Many of the transecting shear-zone systems show a gradation from the breccia shear zones to schist zones. This feature is especially common in the Negus-Rycon system where the gradation can be traced with some degree of confidence. In some of these shear zones the ideal breccia zones grade imperceptibly to schist zones both along the strike and in some cases down the dip. In the transition from the breccia-type zones to the schist zones the fragments of the breccia become elongated and flattened, alteration increases concomitantly, and the fractures separating the fragments are partly or completely obliterated. The final result is a well-developed schist in which only traces of the primary fragmentation may appear, but in general no hint of the original breccia remains. This transition from a breccia to a schist can be traced in many schist zones, but in others no such genetic origin for schist zones can be evoked. The internal features of the schist zones paralleling the flows, and those of the Giant-Campbell and portions of the Con systems, suggest that extensive brecciation was not a major factor in their development.

The principal differences of the two types of shear zones can be summarized as follows: The breccia shear zones are characteristic of shear zones that cut the tabular rocks at a large angle, e.g. Negus-Rycon system; in these shear zones alteration of the breccia fragments and transition to schist zones is not marked except where quartz lenses occur. The major schist zones exhibit zones of rock which have been highly altered throughout their extent, and in contrast to the breccia shear zones are either parallel to, or cut the tabular rocks at a small angle, e.g. Giant-Campbell system, Ranney system.

Shear-zone Systems that Parallel the Lava Flows in Strike and Dip

These shear zones occur throughout the greenstone belt and are localized at flow contacts, along tuffaceous beds, and within incompetent lava flows. Three main systems (Figure 3) have been traced and studied during the field investigations. For description purposes these have been named the Kam Point system, the A.E.S. system and the Ranney system.

Kam Point System

This system outcrops sporadically in the southernmost part of the greenstone belt where it is localized along a series of tuffaceous beds at closely spaced stratigraphic horizons. The zones are highly schistose in character, generally restricted to tuff beds, and seldom ramify into adjacent massive flows and sills. Limited observations indicate that the schist zones as a whole dip with the beds at steep angles to the southeast. Dragged and contorted parts occur along the individual schist zones, and small relatively unsheared horses of rock are a common feature. Quartz lenses and veins occur where contortion of the schist zones has been pronounced and where there is a deflection in the strike or dip of the zones. Most of these lenses give relatively high gold assays, but economic orebodies have not as yet been found in any of them.

The Kam Point system has been offset by faults in several places along its exposed length, and the system as a whole has been offset by the West Bay fault in a northerly direction where it is lost beneath the waters of Yellowknife Bay.

A. E. S. System

The A. E. S. system occurs along the so-called "Cemetery Tuff" which outcrops 4,000 feet north of Yellowknife townsite. The shear zone and tuff have been faulted into three main segments by the West Bay and Akaitcho faults respectively. Drift and linear lakes obscure most of the three segments, but part of the central segment outcrops east of Gar Lake and presents a highly schistose character with local contorted zones in which small, high-grade, gold-bearing quartz lenses are present. Late faults have interrupted the continuity of the shear zone at this locality and have offset it in several places. It is impossible, because of limited outcrop, to determine whether these offsets were once a continuous structure or several shear zones separated by horses of unsheared rock. A more detailed description of this part is given by Jolliffe (1938, pp. 16-17) as follows:

> This vein lies about 1,000 feet east of the West Bay fault. The country rock is pillowed lavas and bands of thinly bedded, cherty sediments up to 10 feet wide striking north 30 degrees east and dipping steeply to the east. South of the southernmost pit on the vein is a drift-covered area. In this pit a rusty schistose zone averaging 6 feet in width is exposed. The schist is highly contorted and encloses quartz lenses. These are up to 8 inches wide and several feet long, and are composed of milky quartz containing tiny curving seams of chlorite that roughly parallel the sides of the lenses. Metallic minerals in the quartz include chalcopyrite, pyrite, and, possibly, tetrahedrite, arsenopyrite, and sphalerite. From the north wall of the pit a milky quartz vein extends in a direction north 30 degrees east for 40 feet, bounded on either side by a foot or two of green schist. Throughout this length the vein varies in width from 8 to 18 inches and contains few metallic minerals. Forty feet north of the pit it is intersected by a fault, which meets the vein at a very acute angle. This fault trends north 25 degrees east, and along it the northeasterly extension of the vein is displaced 30 feet to the south, nearly back to the southernmost pit. From this point the vein can be traced continuously for 135 feet in a direction north 40 degrees east. In this distance the schistose zone enclosing the vein narrows from 5 to 3 feet, and is composed of very fine-grained green schist, except for bands about 6 inches in width on either side of the vein which are rusty and contain considerable disseminated fine pyrite and arsenopyrite. Both schist and vein dip steeply east to vertical. Throughout the length of 135 feet the quartz is commonly less than 1 foot wide, but in places is 20 inches. It is milky to grey in colour and contains chalcopyrite, pyrite, tetrahedrite (?), gold, and electrum. These metallic minerals are for the most part in or near thin chloritic seams lying within the quartz and paralleling the vein walls. Electrum (a pale red to white natural alloy of silver and gold) and red gold occur together in most specimens examined. It is reported (Riley, C., personal communication) that a picked specimen from this section containing electrum showed on assay 65.55 ounces gold and 58 ounces silver a ton. Along the assumed northeasterly extension of the vein, bedrock is covered by drift for a distance of several hundred feet. Within the first 50 feet of this drift area, three test pits show quartz in widths up to 9, 7, and 2 inches, respectively.

Field observations by the author and correlation of limited diamond-drill data indicate that the A. E. S. shear zones dip 70 to 85°SE within the tuffaceous beds in which they are localized. Although high gold values have been found in one place, no economic gold orebody has been found to date.

Ranney System

The Ranney system outcrops a mile north of the southern extension of the A. E. S. system. It is faulted into three main segments by the West Bay and Akaitcho faults, and each segment exhibits several offsets along minor late faults. The portion west of the West Bay fault is localized along a cherty tuff horizon, has a schistose character, and contains an abundance of pyrite and pyrrhotite that is extensively weathered to limonite near the surface. Small quartz lenses in contorted parts are common.

The southern extension of the central segment of the system is covered by David Lake, but diamond-drilling has proved its existence beneath the lake. North of this lake there are two schist zones which are faulted into several parts by crossover faults between the West Bay and Akaitcho faults. Diamond-drilling data indicate that the western schist zone, which is the stronger, dips approximately 65°E and follows a tuff bed. The eastern zone dips nearly vertical and probably joins the western one at depth. Quartz lenses with pyrite and low gold values occur along the western schist zone, but an economic orebody has not been found.

The extension north of the Akaitcho fault is marked by a linear valley containing two well-developed interlacing schist zones. In places a few small quartz lenses containing pyrite, sphalerite, sulphosalts, and low gold values are localized in contorted portions at schist-zone junctions and flexures.

Miscellaneous Shear Zones that Parallel the Flows

The three systems described above are the most distinctive shear zones that parallel the lava flows and are typical examples of this type of shear zone. Several other shear zones of similar type, not examined in detail by the author, occur in the northern part of the greenstone belt in the vicinity of Oro Lake and Homer Lake. Most of these are schist zones that occur within highly altered lava flows or along flow and sill contacts. A few have quartz lenses with scattered sulphides and low gold values, but economic gold orebodies have not been found in any of them.

Structural Control of Mineralized Zones in the Parallel Shear Zones

No economic gold-bearing ore shoots occur within the parallel systems, but nearly all contain quartz lenses with some sulphides and gold. Most of the mineralized parts are localized where the schist of the shear zones has been highly dragged and contorted, particularly at gentle flexures in strike and dip and at shear-zone junctions. In a few places quartz stringers and lenses occur within shear zones which show little contortion and no observable relationship to any internal structural feature. These lenses have probably formed in open dilatant zones that were localized by flexures or other features in the walls of the shear zones.

Age of Parallel Shear Zones

The age relationships of the parallel shear zones are obscure in many cases, but in others it is clear that they cut and offset early meta-gabbro and meta-diorite dykes. Some offset late diabase dykes a few feet, but this appears to be the result of late movement along the shear zones during post-diabase faulting. No good relationships with the western granodiorite were observed. The shear zones that transect the lava flows offset a few of the parallel type, and late faults offset the three systems described. These relationships point to an early origin for the parallel shear zones, and they are probably the result of shearing along incompetent structural features and beds during the initial stage of the folding of the greenstone belt. Some may have been the result of structural failure during the formation of the extensive transecting shear-zone systems.

Shear-zone Systems that Transect the Lava Flows

These shear-zone systems are the most important type from an economic viewpoint because they contain the majority of economic gold orebodies in the greenstone belt. There are seven distinct systems (Figure 3) which, for description purposes, may be conveniently tabulated as follows: Con system, Negus-Rycon system, Giant-Campbell system, Bow Lake system, Crestaurum system, Stock Lake system, Handle Lake system.

Con System

The Con system is the second most important economic shear-zone system in the greenstone belt. It is described first because it exhibits many features which provide a clue to the more complex structure of the major Giant-Campbell system. Detailed descriptions of the ore-bearing parts of the Con system have been given by Campbell (1949), Lord (1951), and Sproule (1952).

The Con system has been traced with certainty from its southern extremity near Kam Lake to the West Bay fault (*see* Figure 4, in pocket). The location of its northeastern extension on the east side of this fault is not so well known, but from detailed field work it seems probable that it is represented by the three westerly shear zones on Giant property (*see* Figure 11, in pocket).

The system strikes N30°E and dips from 60 to 75°NW. Southwest of Pud fault it consists essentially of a single shear zone with local developments of both breccia and schist. No orebodies have been found along this part of the system. Northeast of Pud fault the system assumes an irregular nature, and several shear zones (Shaft system) possessing both breccia and schistose characteristics split from the main shear zone (C-4) in a northerly direction. These north-striking shear zones are narrow, dip 65°W and contain small, high-grade gold-quartz lenses. The main shear zone (C-4) continues northeast to the region of the Con shaft where bifurcations and a ramifying nature are pronounced. This habit continues along the system until it is cut off by the West Bay fault. Across the West Bay fault the system is obscured by drift along most of its length. One exposure, in the bottom of Baker Creek, presents a highly schistose zone which has been mineralized with quartz, pyrite, and other minerals.

Campbell (1949) has concluded that the Con shear system is a thrust fault with approximately 1,000 feet of movement in a dominantly vertical direction, the hanging-wall side moving up and south relative to the foot-wall side. In a broad structural sense, the general nature, mineralization, and spatial relationships indicate that the Con system was formed at the same time as the Giant-Campbell system, and it is probable that it is a subsidiary of this large system.

The part of the system containing the economic gold orebodies consists of several shear zones separated by horses of relatively unsheared country rock. Two general ore localities are recognized; the subsidiary Shaft system of shear zones, and the main ore-bearing part of the Con system which includes the parallel C-4 and C-34 shear zones and other crossover shear zones. The pattern of these two ore localities is illustrated in Figure 5 (in pocket).

The shear zones of the Shaft system are extremely irregular in both strike and dip. They are narrow, well-defined breccia shear zones that contain narrow quartz veins and lenses highly mineralized with pyrite, arsenopyrite, stibnite, chalcopyrite, sphalerite, sulphosalts, galena, and gold. The major control of the ore shoots appears to be flexures in the shear zones in both strike and dip. Some shear-zone junctions are present, and these may have been responsible for the localization of certain ore shoots.

In the shear zones of the main ore-bearing part of the Con system the orebodies consist of quartz lenses, pods, and replacement bodies; the metallic minerals in the orebodies include pyrite, arsenopyrite, stibnite, chalcopyrite, sphalerite, sulphosalts, galena, and gold. The orebodies occur in localities where the schist has been highly dragged, mashed, and contorted. These localities occur either at shear-zone junctions or where slight flexures in strike or dip of the shear zones are present. Shear-zone junctions off the noses of large unsheared horses of country rock are especially favourable. The two plans of the Con system (Figure 5) show that the main ore shoots occur at the junctions of the C-4 and C-36, C-4 and C-34, and C-4 and C-37 shear zones. These mineralized junctions plunge south with the noses of the respective horses; their minor structural features such as small drag-folds, boudinage structures, long axes of small lenses, pods and crenulations have a similar plunge. Other smaller ore shoots in the main Con system occur in drag-folded, corrugated, and crenulated zones of the schist that appear to have been localized by flexures in the strike and dip of the hanging-wall or foot-wall of the shear zones.

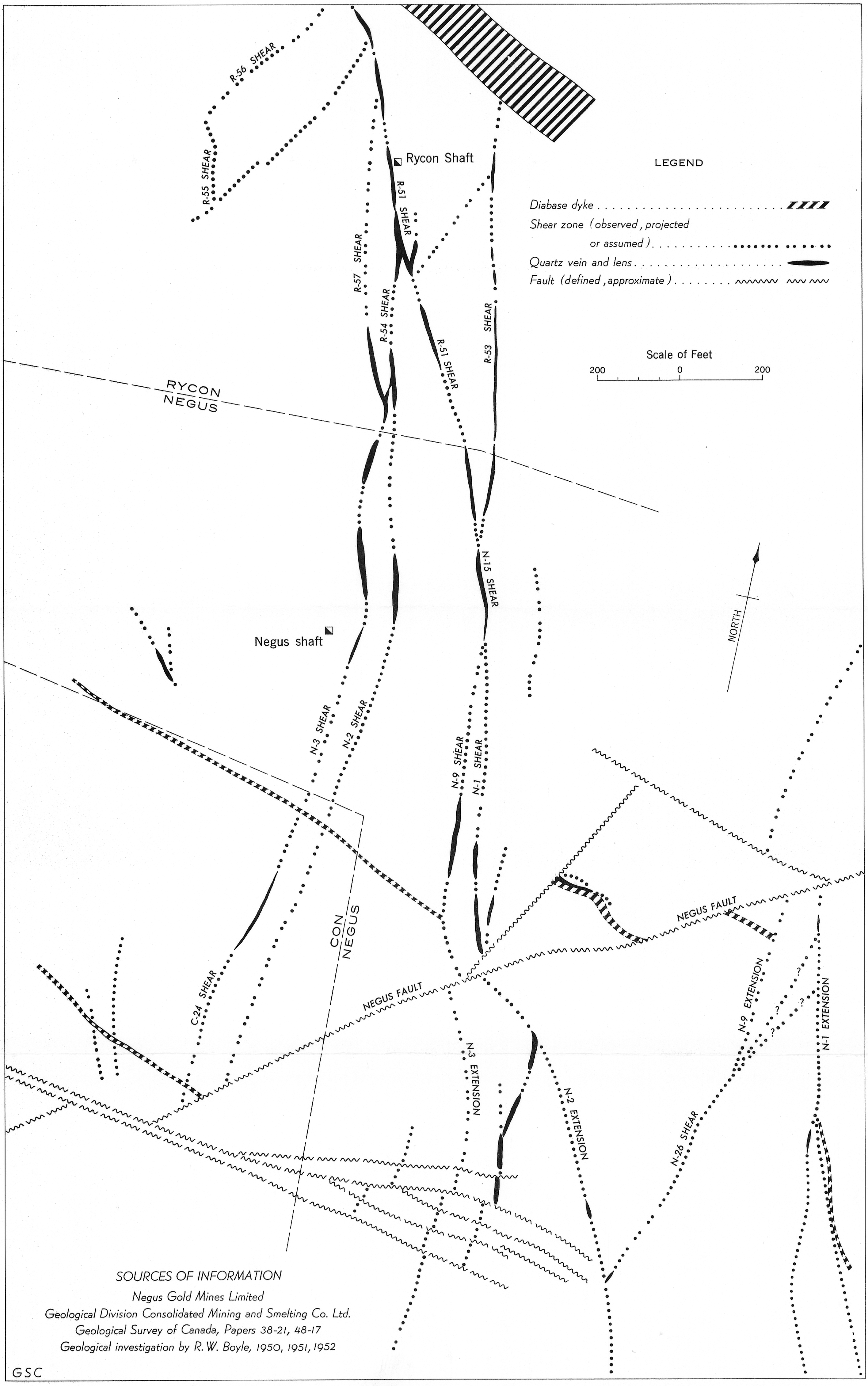
The principal locus for orebodies in the Con system is a complex bulbous portion which contains numerous horses of unsheared country rock with attendant shear-zone junctions. This part of the system is localized within a series of unpillowed lava flows, and plunges south as shown in Figure 5. During the formation of the Con shear-zone system, sections of this bulbous portion have been subjected to repeated movements causing dragging, mashing, and contortion of the schist of the shear-zone system. Shear-zone junctions were especially susceptible to dragging and contortion as a result of the rotation of the horses; other junctions appear to have been opened by the wedge effect of the horses during movement of the walls.

Negus-Rycon System

During the early years of the Yellowknife camp the Negus-Rycon shear-zone system provided the sole production of the Negus mine, and until recently, the production of the Rycon mine. The known orebodies within this system are now exhausted.

The system consists of several narrow interlacing shear zones which have been traced from their appearance on the south shore of Yellowknife Bay near Negus Point to their disappearance beneath Rat Lake where they presumably join the Con system (Figure 4). In the broad structural pattern this system represents a crossover shear-zone system between the major Giant-Campbell and subsidiary Con systems.

A post-diabase fault (Negus fault) and a diabase dyke (Con diabase) divide the system into three parts. The relationships and numeration of the various shear zones in these three segments are shown in Figure 6, and Figure 7 (in pocket). The main shear zones are rarely more than 5 feet in width, strike northwest, dip



SOURCES OF INFORMATION
Negus Gold Mines Limited
Geological Division Consolidated Mining and Smelting Co. Ltd.
Geological Survey of Canada, Papers 38-21, 48-17
Geological investigation by R. W. Boyle, 1950, 1951, 1952

Figure 6. Surface plan, Negus-Rycon system showing relationship of quartz veins and lenses to shear zones flexures and junctions

southwest, and contain both brecciated and schistose sections. Movement along most shear zones is not great. Quartz-feldspar porphyry dykes north of the Negus shaft are displaced only a few feet horizontally by the N-2 and N-3 shear zones, and the vertical movement appears to be small with the west side moving up a few feet relative to the east side. Along the N-15—R-53 shear zone, however, the strike separation of a characteristic meta-gabbro dyke amounts to some 600 feet, and the hanging-wall appears to have moved up and to the north. This suggests that these shear zones were formed by thrust movements during the general period of compressive stress that produced the Giant-Campbell and Con shear systems.

The ore shoots in the Negus-Rycon system occurred in highly mineralized quartz veins and replacement lenses. Metallic minerals in the orebodies included arsenopyrite, pyrite, stibnite, chalcopyrite, various sulphosalts, sphalerite, galena, and gold.

South of the Negus fault the ore shoots in the N-26 shear zone (Figures 6 and 7) occurred where small flexures in strike and dip are present. This shear zone is localized at the contact of an early meta-gabbro dyke, and irregularities in this dyke contact apparently influenced the position and trend of the shear zone. In the N-3 extension a mineralized quartz lens occurred where a flexure in both strike and dip are present. Small mineralized quartz lenses and veins occur in places in other shear zones of the southern segment of the system, but orebodies have not been found.

Shear-zone flexures and junctions are the principal structural controls in the central part of the system. In the Negus mine the sections (Figure 7) show that the N-15 shear zone contained orebodies only on the flat dipping portion of the shear zone. Below the tenth level the dip of this shear zone steepens, and the main orebodies terminate. The N-3 shear zone contained orebodies only above the sixth level. Below this level this shear zone flattens, is tight, and contains very little mineralization. In the N-2 shear zone an ore shoot was localized where a deflection in both strike and dip occurred. On the Rycon property similar conditions prevail; the R-51 shear zone (N-15 extension) steepens in dip between the sixth and seventh levels of the Rycon mine, and productive orebodies did not occur below this point. The R-57 shows a tendency to flatten below the fourth level, and little ore occurred below this level. Thus, in the two main shear zones of the system the major depth control of orebodies appears to be steepening (N-15, R-51) or flattening (N-3, R-57) in the dip of the shear zones.

Shear-zone junctions provide a further structural control for the localization of ore shoots. This is well illustrated in Figures 6 and 7, which show that the principal ore shoots occurred at the junctions of the N-9 and N-1 shear zones in the Negus mine and at the junction of the R-51 and R-54 shear zones in the Rycon mine. Other ore shoots occurred either at or closely related to junctions or local flexures in the shear zones.

The northern portion of the Negus-Rycon system contains no known ore shoots although mineralized sections are present in the R-53 extension. The absence of ore shoots in this portion of the system may be attributed to the lack of a strong development of shear-zone junctions and flexures.

Giant-Campbell System

The Giant-Campbell shear-zone system is the most extensive system in the greenstone belt and contains the largest orebodies. It has been traced from Kam Point in the southern part of the greenstone belt to the unconformity at Jackson Lake, a distance of some 15 miles (Figure 3, in pocket). The production of the Giant mine and part of the production of the Con mine is derived from the system, and in the past a part of the production of the Negus mine also came from its shear zones.

The literature describing the system is rather extensive. Henderson and Brown (1952b) have discussed the broad aspects of the system, and the ore-bearing parts have been described by Dadson and Bateman (1948), Dadson (1949), Campbell (1949), Lord (1951), Bateman (1952), Brown and Dadson (1953), and Brown, Dadson and Wrigglesworth (1959). The author has also dealt with both the broad aspects of the system and the structural control of the ore shoots in a thesis (Boyle, 1953b) and a series of papers (Boyle, 1954a, 1954b).

The southernmost extension of this large shear-zone system is only imperfectly known from diamond-drilling results. Several diamond-drill intersections indicate that the system is a strong one and carries ore values which may warrant considerable attention in the future. All of this part of the system is covered by the waters of Yellowknife Bay and an accurate idea of its nature is not possible. Diamond-drilling suggests that the system consists of several interlacing zones of chlorite schist which has been locally carbonated, sericitized, pyritized, and silicified. As a result of late faulting several segments occur from south to north; these are shown on Figure 3.

The system is exposed along strike for 6,000 feet in the underground workings of the Negus and Con mines (Campbell system), and here it is possible to analyze its nature in considerable detail. Figures 8 and 9 (in pocket) illustrate the principal characteristics of the system as compiled from detailed diamond-drilling and mining operations by the Negus and Con mines. From these plans and sections it is evident that the system is a complex of intertwining schist zones separated by masses of relatively unsheared massive rock—exactly the same conditions that prevail in the Con system, but on a larger scale.

The Negus part of the system comprises two faulted segments each consisting of two shear zones which are separated by a mass of weakly schistose rocks. The dip of the hanging-wall zone is 45 to 50°W throughout the mine, and with local exceptions the schistosity within this zone dips 55 to 65°W. Many local contortions and drag-folds occur within the hanging-wall zone and are the sites of economic mineralization. The foot-wall zone has not been explored in any detail. Where it has been cut by diamond-drill holes or crosscuts it has essentially the same characteristics as the hanging-wall zone, but orebodies, so far as presently known from diamond-drilling, appear to be absent.

In the Con part of the system there are several shear zones, separated by masses and horses of weakly schistose rock. Two general mineralized zones have been recognized, a hanging-wall zone and a so-called "foot-wall zone". The hanging-wall zone dips 45°W, and the schistosity dips from 55 to 65°W, steepening toward the north. The foot-wall zone displays similar characteristics, but the dip has not been ascertained with any degree of certainty.

It should be noted that the workings in the Con and Negus mines expose only the hanging-wall part of the system as a whole. Since the faulted extension of the system is known to consist of several wide shear zones on the Giant property (Figure 11, in pocket) it is probable that other shear zones lie below the two investigated in the Con and Negus mines.

The orebodies are complex, consisting of large sericite zones ribboned with irregular quartz lenses and stringers. In the Negus part the general trend of the mineralized zones and ore shoots parallels the hanging-wall of the western zone, and there is little or no plunge to the ore shoots as shown by the longitudinal section in Figure 8. Individual quartz-carbonate lenses and pods in the complex shoots tend to be subparallel or parallel to the dip and strike of the schistosity, and the plunge of the axes of small drag-folds and crenulations in the ore is horizontal in most places. Details of the ore shoots in the Con part are similar.

The ore controls in both parts are dragged and contorted parts of the shear zones, probably produced by flexures in the walls of the shear zones or by the rotation or buttress action of the large horses of massive rock. The dragging action was produced by thrusting and resulted in the formation of a large number of minor rolls, drag-folds, crenulations, and small faults as illustrated diagrammatically in Figure 10 and shown by the upper part of the ore shoot on Section AB, Figure 8. These drag-folded and crenulated zones were dilatant zones in which extensive mineralization took place.

On the east side of the West Bay fault the system emerges south of Fault Lake, from where it can be traced northeast in a series of faulted segments through the Giant and Akaitcho properties to the Akaitcho fault. North of this fault the system has been traced northeast through the Lynx property to the unconformity on Jackson Lake (Figures 3 and 11).

Southeast of Fault Lake and along its length to the above-mentioned unconformity the system maintains its characteristic pattern of parallel, subparallel, and branching shear zones separated by masses of weakly schistose rock. One notable characteristic is the strong tendency for shear zones on the eastern side of the system to strike into the walls, weaken, and die out.

The surface plan and sections of the Giant, Akaitcho, and Lynx portions (Figure 11) have been compiled from detailed surface and underground mapping of the schistose and massive portions and by projecting diamond-drilling data. While this plan and the accompanying sections do not show all the small details, it is felt that they show a logical interpretation of the facts as they appeared to the author in the field. The zones mapped and shown as shear zones include those containing chlorite, chlorite-carbonate, and sericite-chlorite-carbonate minerals which show a marked schistosity. The rock from these zones breaks along an

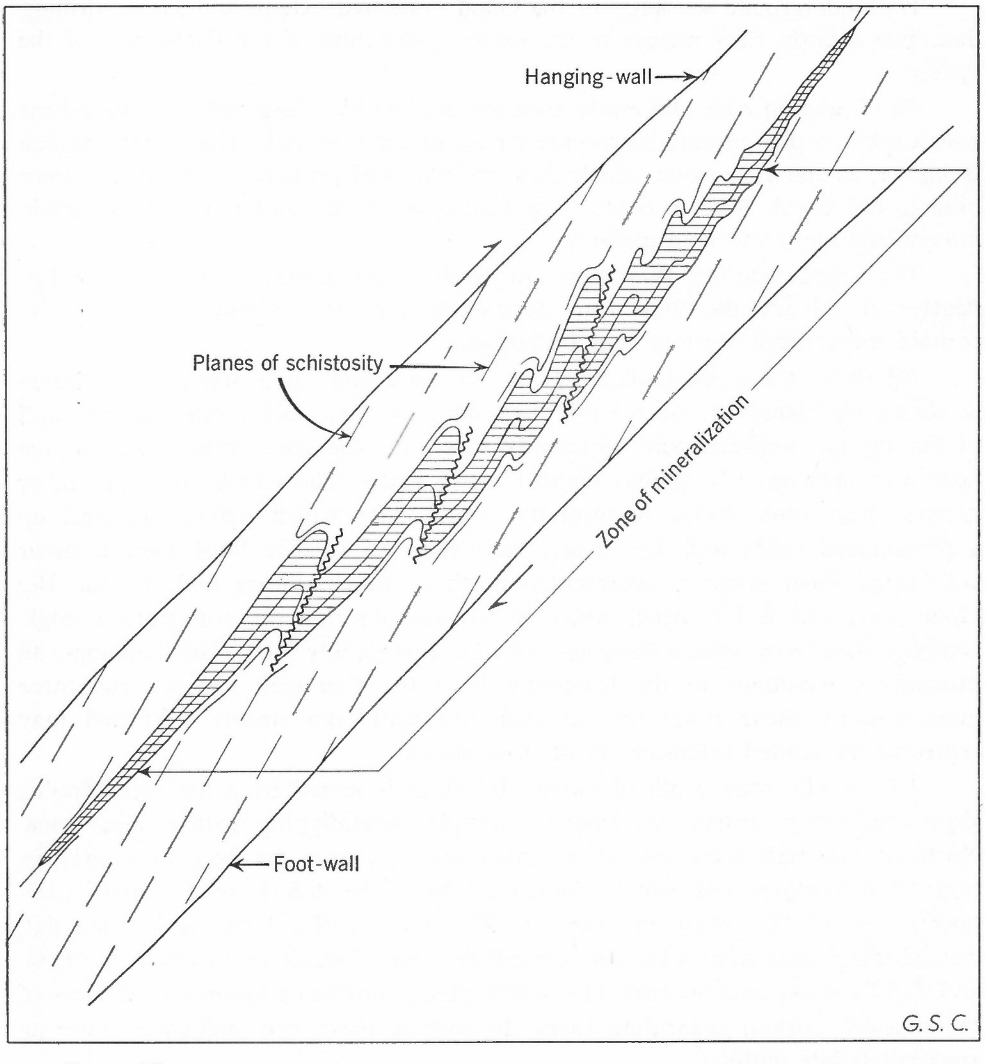


Figure 10. *Section showing nature of drag-folding and ore localization in the Campbell system.*

infinite number of parallel schist planes. The rock mapped as massive (i.e. greenstone country rock) is non-schistose to weakly schistose. In thin sections the shear zones contain chlorite, albite, carbonates, quartz, and sericite, and exhibit a strong foliation. Massive portions contain epidote, carbonates, fibrous amphibole, chlorite, and plagioclase with no pronounced foliation. In some cases, especially in relatively massive parts flanked by shear zones, fibrous amphibole is limited or absent and chlorite is abundant, but foliation is not marked. In these cases, it is generally possible to distinguish original features such as pillows, dyke contacts, etc. It should be noted that the shear zones have gradational contacts over several feet, and in most places on the plan and sections the contacts are approximate.

The underground workings of the Giant mine and extensive diamond-drilling data give a fairly clear picture of the extent and nature of the Giant part of the system.

The Cameron zone and South zone are marked by a large chlorite shear zone which splits in plan around a prominent nose of massive rock. The eastern branch is known as the East zone which dips 55°NW and probably joins the western branch and Creek zone at depth. The Cameron, South, and East zones contain mineralized areas and gold orebodies.

The Creek zone and West zone are parallel shear zones; the Creek zone dips nearly vertical and the West zone appears to dip west. These two zones also contain mineralized sections and orebodies.

All shear zones are faulted by the Townsite fault in a northwest direction as shown on Figure 11. Across this fault the East zone strikes into the east wall of the system, weakens, and apparently dies out. The zone immediately to the northwest behaves in a similar manner along strike. The Creek zone and other narrow shear zones merge to form the A.S.D. zone which strikes northeast up a pronounced valley and dips nearly vertical to 85°E. The West zone together with other shear zones is represented north of the Townsite fault by the Big Giant, Ole, and W.J.T. zones which in the author's opinion, constitute a single complex shear zone with a hanging-wall that dips steeply west. This hanging-wall probably corresponds to the hanging-wall of the Campbell system. The three most westerly shear zones on the plan apparently dip steeply west and may represent the faulted extensions of the Con system.

The A.S.D. zone south of Giant "B" shaft is joined by a flat west-dipping shear zone which crosses over from the complex west-dipping western shear zone. North of the shaft these two shear zones intersect over the nose of a massive body of greenstone rock which plunges 20°NE. The A.S.D. zone contains orebodies west of "C" shaft and east of "B" shaft. In this latter region the flat, west-dipping shear zone is known as the H.G. zone. Considered together, the H.G. and A.S.D. zones contain orebodies which plunge northeast following the nose of the massive portion separating them. In section these two orebodies have an apparent saddle outline.

North of the "312 fault" the structural picture is not too clear owing to limited development work and poor exposures. The H.G. and A.S.D. zones appear to be thrown northwest judging from underground exposures in the Giant mine. Their surface exposure is difficult to project, but it seems probable that their northeastern extension is represented by the Muir zone which appears to consist of a relatively flat east-dipping zone which merges with the North Giant shear zone.

The disappearance of the Muir zone beneath the massive portion of rock as shown in the figure is a complexity not easy to explain. There seem to be two probable explanations which can be verified or disproven by further work. Either the zone weakens and dies out in the walls of the massive rock or it splits into several branches. The latter seems more probable, and the narrow chlorite shear zones shown in the figure and discussed under the Bow Lake system probably represent the surface expression of the Muir zone.

The North Giant zone may represent the western part of the faulted extension of the W.J.T. and Ole zones. The dip of the zone in the North Giant area has not been determined, but judging from the dip of the schistosity which is 65 to 70°W, the zone dips west as shown on the section.

Northeast of the North Giant outcrop, a chlorite shear zone with local sericitic schist bands underlies a pronounced valley to a point south of the Giant-Akaitcho boundary where it appears to be thrown a short distance to the northwest by a fault now occupied by a diabase dyke. The northern extension underlies Moose Lake and is joined by several narrow shear zones that may represent the northern extension of the Muir zone and the faulted extension of the Con system. In this portion of the Giant-Campbell system, Akaitcho Gold Mines have developed a series of gold-quartz lenses in a brecciated schistose zone that dips to the east.

A precise analysis of the structural nature of the Akaitcho part of the system is hampered by a lack of extensive diamond-drilling data and surface outcrop, and hence, only a tentative conclusion can be reached at the present time. It is known that two shear zones occur on the Lynx property to the northwest; one of these dips east, the other west. The east-dipping one can be correlated with the Akaitcho east-dipping zone with confidence because distinctive markers are available. It seems reasonable to assume, therefore, that the steep west-dipping zone is also present on Akaitcho property.

North of the Akaitcho fault the system outcrops northeast of Gold Lake on the property of Lynx Yellowknife Gold Mines. Here, two shear zones have been outlined by diamond-drilling. As mentioned above, one dips steeply west, the other is a flat east-dipping one. Both shear zones have been carbonated and mineralized, and small shoots of ore grade have been found.

Northeast of the Lynx exposures, the system retains its complex nature of interlacing shear zones as far as the unconformity on Jackson Lake. Along this stretch a few mineralized zones occur, but orebodies have not been located.

The Giant part of the system is fairly well exposed by underground workings, and most of the shear zones have been extensively diamond-drilled. It is therefore possible by utilizing the diamond-drilling data in conjunction with field and underground mapping to obtain a fair knowledge of the structural factors responsible for the localization of the mineralized zones and ore shoots.

Orebodies in the Giant mine consist principally of a complex series of lenses, pods, stringers, and irregular masses of quartz intricately intergrown with wisps, seams, and elongated patches of highly dragged, contorted, and mashed carbonate-sericite schist. The majority of quartz lenses and pods occur *en echelon* and parallel the strike and dip of the schistosity; a few are subparallel and cut across it at small angles. In some places vein-like bodies of highly mineralized quartz cut across the general dip and strike of the schistosity at small angles. Metallic minerals in all ore shoots include pyrite, arsenopyrite, chalcopyrite, stibnite, sulphosalts, and gold.

The orebodies within the Giant part of the system show a distinct relationship to shear-zone junctions and flexures. In the Cameron, South, and East zones the mineralized zones and ore shoots occur along and around a prominent nose of massive rock which appears to plunge southwest. The nose and flanks of this massive rock projecting into the shear zones probably acted as a buttress during repeated movements, buckling and severely contorting adjacent parts of the shear zones. It is these parts which are the sites of mineralization and ore shoots.

The ore shoots and mineralized parts of the West and Creek zones occur in two shear zones which form a junction over a nose of massive rock. Their ore shoots and mineralized zones may correspond to the hanging-wall zone in the Con and Negus parts of the Campbell system.

The ore shoots in the south and central A.S.D. zones are steeply dipping and generally occur in highly dragged parts of the shear zones. The controls may therefore be similar to those suggested for the ore shoots in the Negus part of the system.

In a general way the ore shoots in the H.G. and northern part of the A.S.D. zones have an apparent saddle outline (Figure 12, in pocket), plunge north at a low angle, and follow faithfully the nose of relatively massive rock below them. These ore shoots occur in a region where the schist has been highly dragged, buckled, and contorted at the junction and down the limbs of the two shear zones. The tendency of ore shoots to occur at shear-zone junctions is plainly demonstrated in the Con and Negus-Rycon systems, and it seems highly probable that the same phenomenon is repeated at the Giant mine on a larger scale.

The Akaitcho orebody has been described by Manifold (1947) and Merrill (1947), and the Lynx mineralized zones by Lord (1951). In plan the eastern mineralized zone at the Lynx property occurs at a highly dragged shear-zone junction. In section both the east- and west-dipping mineralized zones, if projected upward above the present erosion surface, would be related to a shear-zone junction. The Akaitcho orebody is considered to be the faulted extension of the eastern mineralized zone at the Lynx property, and the same structural elements as those postulated for the Lynx may control the ore shoots.

The Giant-Campbell system is considered by Henderson and Brown (1950b) to have developed along a major thrust fault. The author agrees with this conclusion, and it would appear from the present study that the principal locus of faulting occurred along the west-dipping shear zone which includes the hanging-wall part of the Campbell system in the southern part of the area, the West, Big Giant, W.J.T., North Giant, and part of the Akaitcho zones in the central part, and the western part of the Lynx zone in the northern part. The other shear zones in the system, together with the Con and Negus-Rycon systems, are subsidiaries of this major fault structure. Their orientation in both plan and section are shown in Figure 13.

The direction and amount of movement along the Giant-Campbell system as a whole is not known with certainty. Judging from the faulted relationships of two distinctive series of flows as mapped by Henderson and Brown, the

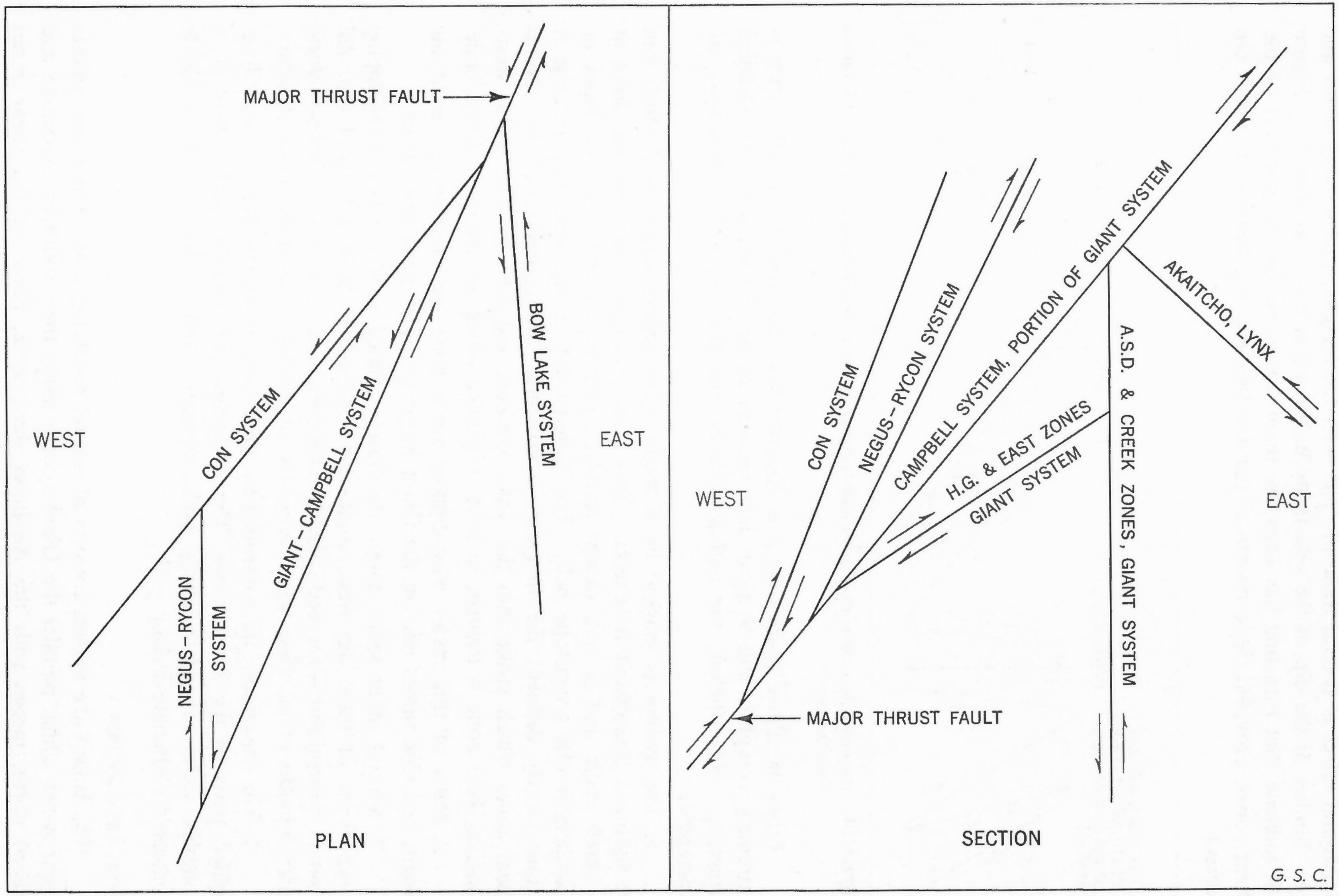


Figure 13. *Diagrammatic plan and section showing the orientation of subsidiary shear zones to the major thrust zone.*

horizontal offset is several thousand feet with the hanging-wall moving south and up. Studies of the dip of the schistosity in the schist zones, as shown by Figure 14, indicate that thrusting has been the main feature in the development of the shear zones, provided the concepts of the development of schistosity in rocks are correct.

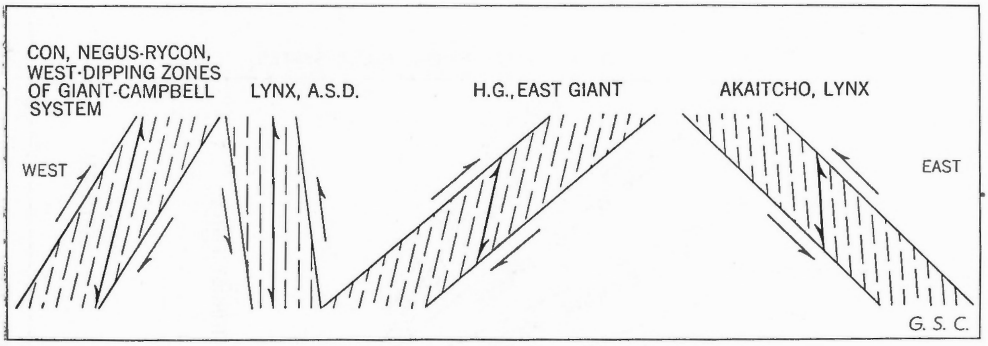


Figure 14. *Diagrammatic sections showing the relationship of the dip of the schistosity to the dip of the various shear zones.*

From the above description it is apparent that the Giant-Campbell system is extremely complex, and a great deal remains to be learned about its detailed structure. Nevertheless, the author believes that the following conclusions are warranted.

1. The system is marked by a major west-dipping schist zone which can be followed throughout its extent. This zone cuts across the volcanic flows at a small angle and is not, except locally, restricted to any series of flows or members in the greenstone belt. The hanging-wall of the west-dipping zone is rather clearly defined; the foot-wall is irregular and characterized by several shear zones which strike into the walls, weaken, and die out. The major west-dipping shear zone is thought to have originated along an extensive thrust fault.

2. Parts of this major west-dipping shear zone are ore-bearing, as at the Negus and Con mines and on the Giant property; other parts are barren.

3. Several other shear zones are closely related to the major west-dipping zone. Some of these dip west, some east, and others have a vertical dip. All contain mineralized zones and some contain orebodies. The most logical structural interpretation of all these schist zones is an extensive imbricate fault structure.

4. The ore shoots are controlled by shear-zone junctions, flexures, and drag-folded parts of the shear zones. The orebodies are irregular and consist of a complex series of quartz lenses, pods, stringers, and silicified zones in highly contorted carbonate-sericite schist.

Bow Lake System

The Bow Lake system consists of several ramifying schist zones and breccia shear zones which parallel the Giant system along their southern exposures and traced north, merge with the Akaitcho shear zone. Some of the shear zones underlie deeply incised valleys and are drift covered. The relationship of this shear-zone system to the Giant system is shown in Figures 3 and 11.

One good exposure occurs on the shore of Yellowknife Bay where the zones consist of 20 feet or more of strongly foliated chlorite schist with a few contorted parts. North of Bow Lake the system consists of many branches which have a brecciated schistose appearance. Silicified areas were not observed, and orebodies are not known to exist within any of these shear zones. A few quartz and carbonate stringers and lenses were seen, but with the exception of some pyrite, no other sulphide minerals occur in any quantity.

The nature of the shear zones of this system and the apparent close relationships shown by the surface plan suggest that this system is related to the Giant-Campbell system. Some of the northern ramifying shear zones of this system may represent the tails of the A.S.D., H.G., and Muir zones of the Giant System.

Stock Lake and Handle Lake Systems

These two systems are grouped together because they exhibit similar features, occur within the same general sequence of lava flows, and probably have had a similar origin and geological history. Both are limited in their extent and contain small quartz lenses and veins, some with gold values, but orebodies of mineable size have not been found in any of the shear zones of the two systems.

The Stock Lake system is an interesting group of four or more narrow breccia shear zones which strike north to north-northeast. Other minor crossover shear zones occur between these main shear zones. The dips of all shear zones are steeply west to vertical, and the widths vary from 2 to 5 feet. The shear zones consist predominantly of slightly foliated chloritic fragments in greenstones, and of poorly foliated sericite schist where granitic bodies are transected. Narrow schist zones are developed about quartz lenses, and transition phases between breccia and schist occur along many of the shear zones. The country rocks are mainly amphibolite (amphibolite facies), but in a few places the shear zones cut across irregular granodiorite masses and aplite and granite dykes.

The Handle Lake system is similar to the Stock Lake system in most respects. It consists of several narrow parallel, subparallel, and crossover shear zones. The major zones strike north to north-northeast and have steep dips. Some of these shear zones contain aplite and granite dykes which exhibit little or no shearing; others enclose similar dykes which have been sheared and contain lenses and stringers of gold-bearing quartz.

Crestaurum System

This system occurs in the area east of Ryan Lake. It consists of two main schist zones, a major western one and a minor eastern one, that appear to be related to probable shear zones underlying Daigle Lake and the draws to the north. Several other schist zones branch from and join these shear zones, producing a complex system, similar in many respects to the Con system.

The major western zone has a uniform dip of 50°SE and underlies a deeply incised valley with only one small outcrop 500 feet southwest of Daigle Lake.

This outcrop exhibits two schist zones separated by a small mass of unsheared rock. Diamond-drilling along the western zone has outlined three small ore shoots: a southern one with fair gold values southwest of Daigle Lake; a central one with low values; and a northern one with fair gold values northwest of the shaft site. The shoots contain quartz, carbonate minerals, pyrite, arsenopyrite, sulphosalts, and gold. A shaft was sunk to 410 feet in 1946, but work was suspended in 1947 owing to rising costs. For a more detailed description of the Crestaurum claims the reader is referred to Lord (1951).

Structural Control of Mineralized Zones

It has been demonstrated in the foregoing that shear-zone junctions, flexures in the walls, and drag-folded parts of the shear zones control the development of the quartz veins, lenses, and irregular silicified orebodies. Much has been written to explain the occurrence of orebodies and mineralized zones at these structural sites in shear zones and a detailed analysis here seems unnecessary. The shear-zone junctions were the sites where buckling, mashing, and extreme contortion of the schist were greatest. This structural disturbance was due to several causes, the chief ones being movements along the shear zones, rotation of horses of rock between two or more shear zones, and the wedging and buttress effect of the noses of horses of country rock.

The physical effect of this structural disturbance was an increase in volume at the junction affected, that is, dilatant zones were formed. In a similar manner differential movements along shear zones produced dilatant zones in the vicinity of flexures, and drag-folding of the schist had the same effect. The dilatant zones were zones of low pressure and low chemical potential. Hence, both pressure and chemical concentration gradients were set up between the dilatant zones and their surroundings, and migrating elements tended to move into these zones where they were precipitated.

Age of Transecting Shear Zones

The age relationships of the shear zones which parallel the flows and those transecting the flows are conflicting. In some places the transecting shear zones offset the parallel type; in others the parallel type seem to be subsidiary to the transecting type. It seems logical to assume, however, that during the early period of folding many shear zones formed along the less-competent bedding planes. Tuff beds, likewise, probably suffered considerable shearing during this period. Thus, the majority of the parallel shear zones were probably developed during the earliest period of shearing and are older than the transecting shear zones. It is, however, probable that a second period of movement took place along some of the earlier parallel shear zones during the thrust faulting that produced the transecting shear zones. In fact, some bedding planes and tuff beds which escaped shearing during the early folding may have been sheared during thrust faulting, and hence some of the parallel shear zones may be subsidiaries of the transecting ones.

The Handle Lake, Stock Lake, and Crestaurum systems give some information on the time of formation of the transecting shear zones. Shear zones of the

Handle Lake and Stock Lake systems cut granite dykes, and sericite schist is developed in these dykes as a result of the shearing and alteration. Certain shear zones of these two systems contain fresh aplite and granite dykes; others contain sheared aplite and granite dykes containing gold-bearing quartz. Some shear zones of the Handle Lake and Crestaurum systems transect the granodiorite greenstone contact. This evidence suggests an early period of shearing which provided a site for granitic bodies, some of which were later sheared, and in which quartz, sulphides, and gold were deposited. All the facts lead to the conclusion that the shearing which took place to form these three systems occurred simultaneously with the development of the western granitic mass and continued after the emplacement of the granite dykes and aplites.

The age of the Giant-Campbell and Con systems relative to the western granodiorite is not known because the two systems are not found in cutting relationships with this body. However, the early shearing along the Con system cuts across the metamorphic facies. From this it can be concluded that the formation of both systems was in part later than the development of the metamorphic facies which is in turn intimately related to the formation of the granodiorite.

Diabase dykes cut through the parallel and transecting shear zones and ore zones, and hence the development of the shear zones and the early gold mineralization took place prior to the intrusion of these dykes. Late faults and fractures offset the shear zones throughout the area.

The age relationships discussed above point to the probability that the early diastrophic forces within the Yellowknife greenstone belt operated in the following time sequence: (1) initiation of folding followed by failure along incompetent structural features, resulting in the formation of parallel shear zones; (2) continued folding, emplacement of granitic rocks and formation of some transecting shear zones; (3) final development of granitic rocks manifested mainly by granite and aplite dykes; (4) formation of the major transecting shear zones and possible formation of some parallel shear zones.

No major time-break appears to have taken place between any of these periods, and the whole process should be conceived as one of increasing intensity of application of the deforming forces.

Pre-diabase Fractures that Cut the Shear Zones

These fractures are numerous in all shear zones but tend to have a maximum development in or about ore zones. Many generations are present within the confines of a single ore shoot.

Most fractures dip at nearly right angles to the schistosity and form a characteristic ladder structure. Strikes are exceedingly variable. Widths range from a fraction of an inch up to a foot. All fractures have been mineralized with quartz and carbonate minerals, and some contain sulphosalts and gold. The contacts of the quartz and wall-rock are knife-sharp and replacement features and wall-rock alteration zones are absent (*see* Plates XV and XVI, facing p. 44 and p. 45).

The quartz-carbonate masses filling these fractures are short, narrow, irregular, lens-shaped bodies. The writer followed a number of these lenses during mining operations and found that they can be completely removed. The lenses and fractures terminate in the schistose walls and connecting fractures appear to be absent.

These post-shear-zone fractures are restricted to the shear zones and appear to be the result of tension forces acting during the final period of formation of these structures.

Pre-diabase Structures in Sedimentary Rocks

General Classification

In the sedimentary rocks of the Yellowknife group all structures are probably of the same age. Those which have been mineralized can be classified as follows:

1. Contorted schist zones and faults containing quartz veins, that transect the sedimentary beds.
2. Schist zones and fractures that parallel the sedimentary beds. These comprise ruptured and sheared beds and bedding planes, dragged slate beds, contacts, and saddle reefs on the noses of folds.
3. Ruptured and sheared axes of isoclinal folds.
4. Other irregular fractures and openings without any continuity or special relationships.

Table 3

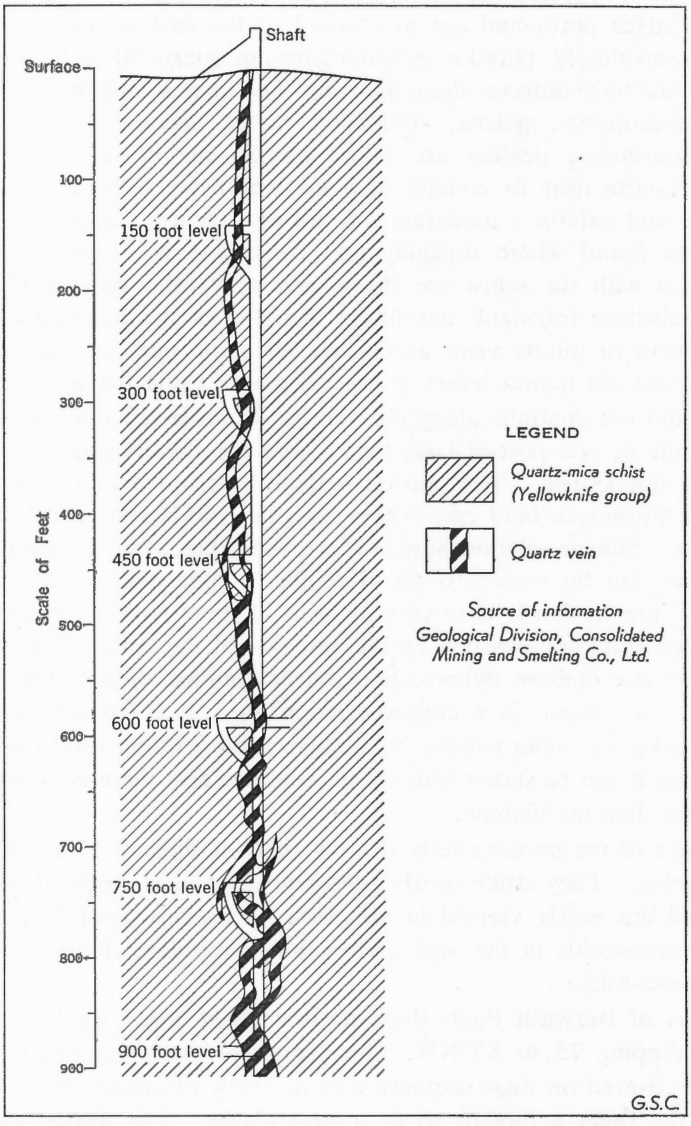
Age Relationships of Faults and Fractures in the Sedimentary Rocks

Structure (oldest first)	Notes on age relationships
Fractures along beds and at contacts, ruptured axes of folds, saddle reefs, contorted schist zones. Fractures occupied by pegmatites. (Some quartz lenses in above structures are gold-bearing.)	Probably all of the same age and related to the extreme folding of the rocks. Some pegmatites cut the quartz lenses in fractures, ruptured axes of folds, etc.
Fractures (non ore-bearing)	Prevalent in quartz veins
Post-diabase faults (non ore-bearing)	
Slips and small faults in country rocks and orebodies (non ore-bearing)	Probably same age as late post-diabase faults; some appear to be younger

Contorted Schist Zones and Faults that Transect the Sedimentary Beds

South of Prosperous Lake several zones of this nature outcrop east and west of the Ptarmigan fault (Figure 3, in pocket). Four main zones are recognized with several smaller ones. All strike northwest, dip nearly vertical, have similar internal features, and contain the same minerals.

The gold orebodies of the Ptarmigan mine were developed along one of the southern zones, and the following description of this zone is typical of all other zones in the general area.



Source of information
Geological Division, Consolidated Mining and Smelting Co., Ltd.

Figure 15. ***Vertical section through Ptarmigan shaft looking northwesterly along strike of Ptarmigan No. 1 vein.***

The Ptarmigan mine was operated during the years 1938-42 by the Consolidated Mining and Smelting Company of Canada. A description of the deposit is given by Lord (1951). The accompanying section through the shaft (Figure 15) is typical of others along the vein.

On the surface the zone outcrops near the shore of a small lake and trends N60°W for approximately 1,300 feet where it disappears beneath drift. The maximum width of the zone in places approximates 25 feet, and the dip is vertical. The wall-rocks of the zone are knotted quartz-mica schists of the Yellowknife group which strike north and are overturned to the east at angles of 65 to 75 degrees. Several closely spaced *en echelon* lenses of quartz 50 to 200 feet long and from 5 to 20 feet wide outcrop along the zone. The quartz contains small quantities of pyrite, arsenopyrite, galena, sphalerite, native copper, gold, and a little scheelite. Tourmaline needles are found locally, and a few feldspar crystals occur in the quartz near its contact with the wall-rock. The walls of the zone are contorted and exhibit a moderate schistosity. Quartz lenses and small veins are commonly found where dragging and contortion has been extreme. The quartz contacts with the schist are sharp, and very little vein quartz occurs in the walls. Schistose fragments are found in many of the individual lenses, and small stockworks of quartz veins are present in some parts of the zone. Small cross-faults offset the quartz lenses at several places along the zone.

Mining did not continue along the vein to its projected intersection with the Ptarmigan fault (a late post-diabase fault), and the relationships of the zone to this fault are not known. The late cross-faults referred to above appear to be related to the Ptarmigan fault and in this case the gold-bearing zone is older than the late faults. Similar relationships hold for the other zones to the north. One of these zones can be traced to the drift-filled valley overlying the Ptarmigan fault, but the intersection is covered with drift. There is a suggestion, however, that the faulted extension emerges on the east side of the fault. The age relationships with the late diabase dykes cannot be determined directly since the zones and dykes are not found in a cutting relationship. It is known, however, that late diabase dykes cut other smaller but similar zones with an identical mineralization, and hence it can be stated with some assurance that these northwest-trending veins are older than the diabase.

The origin of the northwesterly striking zones is difficult to establish without detailed mapping. They strike nearly perpendicular to the strike of the enclosing sediments and dip nearly vertical in all cases. They are parallel to the general trend of the cross-folds in the area and probably represent faulted and dragged axes of the cross-folds.

Southeast of Burwash Point three narrow schist zones mark faults striking N25°E and dipping 75 to 85°NW. The exposures are approximately 300 feet long and are covered on their southern and northern extensions by drift. Cross-faults offset the zones a foot or so in several places. The wall-rocks are greywackes and slates which strike east and are overturned to the south at angles of 75 to 80 degrees.

Burwash Yellowknife Gold Mines investigated the zones in 1935 and 1936 by open-cuts and a vertical shaft, but development work failed to substantiate in depth the rich gold values which were found near the surface, and the workings were abandoned. No further work has been done.

The open-cut exposures show several small quartz lenses having a maximum width of 2 feet enclosed by a few inches of poorly foliated chlorite schist. The contact of the quartz with the schist is sharp in most places, but some quartz exhibits ribbon structures, and small stockworks of quartz stringers occur in parts of the fault zones. The quartz contains arsenopyrite, pyrite, galena, pyrrhotite, chalcopyrite, and some gold.

Little can be said about the age relationships of these zones since cutting relationships with diabase dykes and other structures are absent. It is probable that they had a similar structural origin to those of the Ptarmigan series of schist zones since they parallel the axes of the cross-folds in the general area.

The argillites, greywacke, and acid volcanic rocks in the vicinity of Walsh and Banting Lakes contain several fracture zones and poorly developed schist zones which strike north to northeast, dip nearly vertical, and lie along or cut across the sedimentary beds at small angles. These zones enclose glassy, light to dark grey quartz containing arsenopyrite, pyrite, galena, and sphalerite. Small massive pods of galena and sphalerite up to three feet long and a foot wide occur in some zones. Gold values are low in both the quartz veins and massive sulphide deposits, and no orebodies have been located. The structural relationships of these zones are not known because the writer did not examine them in detail. They are similar to other mineralized zones in the sedimentary rocks and presumably they resulted from the same causes that produced the folding of the sediments and volcanic rocks in which they occur.

Schist Zones and Other Openings that Parallel the Sedimentary Beds

These zones are especially common in the areas underlain by the Yellowknife sedimentary rocks. Fractured and ruptured, highly contorted and dragged zones in beds and along associated bedding planes are widespread particularly in the weak members of the sedimentary assemblage such as argillites and slates.

The internal features of these zones are similar throughout the area. They consist of highly crenulated, dragged and mashed zones of rock. Slaty cleavage may be developed, and small fractures are ubiquitous. Quartz lenses and veins are most abundant where contortion and dragging has been extreme, but occurrences of quartz veins are also widespread along bedding planes exhibiting little structural disturbance. The quartz in many areas is devoid of any sulphides or gold, but in others small quantities of pyrite, arsenopyrite, sphalerite, galena and gold may occur. Mineable gold orebodies have not been found in any of these structures within the area described.

A few schist zones occur at the contacts of the sedimentary and volcanic rocks on the north shore of Duck Lake, on the islands immediately west of Horseshoe Island, and at the southeast end of Walsh Lake. These schist zones are poorly exposed, but some have been prospected and pits expose quartz lenses and small deposits of pyrite, pyrrhotite, galena, sphalerite and arsenopyrite. A low gold content is characteristic of all the deposits.

Quartz saddle reefs on the noses of folds are not abundant within the sedimentary area covered by this report. A few occur, but no economic orebodies are known in structures of this type. Camlaren Mines in the Gordon Lake area is a typical example of this type and the reader is referred to the account by Henderson and Fraser (1948) for further details.

Ruptured and Sheared Axes of Isoclinal Folds

These structures occur where folding has been extremely tight and complex. The axes of anticlines and synclines are fractured, mashed and dragged, and mineralized with quartz. No gold orebodies are known in structures of this type in the district, but many quartz veins contain a little gold and a few scattered sulphides.

Irregular Structures Containing Quartz and Pegmatites

Quartz stringers, lenses, and irregular bodies, usually of limited width and extent, occur throughout the sedimentary assemblage. Many of these occur in fractures and in dragged parts of beds or in other contorted structures which show no special relationships. Many of the quartz veins show ptygmatic characteristics, but others are quite regular. Most of these irregular structures and quartz bodies were probably formed during the intricate folding of the sedimentary strata.

Pegmatites occur in great profusion in the Prosperous Lake granite and in the quartz-mica schist aureole surrounding it. In general, within the granite, the pegmatite contacts are irregular and diffuse and in many places grade imperceptibly into the enclosing walls; in the quartz-mica schist aureole the pegmatites usually exhibit sharp contacts.

Structural Control of Mineralization in the Sedimentary Area

It is most probable that all the fracture zones, faults, and schist zones described above are the same age and originated as a result of complex close folding and cross-folding of the sedimentary strata. The transecting structures appear to be related to cross-folding and probably mark faulted, contorted, or sheared axes of cross-folds. The parallel structures resulted by failure of incompetent beds, bedding planes, and contacts. Isoclinal folding has produced broken and sheared axes of synclines and anticlines. Other fractures, occupied by pegmatites and quartz lenses, are the result of the complex folding or tension forces.

All of the structures in the sedimentary area have a limited extent. They range from microscopic size up to 1,300 feet long in the case of the Ptarmigan zones. Most of the structures and their contained quartz lenses and pegmatites are a few tens of feet in length and cannot have a great vertical extent. The writer has actually seen some of the smaller ones terminate on their dip in massive sediments and was unable to find any feeder channels such as fractures or joints. If the smaller structures and their contained quartz lenses and pegmatites are isolated, it is not illogical to assume that the larger structures are similarly isolated when considered in a broad sense.

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Plate IX. *Typical late fault, Negus Point, Yellowknife.*

One fact of considerable importance is that nearly every fracture, fault, drag-fold, and contorted zone has been filled with some mineral or assemblage of minerals. Extensive voids do not occur. In some places the structures contain quartz or quartz and sulphides; in others pegmatites. This applies down to microscopic size. In the granite, pegmatites are predominant, in the quartz-mica schist areas both pegmatites and quartz lenses are present, and in the relatively unaltered sediments only quartz veins and lenses and small stringers of albite occur.

The field facts in the sedimentary area seem to be best explained by assuming that the structures that have been mineralized constituted dilatant zones of low pressure and low chemical potential in which migrating mineral matter, probably derived from the surrounding rocks, has been precipitated. The alternative postulate that each of the structures in the sedimentary rocks was intimately connected to master mineralization channels is not in accord with the field facts.

Post-diabase Faults and Fractures

Post-diabase faults are a common feature of the Northwest Territories, but in particular they are concentrated within the Snare River-Ingray Lake and the Yellowknife districts. These faults have been discussed in some detail previously (Boyle, 1950), (Brown, 1955), and only a brief summary will be given here.

Seven major post-diabase faults occur within a belt some 10 miles wide in the Yellowknife district. These are from west to east—Kam-Pud fault, West Bay fault, Hay-Duck fault, Walsh fault, Ptarmigan fault, Vega fault, and Madeline fault. Hundreds of other crossover and bifurcating faults related to the major faults occur throughout the area. The principal crossover faults are known as Martin fault, Townsite fault, Aye fault, Negus fault, Akaitcho fault, and Duck fault.

The six major faults strike N10°W to N40°W and dip nearly vertical. The crossover faults have various strikes and dips.

The majority of both the major faults and crossover faults have a left-hand movement. The internal features of all late faults are remarkably similar in all types of rocks. They are commonly only a few feet wide (Plate IX), but in certain places, as at the junction of the West Bay and Akaitcho faults, the fault may be marked by a brecciated zone extending over 200 feet. The fault zones commonly contain a rubble of brecciated and comminuted rock fragments which show no preferred orientation, and neither the fault walls nor the fault zones show any marked degree of schistosity exceeding that imposed upon the rocks during regional metamorphism.

The mineralogy of the late faults is simple. Locally the breccia has been silicified and massive quartz lenses have formed in the fault plane. In some cases the silicification has been extreme and zones several hundred feet long and wide consisting of quartz and some hematite have been developed. These are known as 'giant quartz veins'. In many places relatively unfractured comb quartz is present indicating that little movement took place after the emplacement of this quartz. Hematite is abundant in and around all late faults, and some chalcopyrite and pyrite occur locally.

In the underground workings of all mines many late fractures or slips are present. These consist of a narrow zone rarely over a few inches wide containing gouge and brecciated wall-rock fragments. Locally, carbonate minerals occur, and in the permafrost zone ice veins and lenses are found in the fractures. Some of these fractures are associated with and probably represent small subsidiaries of the late faults; others may be earlier or later and may have a different origin. Many are open and are the channelways for circulating waters which carry considerable mineral matter.

Mineralized zones in the late faults and fractures have been controlled by features similar to those found within the shear zones. In many cases flexures in the walls of the faults have produced low-pressure dilatant zones which have been mineralized with euhedral quartz and hematite. Fault junctions have also been favourable areas, a typical example being the development of a 'giant quartz vein' at the junction of the West Bay and Akaitcho faults.

Chapter IV

MINERALIZATION OF THE YELLOWKNIFE DISTRICT

In this chapter an outline is given of the mineralization history of the district and a brief description of the more important occurrences of the syngenetic, epigenetic, and supergene minerals in the greenstone belt and sedimentary area. The origin of these minerals is discussed in subsequent chapters.

The common minerals were determined by visual inspection, thin sections, and polished sections. The complex minerals were determined by X-ray and spectrographic analyses.

Age Relationships

The mineralization processes in the Yellowknife area are complex. They have extended over a long period of time and are in fact still in progress. The orebodies were probably formed during early Precambrian time[1], and the quartz lenses in the post-diabase faults are late Precambrian in age. Calcite and pyrite are precipitating from underground waters in late fractures at the present time.

Tables 4 and 5 give an outline of the age relationships of the various structures and a list of their characteristic minerals.

Table 4

Mineralized Structures in the Greenstone Belt

Structure (oldest first)	Characteristic epigenetic minerals (most abundant first)
Quartz-filled fractures	Quartz with small amounts of feldspar and pyrite
Parallel shear zones (ore-bearing)	Quartz, carbonates, pyrite, arsenopyrite, chalcopyrite, stibnite, sulphosalts, sphalerite, galena and gold
Transecting shear zones (ore-bearing)	Quartz, carbonates, pyrite, arsenopyrite, stibnite, chalcopyrite, sulphosalts, sphalerite, galena, scheelite and gold
Quartz-filled fractures (mainly non ore-bearing)	Quartz and carbonates with small amounts of pyrite, arsenopyrite, chalcopyrite, tetrahedrite and gold
Post-diabase faults (non ore-bearing)	Quartz, hematite, calcite, chalcopyrite and pyrite; ice in the permafrost zone
Slips and small faults in country rock and orebodies (non ore-bearing)	Calcite, pyrite, marcasite, limonite; ice in the permafrost zone

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[1] The ages given by Wilson, Russell, and Farquhar (1956), as determined from the isotopic ratios of lead ores from Yellowknife, range from 2.1 to 2.5×10^9 years. This places the age of the mineralization as early Precambrian.

Table 5

Mineralized Structures in the Sedimentary Area

Structure (oldest first)	Characteristic epigenetic minerals (most abundant first)
Fractures occupied by pegmatites[1]	Feldspar, quartz, muscovite, tourmaline, and numerous other rare minerals characteristic of pegmatites
Fractures along sedimentary beds and at contacts, ruptured axes of folds, saddle reefs and contorted schist zones (some quartz lenses are gold-bearing)	Quartz, pyrite, sphalerite, galena, tourmaline, carbonates, scheelite, feldspar, and gold
Quartz-filled fractures (non ore-bearing)	Quartz and small amounts of carbonates
Post-diabase faults (non ore-bearing)	Quartz, hematite, and pyrite
Slips and small faults in country rocks and orebodies (non ore-bearing)	Calcite, pyrite, and quartz

[1] Some pegmatites appear to be the same age as quartz lenses in contorted beds, ruptured axes of folds, saddle openings, etc. Others are younger and cut these quartz bodies.

Mineralogy

It is impractical to try to describe all the known occurrences of each mineral, and hence only the significant occurrences are recorded here. These include quartz, the carbonate minerals, the sulphides, sulphosalts, oxides, and native elements of which gold is the most important economically. A brief account is given of the occurrence of the characteristic pegmatitic minerals, but for more details the reader should consult the reports by Jolliffe (1944a), Rowe (1952), and Hutchinson (1955). The supergene minerals are described briefly at the end of this chapter.

The mineralogy of parts of the Yellowknife district has been described by Jolliffe (1938, 1944a), Ridland (1941), and Coleman (1953, 1957). Reports on special investigations of the mineralogy of certain ores from the Yellowknife district, prepared by the former Bureau of Mines and the Mines Branch, are listed in the bibliography.

Quartz

Country Rocks

Quartz is a major constituent of the sedimentary and granitic rocks, pegmatites, and porphyries and occurs in only small amounts in the greenstones and late diabase dykes. In the first suite of rocks the quartz is an original mineral although some rearrangement and migration of silica may have taken place during metamorphism. This is especially true for the sediments in which much of the quartz has undergone recrystallization, resulting in the migration of some silica into fractures where it has been deposited as secondary quartz. In the greenstones quartz is most abundant in the epidote amphibolite and greenschist facies and occurs in close proximity to zones where chloritization and/or carbonitization are present.

This fact suggests that the quartz in these rocks is primarily the result of metamorphic processes. In the late diabase dykes the quartz occurs in micropegmatitic intergrowths and was derived by crystallization from a magma.

The quartz grains in the relatively unmetamorphosed sediments (greywackes, argillites, etc.) have a clastic nature, but in general some secondary growth and recrystallization has obliterated the original angular outlines of the grains. In thin sections the quartz grains show a general sharp extinction and are clear except for some planar and randomly distributed liquid and solid inclusions. The quartz grains in the knotted quartz-mica schists and hornfels usually show only traces of their original angular outlines. They are generally clear with a few inclusions and have apparently been recrystallized.

The quartz in all granitic rocks occurs as colourless coarse- to medium-sized anhedral grains or as micrographic intergrowths with feldspar. In thin sections the quartz is clear, with only a few liquid and solid inclusions. Most grains possess sharp extinction features, except in or near sheared areas where grains with anomalous extinction predominate.

The quartz in parts of the Prosperous Lake granite and in some of the pegmatites associated with this granite is faintly smoky in colour. This colour appears to be the result of electronic darkening produced by the radioactive emanations given off by zircons and other small radioactive minerals in the rocks.

The quartz in the greenstones is generally accompanied by some calcite and occurs as irregular blebs, seams, interstitial grains, and in amygdules. The grains are generally clear, possess sharp extinction, and contain a few liquid and solid inclusions.

Epigenetic Deposits in the Greenstone Belt and Western Granodiorite

At least four distinct ages of epigenetic quartz are present in the greenstone belt, and other intermediate ages occur locally. The principal ages of quartz are tabulated below, the oldest first.

(1) Quartz lenses in early fractures cut by the shear zones.

(2) Quartz lenses and veins in shear zones.

(3) Quartz stringers and veins which cut the shear zones and the quartz veins in (2) above.

(4) Quartz lenses and 'giant quartz veins' in post-diabase faults cutting the greenstones and western granite mass.

Quartz Lenses in Early Fractures

The quartz lenses in the early fractures rarely exceed 25 feet in length and depth, and a few inches in width. They occur principally in the greenstones, but a few are present in the granitic rocks flanking the greenstone belt. The contacts of the lenses with the host rock are knife-sharp in nearly all localities (Plate VI, facing p. 12), but some lenses exhibit a few wisps of unreplaced greenish chlorite adjacent to the slightly chloritized wall-rock.

The quartz in most lenses is coarse grained, but in some it is medium grained with a sugary texture. The colour is usually milky white, and the lustre is vitreous. Most specimens are brittle and break with an uneven splintery fracture.

Thin sections of the early quartz contain coarse- to medium-sized grains that exhibit a moderate degree of undulose extinction and are cut by small ramifying patches of clear quartz grains possessing sharp extinction. Liquid inclusions are present in most of the larger grains and include two types—two-phase inclusions consisting of a large bubble and a liquid, and three-phase inclusions consisting of a large bubble, a liquid, and microscopic crystals. Some inclusions are randomly distributed throughout the grains and may be primary. Others mark rotated parts of the quartz grains, not in optical continuity with other parts of the same grain and are probably of secondary origin. Still other inclusions are randomly distributed along variously oriented planes which form a reticulating pattern. These planes of inclusions cut across grain boundaries and must, therefore, be secondary. All quartz grains contain microscopic acicular crystals and other solid inclusions.

Quartz Lenses and Veins in Shear Zones

The shear zones contain by far the greatest amount and variety of quartz in the greenstone belt. Two generations of quartz are generally present in all shear zones and in some places three or more generations may occur. The first generation of quartz makes up the complex gold-bearing lenses and veins, the second occurs as stringers and lenses cutting the shear zones and the gold-bearing quartz lenses. The first generation is described here; the second in the sections to follow.

The gold-bearing quartz lenses in the Giant-Campbell, Con, Negus-Rycon and Crestaurum systems are essentially the same in structure and will serve as examples of one type. Certain shear zones of the Negus-Rycon system and Shaft zone of the Con system contain well-defined gold-bearing quartz veins with features somewhat different from the quartz lenses and will serve as examples of a second type of quartz deposit in the shear zones.

The quartz lenses in the Giant-Campbell, Con, Crestaurum and parts of the Negus-Rycon systems differ in size because of structural conditions. All lenses have irregular boundaries and grade into a halo of carbonate-sericite schist. They are composite bodies (Plate X) made up of many small pods and irregular lenses of quartz separated by narrow seams, streaks and zones of highly carbonated and silicified sericite schist. In general the small pods and lenses parallel the schistosity but some vein-like masses cut across the schistosity at a small angle. The composite lenses are concentrated in warped, drag-folded, and mashed parts of the shear zones, generally at or near junctions and deflections. In some shear zones the quartz lenses are marked by slips which define the hanging-wall and/or foot-wall of the gold-quartz orebodies; in others the ore boundaries must be determined by assays.

From the abundant residual seams and patches of sericite schist one might conclude that the composite lenses formed by replacement of parts of the shear zone. However, despite the evidence that replacement has taken place locally, the main process in the formation of the composite quartz lenses appears to have

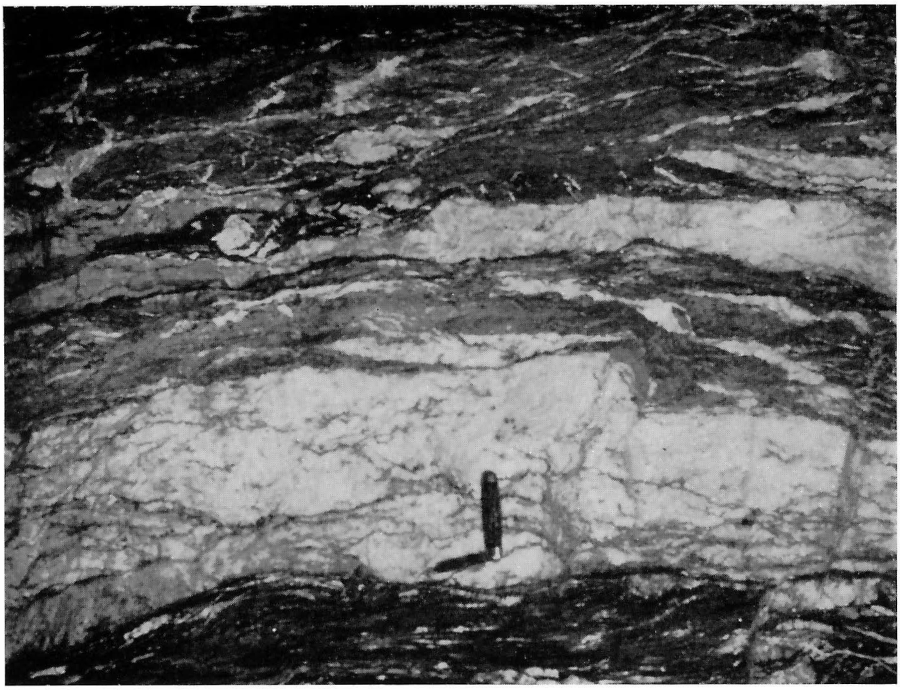

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Plate X. *Typical composite gold-quartz lens, Campbell system, Negus mine.*

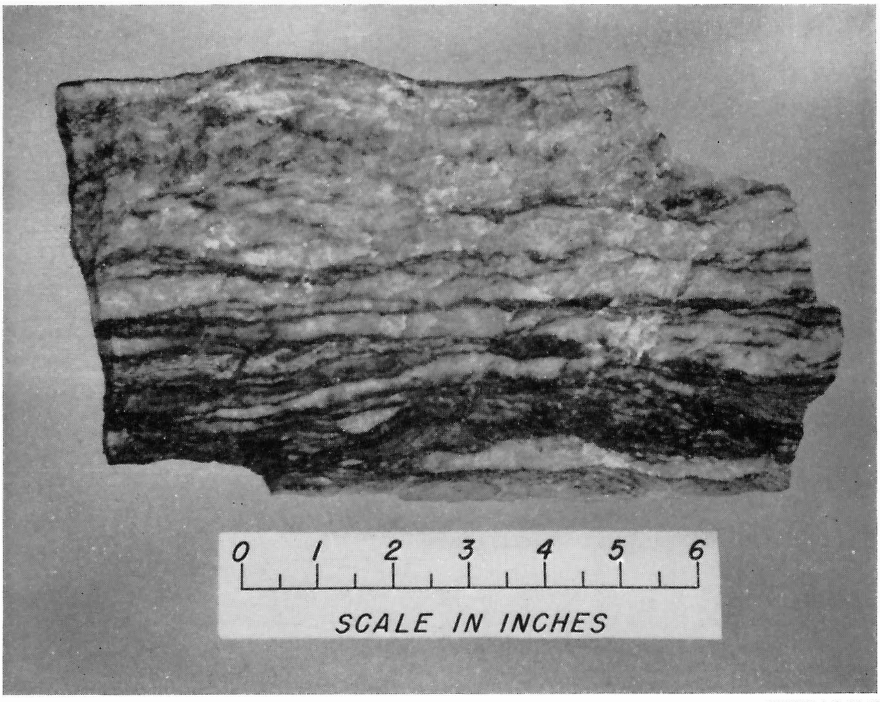

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Plate XI. *Ribbon quartz, Campbell system, Negus mine.*

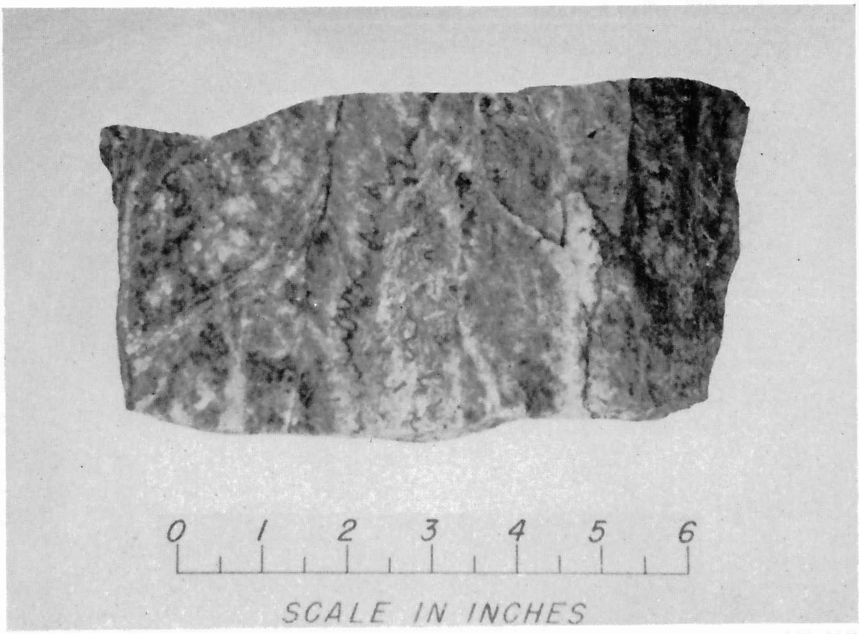

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Plate XII. *Grey quartz exhibiting comb structure, Negus-Rycon system.*

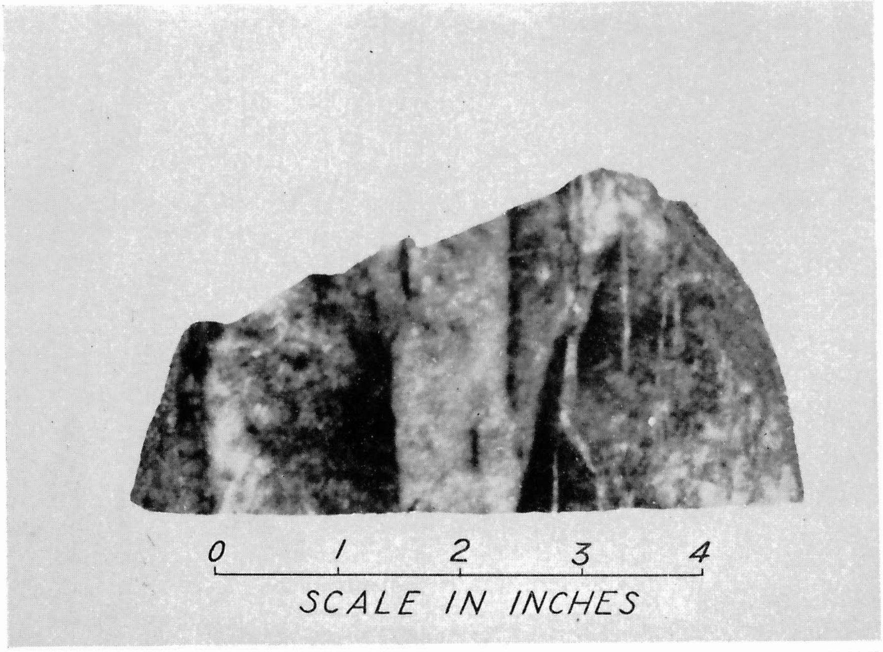

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Plate XIII. *Early black quartz cut by younger generation of white quartz, Negus-Rycon system.*

been the repeated formation of incipient openings in the shear zones, where buckling, dragging, and mashing of the schist was prevalent. These contorted areas were sites of low pressure and low chemical potential into which mineral matter migrated and was deposited.

The large composite quartz lenses probably grew by accretion of numerous small quartz lenses and pods filling dilation zones. Once these small lenses were formed, repeated warping and dragging resulted in recrystallization of the quartz and further dilation, drawing in more silica. This action together with some replacement tended to obliterate the seams and patches of schist surrounding the small lenses, and the final result was ribbon quartz lenses or bodies of massive quartz containing little trains of sericite or carbonate.

The macroscopic features of the quartz in the composite lenses is essentially the same in all occurrences. The colour of the quartz varies from dark to light grey to white depending upon the amount of graphite, grey sulphides, sulphosalts, and liquid inclusions present. In parts of the Campbell system a light flesh-coloured variety occurs in some lenses. Ribbon structures (Plate XI) are ubiquitous in all lenses, but much massive quartz occurs locally. Vugs, containing comb quartz, are rare. Most of the quartz has a vitreous, slightly schistose appearance and is brittle; some varieties, however, have a pronounced cherty appearance, are tough, and break with a conchoidal fracture.

The microscopic features of the quartz in the composite lenses are similar in all occurrences. In thin sections the quartz appears as medium-sized grains and microcrystalline grains. The medium-sized grains generally show extreme undulose extinction and are crowded with innumerable solid and liquid inclusions. These features as well as the presence of abundant microcrystalline clear quartz are indicative of gold-bearing quartz and serve to differentiate it from the quartz in granites, pegmatites and late faults. The microcrystalline quartz is clear with sharp extinction and contains only a few liquid and solid inclusions. It marks the grain boundaries of medium-grained quartz and forms irregular patches, seams and phantom veinlets throughout this quartz.

In most lenses medium-grained quartz predominates and generally constitutes some 70 per cent of the quartz present; in other lenses the microcrystalline type may predominate and a cherty quartz is developed.

The liquid inclusions generally have two phases, liquid and gas. They are distributed at random through the quartz grains, along planes restricted to individual grains, or along diffuse planes transecting the boundaries of several grains. In some medium-sized quartz grains, beady lines of inclusions mark parts of the crystals slightly rotated out of optical continuity. Solid inclusions are distributed throughout the medium-sized grains and the fine-grained clear patches and veinlets. In most cases, where the identity of the solid inclusions can be established, they are fragments of carbonate, sericite, apatite, rutile or tourmaline. Some of these inclusions may be unreplaced fragments of the wall-rock minerals, and others may have crystallized with the quartz.

Some shear zones in the Negus-Rycon system and in the Shaft zone of the Con system contain gold-bearing quartz veins which exhibit features somewhat different from the lenses just described. In these shear zones the veins are flanked by a slight schistose, dense, dyke-like alteration zone (Plate VII, facing p. 12). The quartz veins are markedly vuggy and comb structures are common (Plate XII). The vuggy parts are filled with carbonate minerals, and some contain sulphosalts.

Some shear zones of the Negus-Rycon system contain two ages of early quartz. The first is black to grey in colour and is partly replaced and veined by milky quartz (Plate XIII). In some veins, black and grey quartz abuts the vein walls, and the milky quartz occupies a medial position; in other veins the reverse is true. Many veins contain a mottled variety of quartz which consists of small nuclei of black and grey quartz in a matrix of white quartz (Plate XIV).

Thin sections of the quartz from the above two shear-zone systems show many of the quartz grains to be euhedral or subhedral in outline. Growth lines, marked by primary liquid inclusions, are abundant, and secondary inclusions along planes cutting grain boundaries are common. Microscopic trains of carbon particles occur in the black and grey quartz and are primarily responsible for its colour (Boyle, 1953a).

The decrepitation features of the quartz from the orebodies and barren quartz lenses in the shear zones are described in a previous publication (Boyle, 1954c); the general conclusions reached are:

> . . . there are certain poorly developed patterns in the decrepitation results that may be significant in the analysis of the ore forming process, but none appears to be clear cut enough to determine the direction of flow of mineralizing solutions or predict the possible location of ore shoots. The reason for the poorly developed patterns is the complexity introduced by extreme crushing and recrystallization of the quartz. In this respect the quartz in the Yellowknife orebodies is not suitable for decrepitation studies.

Quartz Stringers and Veins that Cut the Early Quartz Veins and Lenses

Quartz stringers and veins of this age occur in all shear zones and have similar characteristics. The stringers and veins are irregular bodies and cannot be traced far. They terminate in schist in all directions and do not form an interconnected system in any one locality.

In the Con system the veins and irregular lenses cut and appear to replace parts of the early quartz lenses (Plate XV). In the Campbell system the cross-cutting stringers and lenses show a strong development of bulbous masses resembling boudins (Plate XVI). In the Giant system quartz of this age is not abundant, but where present it occurs in irregular veinlets and lenses. The Negus-Rycon system contains only a few quartz stringers of this age.

The macroscopic features of this age of quartz differ from those of the early gold-bearing quartz. In most occurrences the quartz is coarse grained, exhibits euhedral to subhedral crystals, and is vuggy. Quartz in the stringers that have a strong development of bulbous masses is fine grained, slightly schistose, and may be cherty locally. The vuggy parts of the stringers and lenses contain calcite and ankerite and locally tetrahedrite, chalcopyrite, and some gold. Lenses which exhibit replacement features contain abundant unreplaced fragments of sericite schist containing pyrite and arsenopyrite, chlorite schist, and early quartz. The contacts of the quartz with the various types of schists and early quartz is

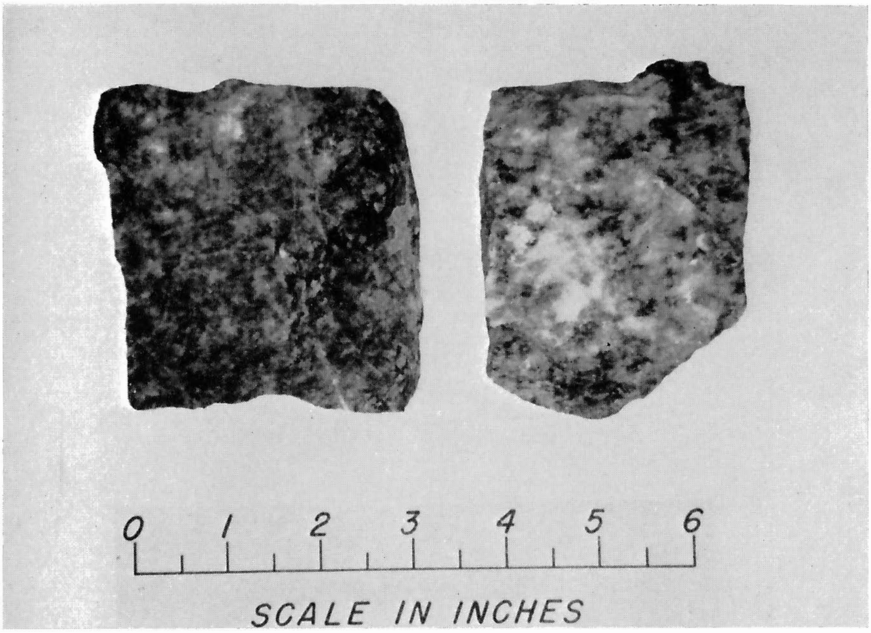

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Plate XIV. *Mottled varieties of quartz, Negus-Rycon system.*

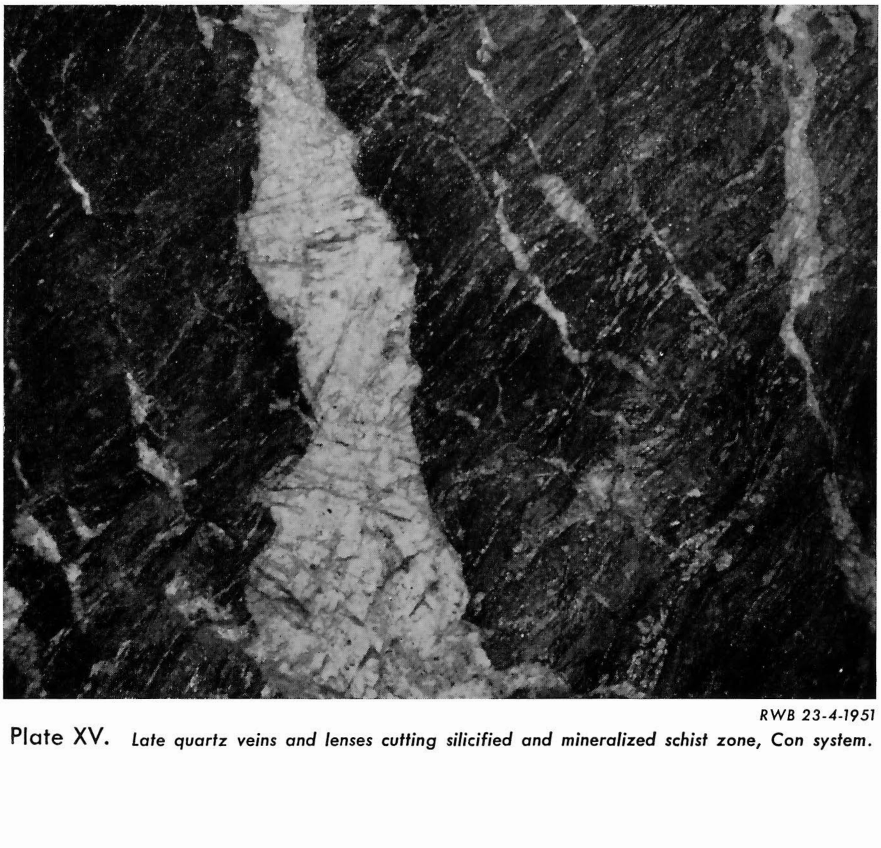

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Plate XV. *Late quartz veins and lenses cutting silicified and mineralized schist zone, Con system.*

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Plate XVI. *Late quartz-carbonate veins showing bulbous masses, Campbell system, Negus mine* generally sharp and alteration zones are absent. The colour of the quartz ranges from white to faintly flesh coloured. Some irregular crosscutting stringers in the Giant system contain black or grey quartz and calcite due to dispersed microscopic particles of carbon in the two minerals.

Microscopic examination of this age of quartz shows many of the grains to be relatively clear and to have a general subhedral to euhedral habit with growth planes marked by primary liquid inclusions. In addition, randomly oriented solid and liquid inclusions, and a few planes of secondary liquid inclusions are generally present. The quartz in the bulbous masses is commonly highly crushed, brecciated, and recrystallized with a development of much fine-grained clear quartz. Grains which escaped mylonitization exhibit extreme anomalous extinction. These facts suggest that the bulbous masses are the result of structural contortion of the veins and stringers with consequent recrystallization in place.

Quartz Lenses and 'Giant Quartz Veins' in Post-diabase Faults

In the greenstones and western granodiorite the post-diabase faults and associated fractures contain two types of lenses which differ in size and character. The smaller of these lenses occurs mainly in the greenstones and consists of narrow irregular bodies of massive and comb quartz. The larger lenses constitute the so called 'giant quartz veins'. One of these veins occurs at the junction of the West Bay and Akaitcho faults where the greenstone and granodiorite walls are highly brecciated. In this locality quartz has replaced parts of the fault breccia, and stringers and veinlets of quartz extend outward from the fault into the granodiorite for hundreds of feet.

In some places the smaller lenses consist of a groundmass of highly intergrown quartz crystals surrounding breccia fragments; in others the lenses are made up principally of prismatic comb quartz which lines cavities in the faults. The colour of the quartz is commonly colourless or milky. In some lenses amethyst may occur.

In thin sections the intergrown quartz crystals of the small lenses exhibit a general euhedral to subhedral character, and relatively little mylonitization is present. Fracturing is common, however, and in most thin sections late carbonates and chlorite may fill the breaks. Primary liquid inclusions mark growth lines, and in some sections abundant secondary planar inclusions are present. Solid inclusions are abundant and include mica, chlorite, carbonates, etc.

The comb quartz is composed of small to large prisms with milky bases and clear tips. In thin sections these crystals exhibit excellent growth zones, and all are crowded with large, two- and three-phase liquid inclusions. Etching of the surface of the crystals is present in places, and solid inclusions such as chlorite, carbonates, and sericite are present within growth zones and along growth planes. Many of the prismatic quartz crystals are fractured and healed by fine-grained clear quartz containing pyrite, chalcopyrite, chlorite, and small amounts of carbonates.

The 'giant quartz veins' are remarkable structures and have been found in many of the late faults in the Northwest Territories. An excellent description of the structural characteristics and texture of these veins is given by Furnival (1935).

The 'giant quartz vein' at the junction of the West Bay and Akaitcho faults is a large stockwork which varies from 100 to 300 feet in width, and though not continuous, extends for nearly 2 miles along the West Bay fault.

The structure of the stockwork is complex and consists of several large lenses of massive white quartz intersected by innumerable veinlets of subhedral milky quartz containing many druses and elongated cavities lined with clear quartz prisms. Hematite is ubiquitous in the druses and cavities and forms a reticulating series of seams and veinlets throughout the massive quartz lenses and adjacent wall-rocks.

Three distinct ages of quartz, each preceded by a period of fracturing, are developed in the stockwork. The first age of quartz is represented by large irregular lenses of massive white quartz which developed after the initial fracturing and brecciation that formed the West Bay fault. Only small amounts of hematite are associated with this age. The lenses appear to have been emplaced partly by replacement of the highly brecciated fault zone because most lenses contain abundant fragments of partly replaced breccia fragments. Thin sections of this age of quartz show it to contain medium-sized to small anhedral interlocked grains enclosing some random liquid inclusions and numerous solid inclusions. Most grains exhibit anomalous extinction, and mylonitization of the larger grains is widespread.

After the massive lenses were formed, a second period of fracturing took place. This brecciated the early quartz lenses and adjacent wall-rocks, especially the granodiorite, for distances up to 300 feet outward from the fault zone. Following this stage of brecciation quartz and hematite were deposited. The quartz is fine grained and anhedral; some is microcrystalline forming a red or black jasper as a result of occluded hematite.

The third stage of brecciation is local in places, but in others it extends outward from the fault plane for 100 feet or more. The fractures formed during this period are filled with comb quartz, and many druses and elongated cavities occur. In some cavities small amounts of red hematite encrust the small quartz prisms. In thin sections the third age of quartz exhibits marked euhedral characteristics; growth lines marked by liquid inclusions and a few solid inclusions are a common feature.

Epigenetic Deposits in the Sedimentary Rocks and Prosperous Lake Granite

Three distinct ages of epigenetic quartz are present in the sedimentary area. These are tabulated below, the oldest first.

(1) Early quartz lenses in fractures along sedimentary beds and at contacts, in ruptured axes of folds, saddle reefs, and contorted zones; quartz in pegmatites cutting the Prosperous Lake granite and adjacent quartz-mica schists.

(2) Late quartz stringers and veinlets that cut ore-bearing and barren quartz lenses.

(3) Quartz lenses in post-diabase faults cutting sediments and the Prosperous Lake granite.

Quartz Lenses and Veins in Relatively Unmetamorphosed Sediments

The quartz lenses in the relatively unmetamorphosed greywackes, slates, and argillites exhibit similar characteristics. In general the lenses are rarely more than 25 feet long and a foot or so wide. The quartz is coarse to medium grained in texture and white to grey to bluish grey in colour. Ribbon structures, due to thin selvedges and slivers of slate, argillite, greywacke, and schist, are common in many lenses. Vugs and prismatic quartz are rare, and late quartz stringers and veinlets cutting the lenses are not abundant.

The features of the quartz deposits in the relatively unaltered sediments are clearly shown in the lenses at the Burwash prospect. Here the quartz occurs in short narrow lenses having extremely sharp contacts with the slightly altered walls. Ribbon structures are rare, but a few fragments of schist and chlorite occur in the quartz. The colour of the quartz in most lenses is bluish black as a result of disseminated graphite; locally a mottled variety composed of diffuse areas of white to light grey quartz in dark grey to black quartz is present. A few grains of albite may occur intimately intergrown with the quartz grains and a few veinlets of albite and carbonate may transect the massive quartz in places.

Thin sections of the bluish quartz show that it is composed of a groundmass of medium-sized grains exhibiting anomalous blocky extinction features and containing numerous ovoid spots of graphite. Other solid and liquid inclusions, arranged at random and along reticulating planes, are common. The groundmass of medium-sized grains is cut and intersected by ramifying veinlets and patches of fine-grained clear quartz with sharp extinction and containing a few specks of graphite and other solid inclusions.

Quartz Lenses and Pegmatites in Knotted Quartz-mica Schist and Prosperous Lake Granite

Three types of quartz occur in the lenses and pegmatites in these rocks. They are:

(1) Grey and white quartz of two ages in lenses and veins mineralized locally with sulphides and gold (Ptarmigan type);

(2) Vitreous quartz of one age in lenses and veins commonly barren of sulphides and gold;

(3) Quartz in pegmatites cutting the Prosperous Lake granite and adjacent quartz-mica schists and hornfels.

The age relationships of these lenses and pegmatites are difficult to establish because of poor cutting relationships. The quartz lenses in (1) and (2) above appear to be contemporaneous in part, but in places (1) may cut (2). The pegmatites in the Prosperous Lake granite have not been observed in cutting relationships with quartz veins, and the age relationships are unknown. In the quartz-mica schist aureole about this granite some pegmatites cut the quartz lenses in (2) above, but the majority of pegmatites are not found in cutting relationships and may be contemporaneous with the quartz lenses in both (1) and (2).

Most of the quartz lenses and veins which contain two ages of quartz and are mineralized with sulphides and gold are localized in the outer part of the knotted quartz-mica schist aureole. Typical examples are the Ptarmigan series of lenses which occur in faults cutting quartz-mica schist. The lenses are commonly arranged in an *en echelon* manner and may average 200 feet in length and 10 or more feet in width. In most places the lenses have sharp contacts with the slightly altered quartz-mica schist, and only a few inclusions of schist occur in the quartz near the walls. Ribbon structures are rare. Vugs containing euhedral quartz crystals, carbonate, pyrite, sphalerite, galena and gold are common; seams of tourmaline, albite and carbonate are present in some parts of the veins.

The Ptarmigan quartz lenses contain two ages of quartz. The first is a mottled bluish grey, medium-grained quartz and makes up most of the lenses; the second is a limpid white medium-grained quartz which cuts across and may replace the first age (Plate XVII).

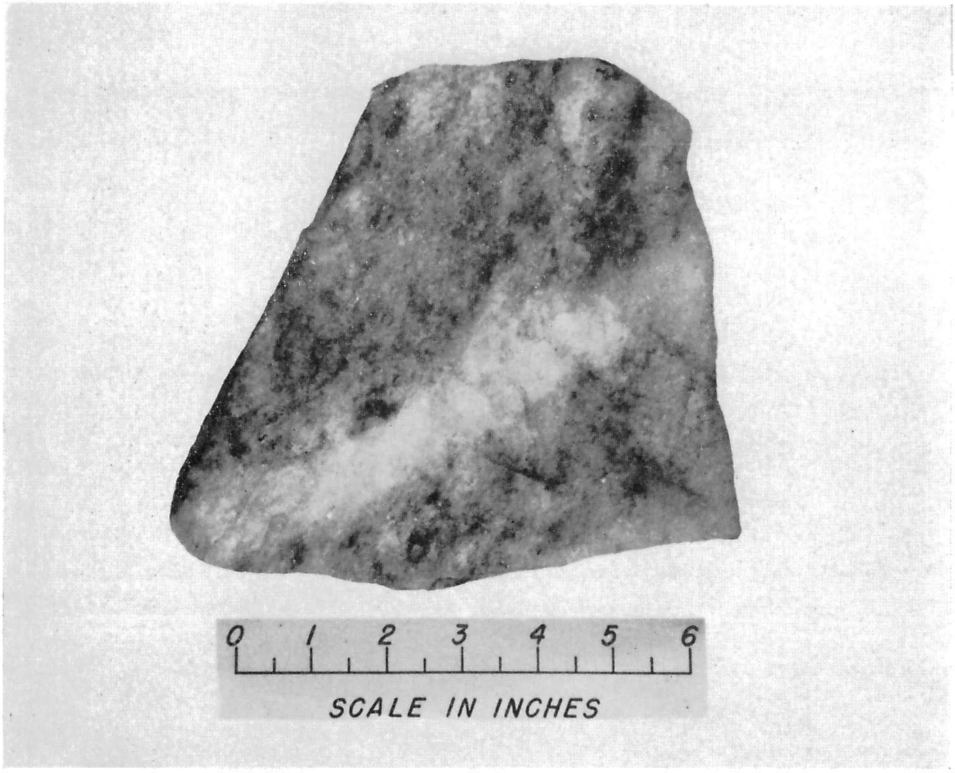
Thin sections show the first age to be composed of medium-sized interlocked grains with a moderate degree of wavy extinction. The most characteristic inclusions in the grains are ovoid spots of graphite which are mainly responsible for the grey colour of the quartz. Small numbers of random and planar liquid inclusions are generally present, together with some chlorite and sericite and a few unidentified acicular needles. The medium-sized grains are intersected by numerous veinlets and patches of fine-grained clear quartz exhibiting sharp extinction and containing a few solid and liquid inclusions. Thin sections of the second age of quartz show that it is composed of an interlocked mass of relatively clear, medium-sized grains which contain a few spots of graphite and some random liquid and solid inclusions.

The type (2) quartz lenses occur in the inner zone of the knotted quartz-mica schist aureole adjacent to the Prosperous Lake granite. Some lenses are regular with short and narrow dimensions; others are highly contorted ptygmatic veins (Plate XVIII). The quartz in the lenses and veins has sharp contacts with the enclosing schist and hornfels, and fragments of wall-rock in the lenses and veins are rare. Alteration haloes about the veins and lenses are not pronounced. Many lenses contain crystals of chalky weathering feldspar, and tourmaline, andalusite, muscovite, and garnet are common in lenses cutting schists that contain an abundance of these minerals.

The quartz in the lenses and veins is clear and vitreous in appearance. Thin sections display a groundmass of clear grains possessing undulose extinction and containing a few liquid and solid inclusions. Patches and irregular veinlets of microcrystalline quartz intersect the groundmass of clear grains in most sections.

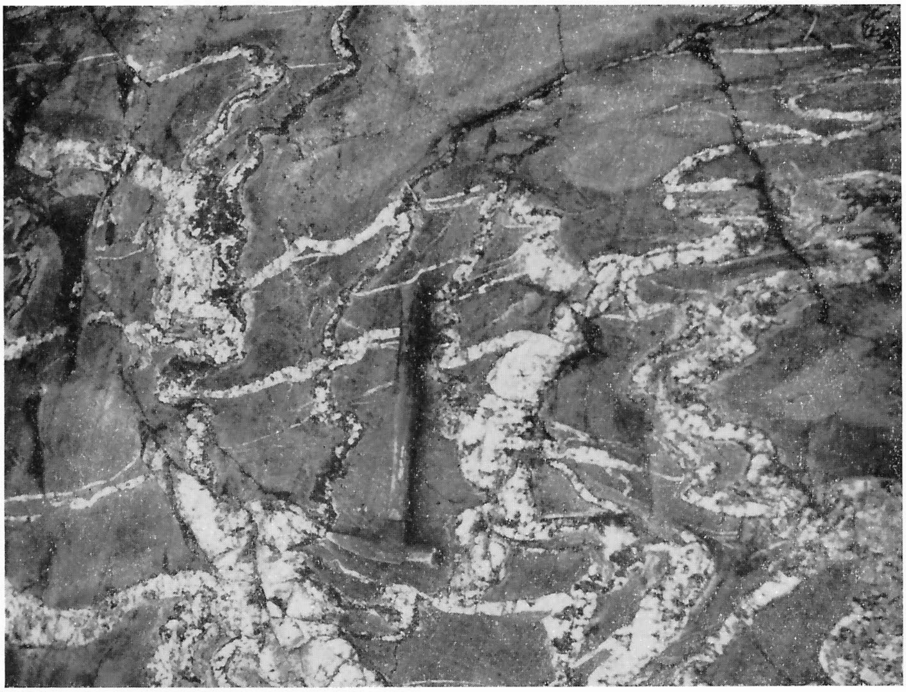
The type (2) quartz lenses and irregular veins resemble pegmatites in some respects and appear to be a transition phase between pegmatites and quartz veins. They have, however, never been observed to grade from one to the other along strike or dip.

Most of the pegmatites are concentrated in the Prosperous Lake granite and in the knotted quartz-mica schist and hornfels immediately adjacent to this granite. The pegmatites can be classed as simple in that they are rarely zoned and only small amounts of rare elements occur in them. The quartz in most pegmatites is



RWB 13-6-1951

Plate XVII. *Early grey quartz cut by later white quartz, Ptarmigan mine, Yellowknife.*



RWB 18-8-1951

Plate XVIII. *Ptygmatic quartz veins in quartz-mica schist, Prosperous Lake, Northwest Territories.*

intergrown with feldspar and muscovite, but small quartz cores and segregations occur in a few dykes. The quartz is clear and faintly smoky in colour.

Thin sections of the pegmatitic quartz show it to be composed of interlocked, clear, coarse grains with a general sharp extinction. Large irregular liquid inclusions with stationary bubbles and negative crystals with similar bubbles are a distinctive feature of the quartz. Solid inclusions include apatite, tourmaline, garnet, zircon, and mica. Tourmaline tends to favour the quartz parts of the pegmatites and garnets have a slight tendency to the same habit.

Quartz Lenses in Post-diabase Faults

Most of the late faults in the sediments and Prosperous Lake granite are drift covered and exposures of mineralized parts are uncommon. Only a few small quartz lenses were observed in the faults cutting sedimentary rocks. These lenses are similar to the small lenses in the greenstone rocks. Vuggy white quartz is predominant, but the Vega fault contains a few lenses of amethyst. A small stockwork was observed in the Ptarmigan fault in the Prosperous Lake granite. This stockwork exhibits features similar to those described for the 'giant quartz vein' in the West Bay fault.

Carbonates

Country Rocks

The sedimentary and granitic rocks, pegmatites, and late diabase dykes contain small amounts of carbonates visible only in thin sections as alteration products of feldspars or as small isolated blebs in the matrix of the rock. Chemical analyses of these rocks (*see* Chapter V, Tables 9, 10, 12 and 14) further emphasize the general low content of carbonates by the small amount of carbon dioxide present.

In the greenstone belt the content of carbonates varies across the metamorphic facies and increases outward from the granodiorite contact. (*See also* Chapter V.) Calcite and ankerite are the principal carbonates. These are generally associated with quartz in blebs and small amygdules, and as an alteration product of fibrous amphiboles and plagioclase.

Epigenetic Deposits in the Greenstone Belt

Most of the epigenetic carbonate minerals are concentrated in shear zones in the epidote amphibolite and greenschist facies. The pre-shear-zone quartz lenses in all facies and the shear zones in the amphibolite facies and western granodiorite contain only minor amounts of carbonates.

Shear Zones

In the epidote amphibolite and greenschist facies both the parallel and transecting shear zones contain two ages of carbonate in most places and three ages locally. The general mineralogical and chemical trend of these three ages of carbonates are enumerated below, the oldest first. *See also* Chapter VIII.

(1) Early ankerite and calcite in alteration zones and in early gold-bearing quartz lenses and veins; the ankerite has a high iron and magnesium content.

(2) Carbonates in quartz-carbonate lenses and veins cutting shear zones and gold-quartz lenses. The carbonates are ankerite or calcite depending on the locality. They have a low iron and magnesium content.

(3) Late carbonate in crosscutting late fractures, small faults, and slips. The carbonate is mainly earthy or scalenohedral calcite, but ankerite and dolomite may occur locally. The content of both iron and magnesium is generally low in this age of carbonate.

The early carbonate is concentrated in alteration zones that occur where extreme buckling, contortion, and mashing of the chlorite schist of the shear zones has taken place, generally at junctions and flexures. Some of the carbonate zones envelope quartz lenses; others extend along the central part of the shear zones linking individual quartz lenses as shown in Figures 5 and 8 (in pocket).

Ankerite, and less commonly calcite, are the principal carbonates in the alteration zones. These minerals occur as irregular patches of crystals intergrown and seemingly replacing chlorite, sericite, and albite. Quartz generally accompanies the ankerite and is intimately intergrown with it in such a manner as to suggest simultaneous deposition. In the early gold-bearing quartz lenses and veins the carbonate occurs in seams of sericite and in fractured zones in the quartz.

The second age of carbonate occurs with quartz in short veins, stringers, and lenses that are markedly concentrated in the parts of the shear zones that have been subjected to the early stage of carbonatization and mineralization. The veins, stringers and lenses are irregular, often exhibit bulbous masses (Plate XVI, facing p. 45), and occur, as noted previously, as isolated bodies which are not connected and have no observable feeder channels. This age of carbonate is either calcite or ankerite with ankerite predominating in the Con and Negus-Rycon systems and parts of the Giant system; calcite is the principal carbonate in the Campbell system. The calcite and ankerite are white to pink in colour and coarsely crystalline with good cleavage. In the lenses and stringers the carbonates in some places fill the spaces between euhedral quartz crystals; in others they may line the fracture walls and are overgrown by quartz. Coarse crystals of tetrahedrite, berthierite, and in some places ramifying plates and networks of gold occur in this age of carbonate.

The third age of carbonate occurs in a few late fractures and faults cutting the shear zones. Scalenohedra of clear calcite predominate, but in some places curved rhombohedra of dolomite and ankerite are present. Earthy calcite is present in many gouge seams, and stalagmites and stalactites of calcite are being precipitated from underground waters issuing from late faults and fractures.

Late Faults

The late faults are notably low in carbonates. This contrasts with the early shear zones in which carbonate minerals are omnipresent and abundant.

Small amounts of ankerite and calcite occur in the late faults as widely scattered blebs and patches in the breccia and gouge and in a few vugs in the quartz lenses. These carbonates are most abundant where the wall-rocks are greenstones; where the faults transect granitic rocks, the carbonates are rare or absent.

Epigenetic Deposits in the Sedimentary Rocks

In the sediments, carbonates are not abundant in the quartz lenses, and they have not been observed in any quantity in the pegmatites. In the Ptarmigan lenses and at the Burwash prospect, calcite and ankerite occur in small amounts filling vugs, fractures, and cracks in the quartz.

Only a few small scattered grains of calcite and ankerite have been observed in the late faults cutting the sediments and the Prosperous Lake granite.

Pyrite and Marcasite (FeS_2)

Country Rocks

Pyrite is the principal sulphide in the greenstones and occurs as disseminated crystals or crystal groups in the body of the rocks and along joint planes. A small but significant difference in the quantity of pyrite in the different metamorphic facies is apparent both from thin-section studies and from a consideration of the chemical analyses of sulphur across the facies (*see* Table 16, Chapter V). The greenschist facies contains the highest amount of pyrite with corresponding lesser amounts in the epidote amphibolite and amphibolite facies respectively.

The sedimentary tuffs interbedded with the greenstones contain large amounts of pyrite as crystals and small masses. Most of the pyrite appears to be an original constituent, but some may have been redistributed in places by shearing and recrystallization.

Pyrite is present in all sedimentary rocks but there is no significant difference in the amounts of the mineral in the metamorphic facies of these rocks as evidenced by thin sections and sulphur analyses across the facies (Table 16). Most of the pyrite is concentrated in the slates and argillites and their metamorphic equivalents. Only small amounts occur in the greywackes, arkose and conglomerate.

Pyrite is the only abundant sulphide observed in the granitic rocks. Thin sections and analyses of the sulphur contents (*see* Table 12, Chapter V) show that both the western granodiorite and Prosperous Lake granite are low in this mineral.

Many quartz-feldspar porphyry bodies contain relatively large amounts of pyrite disseminated through their fine-grained groundmass. Most of the pyrite appears to be original and not introduced subsequent to the crystallization of these bodies.

Late diabase dykes contain small amounts of pyrite as microscopic disseminated crystals.

Epigenetic Deposits in the Greenstone Belt

Only a few small grains of pyrite have been observed in the few pegmatites associated with the western granodiorite. The early quartz lenses cut by the shear zones are also low in this mineral.

Pyrite is markedly concentrated in the shear zones in the greenstones, especially in those cutting the epidote amphibolite and greenschist facies. In these shear zones three ages may be present. They are:

(1) Early pyrite in the chlorite schist and chlorite-carbonate schist of the shear zones and in the early gold-quartz lenses and their associated alteration zones;

(2) Pyrite crystals in quartz-carbonate veins cutting the early gold-quartz lenses above;

(3) Late pyrite in slips and narrow faults which cut ages (1) and (2) above.

The early pyrite is the most abundant sulphide in the shear zones. It occurs alone or with arsenopyrite in the chlorite and chlorite-carbonate schist of the shear zones and in the early gold-quartz lenses and their alteration haloes. In the chlorite schist of the shear zones and in the alteration zones enveloping the quartz lenses, the pyrite occurs as discrete cubes, pyritohedra, or as elongated aggregates. In the chlorite schist and in the chlorite-carbonate schist and sericite schist surrounding quartz lenses, the pyrite is generally associated with ankerite and some quartz. The principal associated sulphide is arsenopyrite.

In all these occurrences the pyrite, together with arsenopyrite, are early minerals in the mineralization sequence. Most of the pyrite has, however, been fractured and crushed, and the fractures are healed with sericite, chlorite, quartz, and carbonate.

The early gold-quartz lenses contain fractured and granulated crystalline pyrite in seams and wisps of sericite schist and in irregular ankerite masses containing some sericite. This pyrite is commonly associated with granulated arsenopyrite and appears to be partly residual after the replacement by quartz of pyritized schist. In most quartz lenses pyrite also occurs in small vugs with sulphosalts, galena, and sphalerite.

Pyrite is uncommon in the quartz-carbonate lenses and stringers cutting the early gold-quartz lenses. In a few places cubes and pyritohedra associated with arsenopyrite and calcite were observed in these veins.

Late fractures, cutting the orebodies, contain some pyrite which is intimately intergrown with calcite scalenohedra or dolomite rhombohedra. This pyrite has a splendent lustre and occurs as cubes and pyritohedra or as crystal aggregates which have a colloform habit. In some fractures alternate bands of pyrite and calcite occur, resulting in narrow banded veins. Locally some marcasite may be intergrown with this pyrite.

The content of pyrite in late faults cutting greenstones is low, and where present it occurs as cubes and small crystalline aggregates in the fault breccia and quartz lenses. In late faults cutting the western granite, pyrite is a rare mineral. In the 'giant quartz vein' at the junction of the West Bay and Akaitcho faults only a few scattered crystals were observed.

Epigenetic Deposits in the Sedimentary Rocks

Pyrite is a constituent of most gold-quartz lenses in the sediments. It occurs disseminated in the slightly altered wall-rocks and occurs as thin films on fractures in the quartz or in small vugs associated with galena, sphalerite, chalcopyrite, pyrrhotite, and gold. The pyrite in the quartz has a dull greenish yellow lustre and forms crystal intergrowths with a globular and reniform habit. On first examination this pyrite could be mistaken for marcasite, but X-ray powder photographs match those for pyrite.

Pyrite is uncommon in the late faults which cut the Yellowknife group sediments and the Prosperous Lake granite.

Arsenopyrite (FeAsS) and Gudmundite (FeSbS)

Arsenopyrite and gudmundite have not been observed as a constituent of the greenstones, sedimentary rocks, granitic rocks, pegmatites, and massive porphyries.

Arsenopyrite is a characteristic mineral in the quartz lenses and their associated carbonate-sericite schist haloes in shear zones cutting the epidote amphibolite and greenschist facies of the greenstone belt. It also occurs in small amounts in the quartz lenses and their associated chlorite-sericite alteration zones in the amphibolite facies, but has not been observed in shear zones cutting the western granodiorite.

Gudmundite has been identified in only a few places in the Con and Negus-Rycon systems. This mineral is, however, difficult to distinguish from arsenopyrite, and it may be more widespread than examination of polished sections might suggest.

The arsenopyrite in the alteration zones surrounding gold-quartz lenses occurs as slender prismatic crystals which often exhibit a marked lineation along the schist planes. In the quartz lenses the arsenopyrite occurs as individual crystals or fine granular masses in wisps of sericite schist and irregular masses of carbonate-sericite or chlorite schist. The fine granular arsenopyrite is often associated with sulphosalts, a mineral assemblage characteristic of quartz lenses that constitute orebodies. In all occurrences arsenopyrite is associated with carbonates and pyrite, and the three minerals appear to have been deposited together.

Arsenopyrite occurs in certain quartz-carbonate stringers cutting the early gold-quartz lenses in the Campbell system. This arsenopyrite occurs as large crystal intergrowths in vuggy parts of the stringers and is associated with calcite with which it has been deposited. In the Con system a few white quartz lenses cutting early gold-quartz lenses contain large crystals and irregular masses of arsenopyrite in highly digested and replaced fragments of the mineralized sections of the shear zone. This arsenopyrite appears to have been derived mainly by recrystallization of smaller crystals once present in the early mineralized fragments.

Arsenopyrite was not observed in late fractures cutting the orebodies, and has not been found in late faults cutting the greenstone belt or western granodiorite.

In the sedimentary area arsenopyrite occurs in small amounts in the wall-rock alteration zones flanking some gold-quartz lenses and to a lesser extent in the lenses themselves. It is generally associated with pyrite, and the two minerals have apparently formed at the same time. Arsenopyrite was not observed in quartz lenses in the knotted zone immediately adjacent to the Prosperous Lake granite, and the mineral is also uncommon in pegmatites. It is absent in post-diabase fractures and faults cutting the sedimentary rocks.

Pyrrhotite ($Fe_{(1-x)}S$)

Pyrrhotite is a minor constituent of the greenstones and sedimentary rocks. It has not been observed in the granitic rocks and pegmatites, but occurs in some porphyries, especially in the porphyry stock southwest of the Con shaft and in some massive porphyry dykes in the underground workings of the Negus and Con mines. In these porphyries the pyrrhotite is associated with pyrite and bleached biotite.

Pyrrhotite is a common mineral in tuff beds, especially in the Ranney tuffs, where it occurs intimately intergrown with pyrite, chalcopyrite, and magnetite in the body of the tuff and in small quartz lenses in sheared parts of the tuff beds. In the Giant system small veins of pyrrhotite occur in a sheared tuff bed.

Pyrrhotite rarely figures among the sulphides characteristic of the alteration zones enveloping gold-quartz lenses nor is it present in any quantity in the lenses. In a few places, however, small amounts of pyrrhotite associated with sphalerite and chalcopyrite occur in fractures outside the confines of the shear zones. The relationship of these mineralized fractures to the shear zones is unknown.

Pyrrhotite occurs in vuggy and crushed parts of the quartz lenses in the sedimentary rocks and is associated with galena, sphalerite, chalcopyrite, and gold.

Pyrrhotite has not been observed in any of the late faults and fractures.

Stibnite (Sb_2S_3) and Bismuthinite (Bi_2S_3)

Stibnite and bismuthinite have not been observed as constituents of the country rocks, nor have they been observed in pegmatites. They do not occur in the quartz lenses cutting the sedimentary rocks and are not present in the mineral assemblage of the late faults.

Stibnite is concentrated in gold-quartz lenses and veins in the shear zones cutting the epidote amphibolite and greenschist facies of the greenstone belt. The mineral has not been observed in shear zones cutting the amphibolite facies and western granodiorite.

In some early gold-quartz lenses and veins the stibnite occurs as nests of intergrown aggregates of acicular and short prismatic crystals in vuggy and crushed areas of the quartz lenses. In other lenses the stibnite occurs as slender prismatic crystals and aggregates of crystals in seams and fractures in the quartz. In both these occurrences the stibnite appears to be a late mineral and is associated with various sulphosalts, native antimony, sphalerite, and chalcopyrite.

Bismuthinite has been recorded in two occurrences in quartz lenses in the subsidiary shear zones of the Crestaurum system where they cut granites and granitized amphibolites. In these lenses it is associated with molybdenite.

Sulphosalts

The sulphosalts are restricted in occurrence to the shear zones cutting the epidote amphibolite and greenschist facies of the greenstone belt. They have not been observed in other shear zones or late faults and are not present in the greenstones, sediments, granitic rocks, and pegmatites.

The following sulphosalts, in approximate order of abundance, have been identified by X-ray powder photographs.

Tetrahedrite series	
Tetrahedrite	$(Cu,Fe,Zn,Ag)_{12}\ (Sb,AS)_4\ S_{13}$
Tennantite	
Freibergite	
Bournonite	$PbCuSbS_3$
Jamesonite	$Pb_4FeSb_6S_{14}$
Boulangerite	$Pb_5Sb_4S_{11}$
Chalcostibite	$CuSbS_2$
Berthierite	$FeSb_2S_4$
Zinkenite	$Pb_6Sb_{14}S_{27}$
Semseyite	$Pb_9Sb_8S_{21}$
Meneghinite	$Pb_{13}Sb_7S_{23}$
Freislebenite	$Pb_3Ag_5Sb_5S_{12}$
Jordanite	$Pb_{14}As_7S_{24}$

The sulphosalts have a widespread distribution in the highly mineralized parts of the shear zones in the Con, Negus-Rycon, Giant-Campbell, and Crestaurum systems. Three ages may be present.

The first age, including all the above-listed sulphosalts, occurs in vugs, fractures, and crushed parts of the early gold-quartz lenses. The sulphosalts always occur where arsenopyrite and pyrite are abundant in the mineralized zones and are intimately associated with stibnite, gold, chalcopyrite, sphalerite, and galena. All the sulphosalts appear to be late minerals and vein the earlier pyrite and arsenopyrite. In nearly all occurrences the sulphosalts and stibnite exhibit remarkably little fracturing or crushing. This suggests that these minerals either have the facility of recrystallizing easily when deformed or that they are the last minerals deposited and have not since suffered fracturing or crushing.

A second age of tetrahedrite, tennantite, freibergite, bournonite, and boulangerite occurs in the quartz-carbonate veinlets and lenses cutting early quartz lenses and mineralized zones. These sulphosalts are intergrown with the carbonate which fills vugs in the stringers and are associated with chalcopyrite, galena, sphalerite, and gold.

In a few places tetrahedral crystals of tetrahedrite occur in late post-diabase fractures cutting quartz lenses and mineralized zones. This age of tetrahedrite is associated with pyrite and crystallized calcite and dolomite.

Sphalerite $(Zn,Fe,Cd)S$

Sphalerite has not been observed as a constituent of the greenstones, sedimentary and granitic rocks, porphyries, and pegmatites.

Sphalerite is present in all shear zones in the epidote amphibolite and greenschist facies. It also occurs in small amounts in the shear zones cutting the amphibolite facies and in a few of the shear zones cutting the western granodiorite.

In the shear zones cutting the epidote amphibolite and greenschist facies an early age of dark sphalerite containing minute exsolved pyrrhotite blebs occurs in vugs, fractures, and crushed areas in the quartz lenses and is associated with sulphosalts, stibnite, chalcopyrite, and in places with masses of pyrrhotite. Later ages of sphalerite, associated with crystalline calcite or dolomite, are generally amber coloured and occur in narrow fractures cutting the gold-quartz lenses and mineralized areas. In one instance sphalerite was observed in a fracture cutting a diabase dyke in the Con mine. This sphalerite was intergrown with axinite and asbestiform amphibole.

Sphalerite occurs with fine-grained galena in small pods in faults and shear zones that cut greenstones and a quartz-feldspar porphyry east of the north end of Likely Lake. Other associated minerals are pyrite, pyrrhotite, arsenopyrite, and chalcopyrite. Jolliffe (1938, pp. 32-34) has given a detailed description of this occurrence (Homer group).

In quartz lenses cutting the Yellowknife sediments sphalerite is the most abundant sulphide next to pyrite. In the Ptarmigan veins it occurs in crushed parts of the quartz, in vugs, and in fractures and is associated with galena, pyrite, and pyrrhotite. In these veins it is considered a fair indicator of gold values.

Sphalerite has not been observed in the late faults or fractures except where they cut the early shear zones and there, only in small amounts.

Chalcopyrite $(CuFeS_2)$

Chalcopyrite occurs as a minor accessory mineral in the greenstone rocks and sediments. It is more abundant in graphitic tuff beds in the greenstones where it occurs as small irregular masses with pyrite and pyrrhotite. It has not been observed in the granitic rocks, porphyries, and pegmatites.

Chalcopyrite is present in small amounts in the early gold-bearing quartz lenses in the shear zones cutting the epidote amphibolite facies. In these lenses it occurs in seams and fractures and in small vugs and is associated with sphalerite, stibnite, and sulphosalts.

Some chalcopyrite occurs in vugs in calcite in the quartz-carbonate stringers cutting early gold-bearing quartz lenses and mineralized zones. In these stringers the chalcopyrite is intergrown with tetrahedrite, tennantite, and gold.

The quartz veins and lenses in the sheared tuffs of the Ranney system contain small amounts of chalcopyrite in seams and vugs; pyrite, pyrrhotite, and some sphalerite are its associates. A similar tuff bed in the Giant mine contains some chalcopyrite associated with pyrrhotite and pyrite.

Chalcopyrite is present in vuggy parts of the quartz lenses in the sedimentary rocks. In these occurrences it is associated with sphalerite, galena, and pyrrhotite.

Chalcopyrite is the most abundant of the small amounts of sulphides in the late faults and seems to occur only where these faults cut greenstones. It is associated principally with ankerite or calcite in vugs and in the breccia. It has also been observed in fractures transecting euhedral quartz crystals.

Galena (PbS)

Galena has not been observed as a constituent of the greenstones, sediments, porphyries, or granitic rocks.

In the greenstones galena occurs only in significant amounts in the shear zones cutting the epidote amphibolite and greenschist facies. In the early gold-bearing quartz lenses in these shear zones it is a late mineral and occurs with sphalerite and sulphosalts in vuggy and fractured parts of the quartz. In places it assumes its characteristic cubic habit, but in general it is highly irregular, and the crystals are intimately intergrown with one another.

In the Campbell system galena occurs in vuggy parts of some quartz-carbonate stringers cutting early gold-quartz lenses and mineralized zones. In the Giant system it is present in calcite in late fractures which cut the orebodies.

East of the north end of Likely Lake a few small pods of massive galena occur in faults and shear zones cutting greenstones and a quartz-feldspar porphyry. The galena is generally fine grained and intergrown with sphalerite, pyrite, pyrrhotite, chalcopyrite, and arsenopyrite. A detailed description of these pods (Homer group) is given by Jolliffe (1938, pp. 32-34).

Galena is a common sulphide in the quartz lenses in the sediments. In these lenses it occurs in fractures, crushed zones, and vugs and is generally associated with sphalerite, chalcopyrite, pyrrhotite, and gold.

Galena was not observed in the late faults throughout the area.

Molybdenite (MoS_2)

Molybdenite has not been observed as a constituent of the greenstones, sediments, or granitic rocks. It occurs as disseminated flakes in massive porphyry dykes in the Con mine, and Jolliffe (1944a) states that it occurs in a few pegmatites associated with the Prosperous Lake granite.

In the greenstone belt molybdenite is present in small amounts in a few shear zones cutting the amphibolite facies and western granodiorite. In these shear zones (e.g. Crestaurum system) the molybdenite occurs in fractures and crushed parts in quartz lenses and is associated with a little pyrite, chalcopyrite, and bismuthinite.

Molybdenite has also been observed in quartz stringers in fractures and shear zones cutting quartz-feldspar porphyries in the Con mine and northwest of the north end of Likely Lake. The molybdenite is associated with pyrite and pyrrhotite at both places and with fluorite at Likely Lake. Jolliffe (1938, p. 38) has described the occurrence at Likely Lake.

Molybdenite has not been observed in quartz lenses in the sediments, nor has it been identified in the mineral assemblage of the late faults.

Gold (Au) and Aurostibite ($AuSb_2$)

Gold has not been observed as a microscopic constituent of the greenstones, sediments, granitic rocks, porphyries, or pegmatites.

In the greenstones, gold is concentrated in economic quantities in the shear zones cutting the epidote amphibolite facies and is also present in small amounts in shear zones cutting the amphibolite facies and western granodiorite. In all these shear zones the gold occurs in the quartz lenses or in pyrite and arsenopyrite in the alteration haloes surrounding the lenses.

Four definite ages of gold are present in most gold-bearing quartz lenses in the greenstones.

The earliest age occurs in pyrite and arsenopyrite in the alteration zones and in unreplaced aggregates of these minerals in the quartz lenses. Some of this gold occurs in microscopic blebs in these two sulphides, and some probably occupies atomic sites in the lattice of the sulphides. A discussion of this phenomena is given in Chapter X.

The second age of gold occurs as plates, blebs, and nuggets in fractures, crushed zones, and vuggy parts in the quartz lenses and is accompanied by clear microcrystalline quartz, some calcite, granulated arsenopyrite and pyrite, stibnite, aurostibite, and sulphosalts. Some specimens of this age of gold possess a light yellow colour and are probably rich in silver, others have a deep golden colour, and still others have a reddish colour. In polished sections the relationships of the metallic sulphides and this age of gold are rarely clear cut. In some sections gold occurs in fractures in the arsenopyrite and pyrite and is later; in other sections the gold plates the crystals of sulphides or occurs intermixed with them, and the age relationships are indefinite. In most sections gold is intimately associated with the sulphosalts and may occur as microscopic blebs in them. Much gold also appears to be held in the sulphosalts in lattice sites because spectrographic analyses of apparently homogeneous sulphosalts show that gold is present, and exhaustive metallurgical tests (*see* Bibliography) carried out on the ores to liberate the gold to facilitate cyanidation, suggest that some of the gold in the ores is tightly bound in the sulphosalts.

A third age of gold occurs in calcite and ankerite filling vugs and crushed zones in quartz-carbonate stringers cutting the early quartz lenses and mineralized zones in the Campbell system. This gold occurs as discontinuous plates and little nuggets and is accompanied by freibergite, bournonite, and chalcopyrite.

A fourth age of gold occurs in late fractures in the Giant system and in one recorded occurrence in the Campbell system. In these fractures the gold occurs as thin films, splendent leaf gold, spongiform gold, and distorted octahedral crystals. It is associated with pyrite and scalenohedral calcite. In one place in the Giant system the leaf and sponge gold were observed in an ice lens (Boyle, 1951).

In the quartz lenses in the sedimentary rocks, gold occurs in the pyrite and arsenopyrite in the adjacent alteration zones, and as small plates and irregular nuggets in vugs, small fractures, and crushed zones in the quartz. In these occurrences it is associated with pyrite, galena, chalcopyrite, and sphalerite. A second age of gold occurs in carbonates in fractures which cut the mineralized quartz lenses.

Gold has not been observed in any of the late faults. According to Jolliffe (1945b) only trace amounts are recorded in assays of mineralized material from these faults.

Aurostibite is a new mineral and has been described by Graham and Kaiman (1952). Crystallographically it is a member of the pyrite group. In polished sections it is isotropic, has a hardness of C—, and is white to slightly pinkish in colour. It gives positive reactions with $FeCl_3$, HNO_3, HCl, and KOH; $HgCl_2$ and KCN are negative. The unit cell containing Au_4Sb_8 has $a=6.646 \pm 0.003$kX. The calculated specific gravity is 9.91.

Most of the aurostibite occurs where gold is present and forms haloes and coatings about the gold particles or is present in narrow seams in the gold. It is also associated with gold as small diffuse aggregates scattered along the contacts of arsenopyrite and sulphosalts. In most polished sections it appears to be later than the gold, but good age relationships are uncommon.

Aurostibite is restricted in its occurrence to the quartz lenses containing concentrations of antimony minerals and gold. It has not been identified in any of the quartz lenses in the sediments or in the late faults.

Scheelite ($CaWO_4$)

Scheelite was observed only in the shear zones cutting the epidote amphibolite facies of the greenstones and in a few quartz veins and irregular skarn lenses in the sedimentary rocks.

In the shear zones the scheelite occurs in the quartz lenses and veins of the Con, Campbell, and Negus-Rycon systems. In the latter system some of the lenses contained small concentrated shoots of scheelite, but the amounts were not large enough to be economic. Scheelite was not observed in the Giant system. In the shear zones, the scheelite occurs as light brown crystals and aggregates in the quartz. It has no close associates except carbonate minerals and appears to have been deposited contemporaneously with the quartz. It is commonly fractured and seamed with sericite and carbonate.

In the sedimentary rocks scheelite occurs in two distinct geological settings. Quartz lenses such as the Ptarmigan type contain a few small irregular crystal aggregates scattered throughout parts of the lenses. The other type of occurrence is in small skarn lenses in which the scheelite is white in colour, resembles quartz and is generally intergrown with garnet, tremolite, pyroxene, carbonates, quartz, epidote, and muscovite. These skarn lenses occur both in the relatively unmetamorphosed sediments, and in the nodular quartz-mica schists and appear to have resulted by regional metamorphism of small interbedded sedimentary lenses of limestone.

Spectrographic analyses of scheelite from representative occurrences are given in Table 6. The absence of molybdenum in the scheelite from the deposits in greenstones and the presence of lead in samples from all types of deposits are notable. The latter feature is explainable since lead has a marked affinity for the tungstate radical and forms a compound, $PbWO_4$ (stolzite), structurally similar to scheelite. Mg, Fe, and V may substitute for Ca or W. Si, Al, Sr, and B are present mainly as contaminants in sericite and carbonates.

Table 6

Spectrographic Analyses of Scheelite from Characteristic Occurrences

Description of Sample	Per-cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
Scheelite in early gold-bearing quartz lenses, Con system	Ca, W	Si	Al	Mg, Fe, Sr	Pb, Cu, B, V
Scheelite in early gold-bearing quartz lenses, Negus-Rycon system	Ca, W	Si, Al	Fe, Sr, Ti	Mg, Cu	Pb, Mn, B, V
Scheelite in early gold-bearing quartz lenses, Campbell system	Ca, W		Si, Al, Sr	Mg, Fe, Zn Pb, Cu	V, Ti, B, Ag
Scheelite in skarn lenses, Prosperous Lake	Ca, W	Al	Fe	Si, Mo, Sr	Mn, V, B, Pb, Cu, Mg

Hematite (Fe_2O_3)

This mineral is uncommon in the massive greenstone rocks, porphyries, and granitic rocks. In the vicinity of shear zones it may occur in small quantities along joint planes and as a diffuse coloration in certain quartz-carbonate-epidote segregations.

Hematite is omnipresent in or near late faults in all rocks. Many variations of the mineral have been observed. The common variety is specularite which generally occurs in intergrown splendent metallic crystals. Other varieties are foliated, fibrous, micaceous, platy, and ocherous. In places rosette forms (iron roses) are common.

The characteristic occurrence of hematite is as small scattered crystals impregnating the breccia, wall-rocks, and quartz lenses of the late faults. Narrow veinlets of nearly pure hematite and some quartz or albite are also common, and in some parts of faults small vugs may contain masses of the mineral. In parts of the 'giant quartz veins' it forms a fine-grained jasper with microcrystalline quartz.

In comb-quartz veins it coats the terminal facies of the quartz crystals and lines vugs between the comb quartz.

A spectrographic analysis of hematite is given in Table 7.

Table 7

Spectrographic Analysis of Hematite from West Bay Fault

Description of Sample	Per-cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
Hematite in veinlet in 'giant quartz vein', West Bay fault	Si, Fe			Al	Mg, Ti, V, Cu, Ca

Magnetite (Fe_3O_4) and Ilmenite ($FeTiO_3$)

Magnetite and ilmenite are minor constituents of the greenstone. X-ray determinations indicate that ilmenite is the principal iron oxide in the sedimentary rocks. Both magnetite and ilmenite may occur in small amounts in the granitic rocks but appear to be absent, or present in only small amounts, in the porphyries and pegmatites. In most occurrences the two iron oxides are rimmed and seamed by leucoxene.

Magnetite occurs in the southern extension of the Ranney shear system in small amounts where it is associated with pyrrhotite and chalcopyrite. In other shear zones magnetite and ilmenite are present in only small amounts as microscopic nodules and particles in pyrite and arsenopyrite. These two minerals are probably partly responsible for some of the unusual trace elements such as magnesium in the sulphide minerals.

Pegmatite Minerals

The pegmatites in the Prosperous Lake granite and its nodular quartz-mica schist aureole contain numerous minerals including feldspar, quartz, muscovite, beryl, spodumene, amblygonite, lepidolite, lithiophilite, cassiterite, tantalite-columbite, tapiolite, tourmaline, garnet, gahnite, graphite, fluorite, scheelite, and molybdenite.

The rarer minerals, with the exception of tourmaline, are not abundant in the pegmatites in the area described in this report. In other areas, however, some pegmatites may contain appreciable quantities of these rare minerals. For a description of these pegmatites and their minerals the reader is referred to the accounts of Jolliffe (1944a), Rowe (1952), and Hutchinson (1955). Tourmaline, which is the most important of the rare minerals in the pegmatites seen by the author, is described below.

Tourmaline

Tourmaline has not been observed as an accessory mineral in the greenstones, but occurs as a constant minor accessory mineral in the sediments. In the western granodiorite and the granite phase of the Prosperous Lake granite, it occurs in a few places but is not abundant; it has not been observed in the porphyries.

Tourmaline is concentrated in the pegmatites in the Prosperous Lake granite and its associated nodular quartz-mica schist aureole. It also occurs in significant amounts in quartz veins in this aureole and has been observed in a few places in small amounts in the quartz veins in the greenstone rocks. It has not been observed in the late faults.

The tourmaline in the pegmatites is generally black, but coloured varieties are present locally. It occurs as small to medium-sized intergrown crystals in the quartz-rich parts of the pegmatites and in the sedimentary wall-rock or granite adjacent to pegmatites.

Most quartz veins in the knotted quartz-mica schist contain small amounts of tourmaline either intergrown with the quartz or in seams and fractures in the quartz. Slivers of rock may also be tourmalinized in parts of the quartz veins, and narrow tourmalinized zones may be present in the wall-rocks of the veins.

In the greenstones a few quartz lenses in shear zones cutting the amphibolite facies contain small amounts of black tourmaline. The mineral is also present in sporadic occurrences in quartz lenses in the Campbell system.

Spectrographic analyses of tourmaline from its characteristic occurrences are given in Table 8. The presence of certain volatile and chalcophile elements such as Zn, As, Ag, etc., is notable.

Table 8

Spectrographic Analyses of Tourmaline from Characteristic Occurrences

Description of Sample	Per-cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
Tourmaline in pegmatite, Prosperous Lake granite.	Al, Si	Fe, Na, Mg, B	Ca	Li, Mn, K, As, Zn	Ti, Cu
Tourmaline in pegmatite, Prosperous Lake granite.	Al, Si	Fe, Na, Mg, B	Li, K	Mn, Zn	Ti, Cu, Ag, Sc, Ba
Tourmaline in vein quartz, Ptarmigan mine	Al, Si	Fe, Mg, Na, B	Ca	Li, Mn, Zn, K	Ag, Pb, Cr, Sr, Ti, V, Ni, Zr, Sc, Cu, Ba, As, Sb
Tourmaline in wall-rock adjacent to quartz vein, Ptarmigan mine.	Al, Si	Fe, Mg, Na, B	Ba, K, Ca	Mn, Zn, Rb, Li	Ag, Pb, Cr, Sr, Ti, V, Ni, Cu, Zr, Sc
Tourmaline in quartz vein in greenstone rocks, Crestaurum area.	Al, Si	Fe, Mg, Na, B	Ca	Mn, Zn, Li, K	Ni, Ti, V, Zr, Cu, Ag, Sr, Sc, Cr, Ba

Miscellaneous Hypogene Minerals

Native copper occurs in a few quartz veins and lenses in the quartz-mica schists. In the Ptarmigan veins it occurs as small wires and dendritic plates in small fractures and crushed zones in the quartz. It generally occurs alone and has no associates.

Native antimony has been observed in microscopic grains and blebs in massive stibnite in the Negus-Rycon system and other shear zones.

Coleman (1953) has observed small quantities of native lead in specimens from a number of localities and notes that it occurs where minerals containing a relatively low percentage of sulphur are abundant. The mineral exhibits no significant relations with other minerals and generally occurs in discrete particles in the gangue.

Zincian stannite, $Cu_2(Zn,Fe)SnS_4$, is recorded by Coleman from one occurrence in the shear zones of the greenstone belt. Gersdorffite, $(Ni,Co,Fe)AsS$, and ullmannite, $NiSbS$, are recorded by the same investigator from the ores of the Giant mine.

Chalcocite, Cu_2S, and covellite, CuS, have been observed in several quartz lenses in the shear zones cutting the greenstones. These minerals generally occur near the surface in the vicinity of or encrusting chalcopyrite and sulphosalts. They are probably supergene in origin in most occurrences.

Axinite, $2[Ca_2(Mn,Fe)Al_2BSi_4O_{15}OH]$, occurs in a few places generally in stringers cutting late diabase dykes. It is usually associated with an asbestiform amphibole. Prehnite, $2[Ca_2Al_2Si_3O_{10}(OH)_2]$, is present in some late faults.

Fluorite, CaF_2, occurs in a few shear zones in the western granodiorite and the amphibolite facies. Jolliffe (1938) has observed the mineral in fractures cutting a quartz-feldspar porphyry northwest of the north end of Likely Lake. It also occurs in a few pegmatites cutting knotted quartz-mica schists.

Apatite, $Ca_5(F,Cl,OH)(PO_4)_3$ is widely diffused in all epigenetic deposits. It is generally intergrown with quartz and carbonate and is present in only small amounts.

Graphite and carbon occur in diffuse specks and along irregular planes in black and grey quartz and carbonate minerals in the epigenetic deposits. They are responsible for the black and grey colour of the quartz and carbonate (Boyle, 1953a).

Some minerals, principally sulphosalts, have not yet been definitely identified by X-ray methods. Coleman lists one which he has called "Mineral Q". It is probable that some of these unidentified minerals are new minerals, and it is hoped that further research will elucidate their chemical composition and structure.

Supergene Minerals

Minerals formed as a result of supergene agencies near the surface include limonite, marcasite, chalcocite, covellite, malachite, azurite, brochantite, jarosite, yellow molybdenum ocher, yellow arsenates and antimonates, erythrite, and supergene calcite. These minerals occur principally as alteration products of exposed mineralized zones. They seldom occur more than a few feet below the surface, except along late faults where some have been observed at depths of a hundred feet or more.

Ice veins are a common feature in the permafrost zone (Bateman, 1949). These veins are short and narrow and occur along late fractures and faults. They contain calcite in a few places, and native gold has been found in one cutting an ore shoot in the Giant system (Boyle, 1951).

Summary

Quartz is the most widely distributed mineral in the Yellowknife district. It is also the most abundant epigenetic mineral in all ages of mineralization and is the principal gangue mineral in all the gold deposits. At least four ages of epigenetic quartz are present in both the greenstone belt and sedimentary area.

Four definite ages of epigenetic carbonate minerals are present in the greenstone belt and there are two definite ages in the sedimentary rocks. In the greenstone belt, the most abundant carbonate in the early gold-quartz lenses and their alteration zones is ankerite. Later ages of carbonate are generally calcite, although some ankerite may occur locally. In the deposits in the sedimentary rocks, calcite and ankerite are present in about equal amounts.

Of the sulphides, pyrite is the most abundant, followed by arsenopyrite, sphalerite, chalcopyrite, stibnite, sulphosalts, pyrrhotite, galena and molybdenite. Pyrite has a widespread distribution and is found in nearly all deposits. Arsenopyrite is concentrated mainly in the shear zones of the greenstone belt, but also occurs in the quartz lenses of the sediments. The majority of pyrite and arsenopyrite is early. Later ages are generally local. Sphalerite, pyrrhotite, chalcopyrite and galena occur in small amounts in the shear zones of the greenstones and next to pyrite are the most abundant sulphides in the quartz lenses in the sediments. Stibnite and the sulphosalts are late minerals and are restricted to the shear zones of the greenstones. They occur in greatest abundance in the gold-bearing quartz lenses and have not been observed in the quartz lenses of the sediments or in the post-diabase faults. Molybdenite is present in a few pegmatites in the sediments, but is most abundant in shear zones and fractures cutting quartz-feldspar porphyry or in those cutting the amphibolite facies near the western granodiorite. Small amounts of chalcopyrite and pyrite are the only sulphides in the post-diabase faults.

Gold and aurostibite are the economic minerals of the district. Gold is concentrated in the shear zones of the greenstone belt and in the early quartz lenses in the sediments. Aurostibite occurs only in the shear zones, where a marked concentration of sulphosalts is present. Four definite ages of gold occur in the gold-quartz lenses of the greenstones and there are two definite ages in the quartz lenses of the sediments. Only trace amounts of gold occur in the quartz and carbonate lenses of the post-diabase faults.

Scheelite occurs in small amounts in the gold-quartz lenses of the greenstone belt, particularly in the Con and Negus-Rycon systems. The mineral also occurs in minor amounts in quartz lenses and as small disseminations in certain skarn lenses in the sedimentary rocks.

Tourmaline is a common mineral in the pegmatites associated with the Prosperous Lake granite and in the high-grade, knotted quartz-mica shist aureole surrounding this granite. The mineral is uncommon in the quartz lenses in the relatively unmetamorphosed sediments. In the greenstone belt only minor amounts of tourmaline occur locally in the shear zones and quartz lenses.

Hematite is omnipresent in or near post-diabase faults in all rocks. In most, though not all places, the mineral is associated with quartz, chlorite, prehnite and carbonates.

The pegmatites associated with the Prosperous Lake granite contain essentially quartz, feldspar, muscovite, biotite and tourmaline. Other typically pegmatite minerals such as beryl, spodumene, tapiolite, scheelite and fluorite are present in some pegmatites.

Chapter V

GEOCHEMISTRY OF THE COUNTRY ROCKS, PEGMATITES, AND PORPHYRIES

In this chapter chemical analyses are given of all important rock types, and the geochemistry of minor elements in the different rock types is outlined and discussed.

The second part of the chapter, which discusses the geochemistry, origin, and mobility of water, carbon dioxide, sulphur, boron, and chlorine in the greenstones, sediments, and granites, is important in assessing the part played by the volatiles during metamorphism and ore-forming processes.

Greenstones

The greenstone belt displays three regional metamorphic facies (*see* Figure 2, facing p. 6). Two of these, the amphibolite facies and the epidote amphibolite facies, are well developed, but the third, the greenschist facies, is complicated by shear zones and faults and is difficult to map. A fourth facies represented by the chlorite and chlorite-carbonate schist phases of the shear zones is superimposed upon the three regional facies.

In the amphibolite facies, the stable minerals in the volcanic rocks are hornblende, andesine, sphene, magnetite, ilmenite, quartz, and epidote. In the tuffs garnet is a characteristic metamorphic mineral. The stable minerals in the epidote amphibolite facies are a fibrous amphibole (actinolite), oligoclase, epidote and zoisite, carbonates, magnetite, leucoxene, chlorite, and quartz. In the greenschist facies, fibrous amphibole (actinolite), chlorite, albite, carbonate minerals, leucoxene, epidote, and quartz are stable. The chlorite and chlorite-carbonate phases of the shear zones contain essentially chlorite, albite, ankerite, and quartz. The rocks in all facies contain pyrite, pyrrhotite, minor amounts of chalcopyrite, and apatite.

Chemical analyses of the rocks in the two well-defined facies and of the chlorite and chlorite-carbonate phases of the shear zones are given in Table 9. These analyses were made on composite samples of the volcanic rocks taken along the length of the amphibolite and epidote amphibolite facies, and on a composite sample taken across a well-defined part of the Campbell shear-zone system. The analysis of the meta-diorite and meta-gabbro dyke rocks was made on a composite sample from the amphibolite and epidote amphibolite facies.

In Table 9 average analyses of andesite and basalt are given for comparison with the greenstones. It may not be correct to compare the greenstones with these rocks because in reality the original rock type or composition of the greenstones is not known. However, there are certain similarities which seem to be significant.

As regards the major components such as SiO_2, CaO etc., there is little apparent difference from the average basalt, with perhaps an exception for alumina and total iron, which are lower and higher respectively, in the greenstones. As to water, carbon dioxide, potash, and soda, there are some marked differences which are undoubtedly due to metamorphic processes. A discussion of the first two volatile components is contained in a later section.

Table 9

Analyses of Composite Samples of Greenstone Rocks, Yellowknife Greenstone Belt

Constituent	10061 Composite Sample of Amphibolite Facies	10161 Composite Sample of Epidote Amphibolite Facies	Composite Sample of Chlorite and Chlorite-Carbonate Schist Phase of Shear Zones	10261 Composite of Meta-diorite and Meta-gabbro Dykes	Average Andesite[1]	Average Basalt[1] (Central Basalt)
	%	%	%	%	%	%
SiO_2	50.03	50.45	40.36	48.76	54.20	51.33
Al_2O_3	14.52	13.96	12.87	14.63	17.17	18.04
Fe_2O_3	1.57	2.00	1.06	1.67	3.48	3.40
FeO	11.46	9.61	12.00	9.87	5.49	5.70
CaO	8.99	10.23	8.94	9.94	7.92	10.07
MgO	6.51	6.53	8.43	8.08	4.36	6.01
Na_2O	2.36	1.85	0.90	2.13	3.67	2.76
K_2O	0.66	0.39	0.41	0.58	1.11	0.82
H_2O^+	1.70	2.36	5.20	2.43	0.86	0.45
H_2O^-	0.14	0.11	0.13	0.12		
TiO_2	1.12	1.02	1.05	0.89	1.31	1.10
P_2O_5	0.13	0.13	0.11	0.08	0.28	0.16
MnO	0.21	0.21	0.22	0.24	0.15	0.16
CO_2	0.09	0.68	8.03	0.18		
S	0.11	0.22	0.12	0.12		
Cr_2O_3	0.02	0.03	0.03	0.04		
Cl	0.03	0.02	0.00	0.02		
C	0.04	0.04	0.12	0.06		
Total	99.69	99.84	99.98	99.84		
Less O=S, Cl.	0.05	0.10	0.05	0.05		
Net Total	99.64	99.74	99.93	99.79		
Specific gravity	2.97	2.99	2.75	2.97		
Analyst	J. A. Maxwell	J. A. Maxwell	S. Courville	J. A. Maxwell		

[1] Nockolds, S. R.: Average Chemical Compositions of some Igneous Rocks; *Bull. Geol. Soc. Amer.*, vol. 65, pp. 1007-1032, 1954.

The soda and potash content of the greenstones is lower than either the average basalt or andesite. Here, there is the possibility that the original greenstones were olivine basalts or similar rocks with average soda and potash contents of 2.0 and 0.50 per cent respectively. This, however, seems unlikely considering the high SiO_2 content of the greenstone rocks, and it may, therefore, be concluded, that there has been some migration of potash and soda during metamorphism.

Comparing the composition of the amphibolites of the two facies with the meta-diorite and meta-gabbro dykes, we see relatively little difference. The dykes are a little lower in silica and higher in magnesia suggesting that they may have originally been olivine gabbro or diabase, similar to the late diabase of the region (*see* Table 14, p. 77).

A comparison of the chemical composition of the rocks in the two high-grade metamorphic facies shows that there is relatively little difference in the major constitutents with the exception of total iron, which is lower in the epidote amphibolite facies. Among the minor constituents the alkali content is lower, and the water, carbon dioxide, and sulphur content higher in the epidote amphibolite facies.

There are certain marked differences between the rocks of the two regional facies and the shear zones. The shear zones are much lower in silica and soda and exhibit a pronounced enrichment of water and carbon dioxide. These chemical differences are discussed further in the next chapter.

Sediments

The sedimentary rocks of the Yellowknife group have been subdivided into two general metamorphic facies by Jolliffe (1938) and by Folinsbee (1942). These facies are distinctly related to the Prosperous Lake granite and in an indefinite way to the southeastern granite mass.

The relatively unaltered sediments include greywacke, quartzite, argillite, slate, arkose, and conglomerate. The characteristic stable minerals in these rocks include quartz, albite, sericite, chlorite, carbon, ilmenite, pyrite, and tourmaline. The relatively unaltered sediments grade sharply in most areas into assemblages of quartz-mica schist, hornfels, slate, and knotted quartz-mica schist. The stable minerals in this facies are quartz, albite-oligoclase, biotite, tourmaline, garnet, andalusite, cordierite, staurolite, and graphite. Locally, the garnet, andalusite, cordierite, and staurolite have been sericitized and chloritized.

Chemical analyses of composite samples of typical greywacke and argillite and slate are given in Table 10. These are accompanied by analyses of the various types of schists found in the knotted quartz-mica schist areas. Details of the latter analyses are given by Folinsbee (1942).

Regional metamorphism of typical greywacke beds has yielded principally quartz-mica schist with only a few knots; the argillite and slate, which are high in alumina and magnesia, have given rise to schists containing a great abundance of knots containing andalusite, cordierite, etc. During these metamorphic processes, there has been relatively little change in either the major or minor components of the rocks. Water is, however, an exception. The content of this constituent is significantly lower in the highly metamorphosed knotted rocks than in the argillite and slate.

The Yellowknife sediments were derived both by mechanical and chemical processes. The greywacke, quartzite, arkose, and conglomerate represent mechanical accumulation of erosional detritus. Part of the components of the shale and argillite were also deposited by mechanical agencies. The sulphur and carbon, however, are probably of biogenic origin, and much of the silica, alumina, and iron were precipitated from sea water by hydrolysis. Later diagenetic changes, followed by regional metamorphism, have led to a rearrangement of the original components of the sediments giving the rocks their present composition and texture.

Table 10

Analyses of Sedimentary Rocks of the Yellowknife Group

Constituent	Greywacke	Composite of Argillite and Slate	Staurolite-Biotite Schist	Sericitized Staurolite Schist	Garnet-Cordierite Schist	Cordierite-Andalusite Schist	Sericitized Andalusite Schist
	%	%	%	%	%	%	%
SiO_2	62.61	53.08	66.20	66.11	54.61	55.56	52.51
Al_2O_3	16.78	20.16	17.14	15.97	17.59	22.19	22.63
Fe_2O_3	0.38	1.25	1.45	0.79	0.90	.53	2.14
FeO	5.81	7.17	3.31	4.30	13.95	7.99	5.46
CaO	2.80	1.04	1.64	1.21	2.91	0.76	0.60
MgO	2.99	5.02	2.71	2.97	3.44	4.41	3.61
Na_2O	3.79	1.83	3.29	2.74	1.19	1.21	1.50
K_2O	1.56	3.75	1.96	2.30	1.88	3.29	4.74
H_2O^+	1.94	4.55	0.91	2.36	2.14	2.39	3.86
H_2O^-	0.12	0.15	0.01	0.05	0.04	0.05	0.09
TiO_2	0.68	0.79	0.56	0.59	0.74	0.83	0.76
P_2O_5	0.16	0.15	0.11	0.12	0.19	0.14	0.19
MnO	0.08	0.11	0.03	0.04	0.10	0.09	0.06
CO_2	0.10	0.05					
S	0.14	0.11	0.03	0.10	0.03	0.35	1.59
Cl	0.02	0.01					
Cr_2O_3	0.01	0.03	0.02	0.02	0.03	0.03	nil
C	0.13	0.26	trace	trace	0.20	trace	0.47
BaO			0.04	0.05	0.02	0.07	0.11
SO_3			nil	nil	nil	trace	0.05
Total	100.10	99.51	99.61	99.72	99.96	99.89	100.39
Less O = S, Cl	0.06	0.05	0.01	0.04	0.01	0.13	0.68
Net Total	100.04	99.46	99.60	99.68	99.95	99.76	99.71
Specific gravity	2.73	2.77	2.77	2.72	2.99	2.80	
Analyst	J. A. Maxwell	J. A. Maxwell	R. E. Folinsbee	R. E. Folinsbee	R. E. Folinsbee	R. E. Folinsbee	R. E. Folinsbee

In the greenstone belt, various types of thinly bedded sedimentary rocks, locally called tuffs, occur in bands, ranging in thickness from a few inches to a hundred feet or more (Plate II, facing p. 4). These rocks are interbedded with the volcanic flows and provide excellent structural markers. In most occurrences, they are well bedded and may exhibit grain gradation, providing a means for determining tops.

The tuffs weather white, pink, or grey and are light grey to black on freshly broken surfaces. Most of the tuffs are fine grained and cherty, but some are coarse grained and have been called crystal tuffs. In the lower-grade facies, the stable minerals are quartz, feldspar, carbonates, sericite, chlorite, pyrite, pyrrhotite, and graphite. In the amphibolite facies quartz, feldspar, garnet, amphibole, carbonates, pyrite, pyrrhotite, and graphite are stable.

An analysis of a composite sample of graphitic tuff is given in Table 11. The unique features are the high content of sulphur, carbon dioxide, and carbon.

The tuffs represent definite breaks in the outpouring of the lava flows during which sedimentary conditions prevailed for short periods of time. Much of the matrix material in the tuffs is probably of volcanic origin and was once ash, dust, and comminuted fragments of various minerals.

The constant association of relatively high contents of carbon and sulphur, elements essential to life, suggests that these two elements were concentrated by biogenic processes. In the early seas it is probable that bacteria were abundant, especially those types dependent on the sulphur cycle. It can be inferred that such bacteria acting on the sulphates of the sea water produced hydrogen sulphide which bound the available iron into fine-grained sulphides. These were later recrystallized during diagenetic and metamorphic process to give pyrite and pyrrhotite. On the death of the bacteria their carbon content was incorporated in the tuffaceous material and now appears as graphite.

Table 11

Analysis of a Composite Sample of Graphitic Tuff, Yellowknife Greenstone Belt

Constituent	Per cent	Constituent	Per cent
SiO_2	60.74	P_2O_5	0.25
Al_2O_3	15.83	MnO	0.08
Fe_2O_3	0.50	CO_2	5.55
FeO	1.80	S	1.45
CaO	4.03	Cl	0.03
MgO	2.04	Cr_2O_3	0.01
Na_2O	0.39	C	1.28
K_2O	3.95	As_2O_3	trace
H_2O^+	1.45		
H_2O^-	0.11	Total	100.16
TiO_2	0.67	Less O = S, Cl	0.54
Analyst—S. Courville		Net Total	99.62

Many of the tuffs are highly siliceous and have a cherty appearance. The silica may in part be a chemical precipitate or it may have had a biogenic origin. The carbonate content of certain tuffs may have had a similar origin. In seeking an answer to the origin of fine-grained quartz and carbonates in such deposits there are no definite criteria for determining just what the processes have been.

Granitic Rocks, Pegmatites and Porphyries

The western granodiorite is massive and in general is homogeneous in texture. Locally porphyritic varieties are present. The mineral composition is variable. A typical specimen from the contact zone contains 40 per cent quartz, 45 per cent oligoclase, 10 per cent microcline and 5 per cent biotite and/or hornblende. Some phases contain up to 5 per cent muscovite. Towards the centre of the granitic mass, the amount of quartz and potassic feldspar increases and sodic feldspar, biotite, and hornblende decrease. In all phases the biotite and hornblende are chloritized and the feldspars are mildly sericitized. Accessory minerals include epidote, sphene, apatite, zircon, magnetite, rarely tourmaline and small amounts of pyrite and carbonates.

The Prosperous Lake granite is relatively inhomogeneous containing many tourmaline-bearing pegmatites with some aplites. Specimens of the granite in thin sections contain 30 to 35 per cent quartz, 25 to 30 per cent microcline, 20 to 25 per cent oligoclase, 5 to 10 per cent muscovite and 5 to 10 per cent biotite. In the contact zones where ghosts and relicts of sedimentary material abound, the granitic rock is higher in biotite. Accessory minerals in all phases include garnet, apatite, zircon, tourmaline, and very minor amounts of pyrite.

Chemical analyses of composite samples of the western granodiorite and Prosperous Lake granite are given in Table 12.

Table 12

Analyses of Composite Samples of Granitic and Porphyry Bodies, Yellowknife District

Constituent	10361 Composite of Western Granodiorite in Contact Zone	10461 Composite Sample of Western Granite, 2 Miles from Contact Zone	10561 Composite of Prosperous Lake Granite	10661 Composite of Quartz-feldspar Porphyry in Greenstone Belt
	%	%	%	%
SiO_2	72.95	75.92	74.28	73.09
Al_2O_3	14.11	13.46	14.38	14.01
Fe_2O_3	0.37	0.11	0.32	0.32
FeO	1.89	1.51	0.77	0.89
CaO	1.46	1.34	0.60	2.05
MgO	0.56	0.21	0.16	0.37
Na_2O	4.29	2.14	4.18	4.15
K_2O	2.80	4.17	4.15	1.63
H_2O^+	0.69	0.69	0.42	0.72
H_2O^-	0.06	0.08	0.01	0.05
TiO_2	0.19	0.07	0.07	0.20
P_2O_5	0.06	0.10	0.11	0.05
MnO	0.06	0.08	0.04	0.02
CO_2	0.14	trace	0.18	1.80
S	0.02	0.04	trace	0.80
Cl	0.02		0.02	trace
Cr_2O_3	0.01		trace	0.04
Total	99.68	99.92	99.69	100.19
Less O = S, Cl	0.01	.02		0.34
Net total	99.67	99.90	99.69	99.85
Specific gravity	2.66	2.65	2.60	2.69
Analyst	J. A. Maxwell	R. J. C. Fabry	J. A. Maxwell	J. A. Maxwell

The contact phase of the western granodiorite has a high soda-to-potash ratio. Outside of the contact zone the rock is essentially a granite with a high potash-to-soda ratio.

The Prosperous Lake granite contains about equal amounts of soda and potash. Certain phases, however, judging from thin-section studies, are higher in potash and would have a relatively high potash-to-soda ratio. Comparing the two granitic bodies it can be seen that the Prosperous Lake granite is more acidic than the western granitic mass and contains much less iron, calcium, and magnesium.

Chemical analyses of a series of rocks in a granitized area near Ryan Lake are given in Table 13. The purpose of these analyses was to determine the chemical trend during granitization processes. The zone from which the samples were taken is clearly granitized, sharp contacts are rare, and ghosts and inclusions of amphibolite abound in the granitic rocks.

Table 13

Analyses of Granitized Rocks, Ryan Lake, Yellowknife

Constituent	Amphibolite	Granitized Amphibolite	Grey Granite in Granitized Zone	Granite 2 Miles West of Granitized Area	Aplite Cutting Granitized Amphibolite
	%	%	%	%	%
SiO_2	50.41	52.87	74.80	75.92	78.80
Al_2O_3	15.21	13.02	12.98	13.46	10.73
Fe_2O_3	0.63	1.30	0.62	0.11	1.78
FeO	11.65	8.54	1.40	1.51	0.39
CaO	9.48	8.65	1.96	1.34	1.63
MgO	7.02	9.35	0.06	0.21	0.62
Na_2O	1.64	1.80	2.85	2.14	2.10
K_2O	0.74	1.12	3.17	4.17	2.43
H_2O^+	2.56	1.89	0.79	0.69	0.27
H_2O^-	0.05	0.03	0.08	0.08	0.26
TiO_2	0.79	0.74	0.36	0.07	0.31
P_2O_5	0.09	0.20	0.08	0.10	0.15
MnO	0.23	0.19	0.09	0.08	0.06
CO_2	0.02	0.35	0.93	trace	trace
S	0.08	0.20	0.03	0.04	0.16
Total	100.60	100.25	100.20	99.92	99.69
Less O = S	0.03	0.07	0.01	0.02	0.06
Net total	100.57	100.18	100.19	99.90	99.63
Specific gravity	2.95	2.80	2.70	2.65	2.65
Analyst	R. J. C. Fabry	R. J. C. Fabry	R. J. C. Fabry	R. J. C. Fabry	R. J. C. Fabry

It is clear that as the amphibolite is tranformed into granite there is a consistent increase in the content of silica and the alkalies and a marked decrease in aluminium, calcium, iron, magnesium, and manganese. There is also a constant decrease of water through the series and a decrease of carbon dioxide in the final stages. Sulphur, however, behaves erratically through the sequence.

The few small pegmatites associated with the western granitic mass are rarely more than 10 feet long and a foot wide. All are simple, containing essentially quartz, feldspar, and muscovite. Tourmaline occurs in a few dykes and is the only common rare mineral.

Pegmatite bodies compose nearly 50 per cent of the Prosperous Lake granite and occur in great profusion in its associated knotted schist aureole. These bodies are dyke-like in many places and have relatively sharp contacts with the granite; in other places the pegmatites are highly irregular and have diffuse gradational contacts. In the knotted schist aureole the pegmatites have relatively sharp contacts with the metamorphosed sediments. In places a tourmalinized zone is developed in the schist or hornfels. The pegmatites in the granite are generally simple, containing mainly quartz, microcline, cleavelandite, perthite, muscovite, black tourmaline, and small amounts of the accessories, garnet, ilmenite, and apatite. Most of the pegmatites in the meta-sediments are simple and contain the same suite of minerals listed for those in the granitic area. A few are complex and in places exhibit a rude zoning. In addition to the usual pegmatite minerals these may contain small amounts of beryl, spodumene, amblygonite, lithiophilite, petalite, tantalite-columbite, tapiolite, scheelite, and molybdenite.

No analyses of the pegmatites were made, mainly because the bodies are inhomogeneous and not readily sampled. Mineralogical and spectrographic studies indicate, however, that these bodies represent marked concentrations of silica, potash, soda and alumina. In addition some are enriched in boron, lithium, beryllium, phosphorous, columbium, tantalum, and other rare elements.

The quartz-feldspar porphyries form dykes and irregular masses with many ramifying tentacles. Some dykes are continuous for several thousand feet, others are discontinuous. They are restricted mainly to the greenstones, but a few cut the Yellowknife sediments in places. They have not been observed cutting the western granitic mass or Prosperous Lake granite. Their cutting relationships show that they are younger than the meta-gabbro dykes and sills, and they may be older than the western granitic mass, but the relationships are not too clear.

Most dykes have a porphyritic texture, but some are very fine-grained and have a cherty appearance. Many have a finer-grained phase at their contacts with the greenstones, but others show no such grain gradation being relatively coarse grained throughout. In some dykes angular fragments of relatively unaltered greenstone are present, in others the fragments are highly altered and porphyritized. The minerals in most dykes are altered, probably as a result of regional metamorphism, and some dykes are highly sheared and reduced to masses of sericite and quartz where they are cut by the shear-zone systems.

In thin sections the unsheared quartz-feldspar porphyries contain essentially quartz and zoned plagioclase phenocrysts in a groundmass of fine-grained plagioclase, quartz, microcline, muscovite, carbonates, and chloritized biotite. The cores of the plagioclase phenocrysts are generally altered to sericite and carbonate. Pyrite and pyrrhotite are particularly abundant in the porphyries in the vicinity of the Con Mine, and molybdenite is present in a few dykes and irregular bodies in several places. The sulphides appear to be primary constituents and probably crystallized with the quartz and feldspar, because they fill interstices between these minerals and form along the cleavage planes of biotite. The carbonates may be partly primary and partly due to regional metamorphism. Accessory minerals in the porphyries include apatite, zircon, rutile, and epidote.

An analysis of a composite sample of massive quartz-feldspar porphyry is given in Table 12. It is noticed that the composition of the porphyry closely resembles that of the contact phase of the western granodiorite as regards the major elements. The same relatively high soda-to-potash ratio is also evident. Some porphyries, however, have a relatively high sulphur and carbon-dioxide content and exhibit an enrichment in chromium, features uncommon to most granitic rocks.

Origin of the Granitic Bodies

Opinion on the origin of granitic bodies is divided into two schools. On the one hand are those who hold that granites and similar rocks are derived by magmatic differentiation processes; on the other are those who call upon metamorphic agencies. During the field and laboratory study of the Yellowknife rocks the author had both concepts in mind, but despite much work and thought on the origin of the various granitic rocks he can add little beyond speculation and opinions.

In the field, certain features of the western granitic mass such as sharp contacts, granite dykes, etc. provide undoubted evidence for magmatic or remobilized metasomatic granite. On the other hand, in certain contact zones, there is clear evidence that parts of the western granitic mass were emplaced by granitization. Furthermore, the basic phase of the granitic mass adjacent to the greenstone belt could be interpreted as a metasomatic zone in which granitization has not gone to completion. In the classical sense this zone could also be interpreted as the result of the reaction of greenstones with a granitic magma.

On a regional scale the western granitic mass is some 30 miles in width. Its eastern flank is marked by the Yellowknife greenstone belt and its western flank by Yellowknife group sediments in the vicinity of Stagg and Wheeler Lakes (see Figure 1, in pocket). These regional features together with the relationships shown south of Fishing Lake suggest that the Yellowknife greenstone belt was originally a series of lava flows, tuffs, etc. interbedded with Yellowknife group sediments.

Considering these facts and probabilities the author believes that the western granitic mass was formed principally by granitization of a great thickness of sediments which once lay stratigraphically below the greenstones. As the metasomatic granite developed, the sediments were engulfed, and the granitic material was partly mobilized. When the lavas (greenstones) were reached, the process halted because of the contrasting chemical environment, and hence only a limited amount of granitization of the lavas took place. This explains the development of a basic phase in the granitic mass at its contact with greenstones as well as the local areas of granitization in the greenstones.

To digress for a moment it is interesting to speculate on how this concept can be extended to the Canadian Shield as a whole. There is much evidence to suggest that the oldest Precambrian rocks were a great series of interbedded sediments and lavas, and as is well known, all of these rocks have been subjected to extreme metamorphism. During the mountain-building of the Shield and attendant metamorphic changes, it is probable that large volumes of the sediments were transformed to granitic rocks, whereas the lavas, because of their contrasting chemistry, resisted such a transformation. This would yield residual belts of greenstones (and some sediments) in vast expanses of granitic rocks, a feature which is characteristic of the Shield.

In discussing the chemical changes during local granitization of the greenstones we are faced with the perplexing problem of the enrichment of the alkalies and silica and the depletion of the cafemic components. The hypotheses advanced to explain these phenomena are as follows:

(1) The cafemic elements escaped to the surface, or to higher levels now eroded away;
(2) The cafemic elements migrated downward with a resultant enrichment of silica and alkalies in the granitized zones; and
(3) The cafemic elements migrated into the greenstones, forming a basic front and leaving an enrichment of silica and alkalies in the granitized zones from which they came.

It is not possible to determine whether the first two hypotheses are valid, and we must leave them as probable explanations. As for the third, chemical analyses (Table 9, p. 67) show that the rocks across the metamorphic facies exhibit only minor differences in their cafemic components, a feature which rules out an extensive basic front. There are, however, within the greenstone belt, numerous meta-gabbro dykes, sills, and irregular masses, concentrated principally in the amphibolite facies. These bodies may represent the basic components expelled during the limited granitization of the greenstones, but the chemical details of the processes and the emplacement of the bodies is a matter of speculation.

If we assume that the western granitic mass was magmatic in origin and came from depth we are faced with a stupendous space problem as well as the problem of disposing of enormous amounts of basic material resulting both from differentiation processes and reaction with the greenstones. This poses two problems instead of one, and the facts are perhaps best resolved by assuming that the western granitic mass was derived mainly by metasomatic processes followed by partial mobilization and injection in places.

The Prosperous Lake granite exhibits intrusive features in some areas, but again there is ample evidence to suggest that this mass has been derived by granitization of the Yellowknife sediments. The same problem of disposing of the cafemic elements presents itself when discussing the origin of this granite, as can be seen by comparing the composition of the Yellowknife sediments and Prosperous Lake granite.

A detailed discussion of the origin of the pegmatites associated with the Prosperous Lake granite is beyond the scope of this memoir. Certain features of the pegmatites, however, seem to preclude a magmatic origin for these bodies. These can be summarized as follows: (1) The pegmatites represent concentrations of silica, potash, soda, and alumina. In addition some are enriched in boron, lithium beryllium, and other rare elements. All these elements are present in sufficient quantity in the granites and sediments to form the pegmatites. (2) The pegmatites occur either in the granite or in the knotted quartz-mica schist aureole, suggesting that they were formed at relatively high temperatures. (3) The pegmatites are structurally isolated in dilatant structures such as fractures, folds, etc. They exhibit no obvious magmatic feeder channels. (4) The pegmatites are developed in water-deficient rocks such as granites and high-grade schists, and they are not surrounded by hydrous aureoles, two facts suggesting that large quantities of water were not involved in their formation. (5) In most cases it is apparent that the pegmatites formed after the consolidation of the granite because they cut the granite.

The above features suggest that the pegmatites were formed by diffusion of the pegmatitic constituents from their host rocks. Where they occur in the granite, diffusion of their constituent elements undoubtedly took place when the granite was completely crystallized but still at a high temperature. The pegmatites in the knotted schists were probably formed during the metamorphism of the sediments and are, therefore, the result of the mobilization, migration, and concentration of various elements at relatively high temperatures.

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 the western granodiorite. This suggests that they may have originated either by magmatic or granitization processes. The latter seem to fit the facts best, and the author is of the opinion that the porphyries represent concentrations of various elements mobilized during granitization at depth.

Regardless of the mode of origin of the porphyry bodies, two facts are certain: first, they are cut by the shear zones, and second, they were completely crystallized solid bodies before the orebodies were formed. The porphyries could not, therefore, have been the source of mineralizing solutions.

Diabase

The diabase dykes and basic sills are the youngest rocks in the area and are relatively unaltered except where cut by late faults and fractures. They contain essentially plagioclase, augite, olivine, some quartz, and minor amounts of serpentine. Accessory minerals are ilmenite and/or titaniferous magnetite, apatite, pyrite, and pyrrhotite.

A chemical analysis of a composite sample of fresh diabase is given in Table 14, together with an analysis of an average gabbro for comparison. The diabase is similar in composition to the gabbro but has a somewhat higher water content. Most of the water is present in serpentine and may have been absorbed from greenstones or sediments. This is substantiated by the observation that serpentinization is often more marked in diabase dykes cutting the water-rich sediments and greenschist facies than where they cut the water-poor granites or amphibolites.

Table 14

Analysis of Composite Sample of Fresh Diabase, Yellowknife

Constituent	Diabase %	Average Gabbro[1] %
SiO	48.68	48.36
Al_2O_3	15.55	16.84
Fe_2O_3	1.94	2.55
FeO	8.37	7.92
CaO	11.34	11.07
MgO	8.50	8.06
Na_2O	1.84	2.26
K_2O	0.46	0.56
H_2O^+	1.47	0.64
H_2O^-	0.05	
TiO_2	0.89	1.32
P_2O_5	0.09	0.24
MnO	0.15	0.18
CO_2	0.27	
S	0.07	
Cl	0.02	
Cr_2O_3	0.06	
Total	99.75	
Less O = S,Cl	0.03	
Net total	99.72	
Specific gravity	3.005	
Analyst	J. A. Maxwell	

[1] Average gabbro quoted by Nockolds, S.R.: Average Chemical Compositions of Some Igneous Rocks; *Bull. Geol. Soc. Amer.*, vol. 65, pp. 1007-1032, 1954.

Minor Elements in Country Rocks, Pegmatites, and Porphyries

During the course of the investigation of the minor elements, each rock type was crushed and separated into its light, heavy, and magnetic components and where possible into its mineral constituents by means of magnetic methods, heavy liquids, and hand picking. While great care was taken in this work it became evident after much effort that pure minerals could seldom be obtained due to the highly intergrown nature of the minerals and the fact that most minerals are more or less altered. In spite of this difficulty some significant trends were established for the minor elements, but quantitative results appear to be impossible to obtain. It should, therefore, be borne in mind that most of the results quoted here as regards the enrichment of elements in mineral phases, are qualitative only.

The results of the minor-element work on the rocks are recorded in Table 15. Some of the values, such as those for sulphur, chlorine, titanium, and chromium, have been compiled from precise chemical analyses on composite samples of the rock types. Others have been compiled from spectrographic analyses made on composite samples both directly and in some cases after preliminary enrichment by chemical methods. The data on gold and silver have been compiled from assays of composite samples and from spectrographic analyses of sulphides separated from the rocks.

Table 15

Minor Elements in Rocks of the Yellowknife District

Element (p.p.m.)	Amphibolite Facies	Epidote Amphibolite Facies	Metadiorite and Gabbro Dykes	Diabase Dykes	Tuffs	Argillite and Slate	Greywacke	Quartz-mica Schist	Western Granodiorite	Quartz-feldspar Porphyry	Prosperous Lake Granite	Pegmatites
Li	20–100	20–100	20–100	40–80	20–150	50–150	30–70	50–200	40–100	40–100	50–100	100–1,000
Rb	50–100	50–100	50–100	50–100	150–400	150–800	50–100	50–600	200–800	200–400	200–1,200	1,000–2,500
Cs	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Be	< 5	< 5	< 5	< 5	< 5	5–10	5–10	5–10	< 5	< 5	< 5	>10
Sr	50–800	50–500	50–800	50–800	20–800	50–1,000	50–1,000	50–1,000	50–400	50–800	20–150	<50
Ba	100–300	100–200	100–200	100–300	100–1,500	600–1,000	600–1,000	150–1,000	400–1,000	400–1,000	100–200	<200
B	<10	<10	<10	<10	10–100	50–100	50–100	40–100	20–40	20–60	40–300	400–2,000
Y	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	~20
La	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	~20
Ce	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	~20
Yb	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	~20
Zr	10–70	10–70	10–40	10–40	100–200	20–100	25–100	20–150	20–100	20–100	10–20	5–20
Ti	6,700	6,100	5,300	5,300	4,000	4,700	4,100	4,100	1,100	1,200	420	20–100
V	30–100	30–100	30–100	30–100	20–100	30–100	50–150	30–100	10–30	10–30	<20	<20
Cr	135	135	270	410	68	200	70	100	135	270	20	~20
Mn	1,625	1,625	1,850	1,150	620	850	620	500	460	150	310	100–200

Co	5–10	5–10	5–10	5–10	30–50	30–50	30–50	30–50	<10	5–10	<10	<10
Ni	50–100	50–100	50–100	50–100	20–100	20–100	20–100	20–100	30–50	30–50	5–10	<10
Cu	20–100	20–120	20–100	20–100	15–650	30–100	20–80	20–100	20–40	20–150	10–40	10–20
Zn	10–80	10–100	10–80	10–100	10–1,500	50–250	10–100	10–100	10–40	20–100	10–40	10–40
Pb	10–20	5–15	5–20	1–10	10–20	10–30	10–30	10–30	10–20	5–25	10–30	10–30
As	2–10	2–10	2–10	4	5–100	10	15	10	2	140	2	<5
Sb	1	1.5	<1	<1	1–25	<1	1.5	1	1	5–10	<1	<1
Mo	<5	<5	<5	<5	10–50	5–10	5	5	<5	5–20	5	>5
Sn	<5	<5	<5	<5	8–22	5–10	5	5	<5	5	5	>5
W	<5	5	<5	<5	<5	<5	<5	<5	<5	5	5	>5
Ag	0.6–1.4	0.3–1.2	0.3–1.4	1.4	0.2–2.0	0.3–2.0	0.3–1.2	0.9–1.2	0.4–1.4	0.6–2.0	0.3–1.4	0.20
Au	0.01	0.008	<0.01	<0.01	0.01–0.07	0.01	<0.01	0.01	<0.01	0.10	0.01	<0.01
S	1,100	2,200	1,200	700	5,000–15,000	1,100–10,000	1,400	1,300	200	8,000	trace	trace
Cl	300	300	200	200	300	100	200	400	200	trace	200	trace

Notes:

1. Au and Ag analyses by assay, Mines Branch, Ottawa, and confirmed by spectrograph and chemical methods.
2. Ti, Cr, Mn, S, and Cl analyses by J. A. Maxwell and S. Courville.
3. Cu, Zn, Pb analyses by dithizone methods by R. W. Boyle and M. A. Gilbert.
4. As, Sb analyses by M. A. Gilbert.
5. All other elements by Spectrographic Laboratory, Geological Survey of Canada.

Most of the minor elements show an erratic distribution in the various rock types and vary from flow to flow in the greenstones, and from bed to bed in the sediments. In order to present a reasonable estimate of the amount of the particular element present, the values were grouped, exceptionally high or low values have been discarded, and the values are recorded as a range. Thus a value of 10-50 ppm signifies that most analyses of the particular rock type fall within the range of 10 to 50 parts per million.

In the following outline the probable location of the bulk of each of the minor elements is given and their geochemical relationships to the major elements of the rock type are discussed. It is recognized, of course, that small quantities of each minor element may reside in small fractures and along grain boundaries and other discontinuities in the rocks. The amounts in these sites are generally small, however, and in the author's opinion would not radically affect the conclusions drawn from the chemical results.

Geochemistry of the Minor Elements

Lithium is concentrated principally in the sedimentary and granitic rocks and is present in lower amounts in the greenstones and late diabase. It is strongly enriched in the pegmatites, forming lithium minerals in some. In the sedimentary rocks, granites, and simple pegmatites the element is found mainly in the micas. In the greenstones lithium is present in the amphiboles and chlorite where it probably replaces Mg^{2+} and Fe^{2+} as a result of the similarity of the ionic radii of the three elements ($Mg^{2+}=0.66$Å, $Fe^{2+}=0.74$Å, $Li^{+}=0.68$Å)*. In the diabase, lithium occurs principally in the pyroxenes where a similar replacement takes place.

Rubidium and *cesium* follow potassium closely in their geochemistry and are concentrated in the feldspar and micas of the granitic rocks, quartz-feldspar porphyry, and sediments. In the greenstone and late diabase the two elements are concentrated in the plagioclase, but small amounts also occur in the amphiboles, pyroxene, and chlorite.

The distribution of *beryllium* in the rock types is not known with certainty, principally because the values are generally low in the rocks and difficult to determine accurately. The sedimentary rocks contain the bulk of the element. Spectrographic analyses of micas and chlorite show that the element is concentrated mainly in these minerals. The radius of Be^{2+} (0.35Å) is very near that of Si^{4+} (0.42Å) and it is probable that some beryllium replaces silicon in the silicates. Beryllium is generally enriched in the pegmatites but only locally does it reach a high enough concentration to form beryl.

Strontium, with an ionic radius of 1.12Å, generally replaces Ca^{2+} (0.99Å) or K^{+} (1.33Å). The analyses show that the element is present in larger amounts in the greenstones, diabase, quartz-feldspar porphyry, and sediments than in the granitic rocks and pegmatites. It is apparent, therefore, that the strontium content tends to follow closely the calcium content of the rocks. Analyses of the separated mineral

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* Ionic radii from Green, J.: Geochemical Table of the Elements for 1953; *Bull. Geol. Soc. Amer.*, vol. 64, No. 9, pp. 1001-1012, 1953.

phases show that strontium is concentrated mainly in the calcic feldspars, amphiboles, and pyroxenes. Small amounts are also present in the carbonates and in apatite.

The content of *barium* is highest in the sedimentary rocks, lower in the basic rocks, and shows differences in the two types of granitic rocks. The pegmatites are generally low in the element. Among the various minerals, barium is concentrated mainly in the feldspars, but some is present in the micas, amphiboles, pyroxenes, carbonates, and apatite. Geochemically it prefers potash-rich minerals in which it replaces potassium because of the similarity of the radii of the two elements Ba^{2+} (1.34Å), K^{+} (1.33Å). In the other minerals it probably replaces Ca^{2+} (0.99Å).

Boron will be discussed in some detail in the next section, and we need only note its general distribution at this point. The content of boron is notably low in the greenstones and diabase and relatively high in the sedimentary rocks. The western granodiorite has a lower boron content than the Prosperous Lake granite, a fact substantiated by the field observation that tourmaline is rarely developed in the western granodiorite whereas in the Prosperous Lake body it is very common. Nearly all the pegmatites associated with the latter granite are enriched in boron.

Boron B^{3+} (0.23Å) may replace Si^{4+} (0.42Å) in the SiO_4 tetrahedra of silicates, and in the greenstones and diabase may be present in this form. In the sediments and granitic rocks, boron is present principally in minute needles of tourmaline. In nearly all rocks the separated mica minerals and chlorite contain some boron probably substituting for Si^{4+}. In the pegmatites nearly all the boron is present in tourmaline, but some occurs in the various types of micas.

Yttrium and the rare earths occur in small amounts in all rock types but seldom exceed 20 ppm in abundance with the exception of the pegmatites. These elements report principally in the heavy constituents of the rocks and are particularly enriched in apatite, monazite, allanite, sphene, epidote, and garnet. In addition they occur in very small amounts in amphiboles, plagioclase feldspars, and pyroxenes where they may replace Ca^{2+}. The carbonates in the various rocks also contain traces of yttrium and rare earths. In the pegmatites, the rare-earth content is concentrated mainly in apatite, garnet, monazite, fluorite, xenotime, and in the plagioclase and mica of these rocks.

Zirconium is present in all rock types in about equal amounts with the exception of the tuffs which generally contain more than 100 ppm. The granitic rocks are not notably enriched, and the Prosperous Lake granite in particular appears to be low in the element. The pegmatites, likewise, contain relatively low amounts. In the granitic rocks and sediments, zirconium is present mainly in zircon. In the greenstones and diabase, the bulk of the zirconium is present in the amphiboles, pyroxenes, and other minerals such as apatite, magnetite, and biotite.

The *titanium* content of the greenstones, diabase, and sedimentary rocks is much higher than that of the granitic rocks, porphyries, and pegmatites. In the greenstones and diabase the bulk of the titanium is contained in ilmenite, magnetite, sphene, leucoxene, and rutile, but some is also present in the pyroxenes, amphiboles, and chlorite. In the latter mineral, Ti^{4+} (0.68Å) may replace Si^{4+} (0.42Å) in limited amounts, and Ti^{3+} (0.76Å) probably replaces Al^{3+} (0.51Å), and Fe^{3+} (0.64Å), and probably also Mg^{2+} (0.66Å). In the sedimentary rocks the titanium is present principally in ilmenite, sphene, leucoxene, and rutile. Some also occurs in biotite, chlorite, and in the few metamorphic amphiboles. In the granitic rocks, porphyries, and pegmatites the element is concentrated in sphene, ilmenite, magnetite, and rutile, with smaller amounts in hornblende and biotite.

Vanadium is present in relatively high amounts in the greenstones, diabase, and sedimentary rocks, with lower amounts in the granitic rocks, porphyries, and pegmatites. The element reports principally in the heavy constituents of the rocks and is particularly concentrated in magnetite and ilmenite, with smaller amounts in sphene, leucoxene, rutile, apatite, and sulphides. In the basic rocks, amphiboles and pyroxenes contain small amounts and in the sedimentary and granitic rocks the mica minerals may contain amounts up to 400 ppm.

Vanadium occurs in three valences in igneous and sedimentary rocks—V^{3+} (0.74Å), V^{4+} (0.63Å), and V^{5+} (0.59Å). The element appears to follow titanium closely and in titanium minerals such as sphene, V^{4+} probably replaces Ti^{4+} (0.68Å). The quadrivalent ion may also replace Fe^{3+} (0.64Å) and Al^{3+} (0.51Å) in amphiboles and similar silicates. In apatite, V^{5+} may replace P^{5+} (0.35Å), and in micas the vanadium as V^{4+} or V^{5+} probably replaces Fe^{3+} and Al^{3+}.

The *chromium* content of the amphibolites, western granodiorite, and sediments is about the same, averaging about 120 ppm. The quartz-feldspar porphyries, early meta-gabbro and diorite dykes, and late diabase dykes are relatively enriched in the element. The Prosperous Lake granite and its associated pegmatites contain only small amounts of chromium.

The chromium content of the heavy fractions of the rocks is high, and separation of the various minerals shows that most of the chromium in the greenstones is concentrated in ilmenite, leucoxene, magnetite, and epidote. In the sedimentary rocks, garnet, ilmenite, and the micas are the principal hosts. Olivine, magnetite, and epidote, are the principal carriers in the diabase. In the basic rocks both the pyroxenes and amphiboles carry small amounts of chromium, and chlorite may also contain traces. In the granitic rocks most of the chromium occurs in the accessory minerals such as magnetite and epidote, and the remainder is contained in the micas and amphiboles. Much of the chromium content of the quartz-feldspar porphyry is present in a greenish sericite, probably fuchsite. In the silicate minerals, Cr^{3+} (0.63Å) probably replaces Fe^{3+} (0.64Å), but replacement of Al^{3+} (0.51Å) is also possible.

Manganese is concentrated in the basic rocks with lower contents in the sediments and only small amounts in the granitic rocks. In the greenstones and diabase most of the manganese is concentrated in the pyroxenes, amphiboles, and chlorite with some in the iron oxides, carbonates, apatite, and sulphides. In the sedimentary rocks the element is bound principally in biotite, in the metamorphic amphiboles, and in garnet, iron oxides, and sulphides. In the granitic rocks, micas, iron oxides, carbonates, sulphides, and hornblende are the principal carriers of manganese. Geochemically, manganese follows iron closely and in the above minerals there is probably a general replacement of Fe^{2+} (0.74Å) by Mn^{2+} (0.80Å) as well as a replacement of Mg^{2+} (0.66Å) and Ca^{2+} (0.99Å).

Cobalt and *nickel* form a coherent pair of elements geochemically speaking and hence will be considered together. In most of the rock types, nickel is more abundant than cobalt with perhaps an exception for some granites and pegmatites in which about equal amounts of the two elements are present. Both elements are concentrated in the basic rocks, but significant amounts are also present in the sedimentary rocks, especially in the tuffs, slates, and argillites with a relatively high sulphide content. The amounts in the granitic rocks, porphyries, and pegmatites rarely exceed 10 ppm for cobalt and 50 ppm for nickel. In nearly all rock types much of the nickel and cobalt are bound in the sulphides, especially pyrrhotite. The iron oxides also contain significant amounts of the two elements, and the amphiboles, pyroxenes, olivine, chlorite, biotite, and epidote are carriers. In all these minerals Co^{2+} (0.72Å) and Ni^{2+} (0.69Å) probably replace either Mg^{2+} (0.66Å) or Fe^{2+} (0.74Å).

Copper, lead and zinc have a general erratic distribution in the various rock types, and the amounts of these elements appear to depend principally on the amount of sulphides and iron oxides present in the rock.

Copper is concentrated principally in the greenstones, diabase, porphyries, tuffs, and sediments, and only small amounts occur in the granitic rocks and pegmatites. In the greenstones and diabase the copper is contained principally in pyrite, pyrrhotite, and chalcopyrite, the common sulphides in the rocks. Small amounts occur in the iron oxides and in the silicates such as amphiboles, pyroxenes, and epidote. In the sedimentary rocks the highest concentrations of copper are present in the black argillaceous beds containing an abundance of syngenetic sulphides and graphitic material. Most of the copper in these sediments, as in the others, is present in the sulphides; some is bound in the iron oxides and nondescript colloidal material, and a little is present in the biotite. The tuffs in the greenstone belt are strongly enriched in copper, and in places chalcopyrite may occur in the assemblage of syngenetic sulphides. The low amounts of copper in the granitic rocks are contained principally in scattered sulphides and in the dark silicates. The porphyries may be enriched in copper, especially those containing an abundance of pyrite and pyrrhotite.

Zinc is concentrated principally in the iron oxides and in the sulphides. In the former, amounts up to 350 ppm have been recorded, and in the latter, amounts up to 500 ppm may be present. The greenstones and diabase contain 10-100 ppm zinc on the average, but some samples may be higher. Most of the zinc occurs in magnetite and ilmenite and in various sulphides; some is present in the dark silicates and in chlorite. In the quartz-feldspar porphyries most of the zinc is present in the sulphides and oxides, and some occurs in the silicates. The same is true for the other granitic rocks. The sediments are relatively high in zinc, especially those containing much black carbonaceous matter and syngenetic sulphides. The zinc occurs in the iron oxides, sulphides, and also in biotite and muscovite. In the tuffs most of the zinc is bound in iron oxides and in the syngenetic sulphides.

The *lead* content of all rocks is low, rarely exceeding 30 ppm. The sediments, granitic rocks, and pegmatites contain slightly higher amounts than the greenstones and diabase. In the sediments and greenstones much lead is present in scattered sulphides. This is obviously because lead is a chalcophile element and tends to be enriched in the sulphide phases. In the granitic rocks and pegmatites most of the lead is present in potash feldspar and mica because of the similarity of the ionic radii of potassium and lead, Pb^{2+} (1.20Å), K^{+} (1.33Å). In all rocks a certain small percentage of lead is present in zircons and other radioactive minerals. This lead results from the decay of the uranium, actinium, and thorium families.

The highest contents of *arsenic* and *antimony* are present in the quartz-feldspar porphyry, tuffs, and sediments. The greenstones contain an average of 3 ppm As and the granitic rocks about 2 ppm.

In nearly all rocks at Yellowknife the arsenic and antimony are concentrated in pyrite and pyrrhotite. Very minor amounts are also present in the silicates, iron oxides, and in apatite.

Molybdenum, tin, and tungsten are all very low in amount in the normal rock types but show an enrichment in some tuffs, porphyries, and pegmatites. In the porphyries, molybdenum is sufficiently concentrated in some bodies to form the mineral molybdenite (MoS_2). In the pegmatites, cassiterite and scheelite may occur as a few scattered crystals. In the country rocks the three elements are bound principally in the sulphides and iron-titanium oxides, but small amounts occur in the amphiboles, pyroxenes, feldspars, tourmaline, and the micas. Tin is especially concentrated in the micas of pegmatites and is also enriched in the micas of granitic rocks, porphyries, and sediments. In the sediments, certain skarn rocks are enriched in tungsten, sufficiently so in places that scheelite occurs in the mineral assemblage.

Gold and *silver* occur in small amounts in all rock types. Silver is relatively easy to estimate accurately by spectrographic methods, but gold is particularly difficult because the low concentration in the rocks is usually below the sensitivity limit. Both elements have been determined, however, by fire assay and the values confirmed where possible by spectrographic and other chemical methods.

In all rocks gold and silver are present mainly in pyrite, chalcopyrite, and pyrrhotite. Minor amounts may also occur in the dark silicates and in the iron and titanium oxides. Sulphides separated from the greenstones, tuffs, and sediments yield silver contents ranging from 1 to 10 ppm, and gold contents between 0.10 to 0.50 ppm.

In the various rock types, gold and silver are original constituents although there may have been some rearrangement of the two elements during metamorphic and granitization processes. Two of the rock types, quartz-feldspar porphyry and tuff, are enriched in gold and silver. The enrichment in the porphyry, a rock carrying abundant sulphur, would be expected because of the marked chalcophile nature of both gold and silver. The tuffs are sediments containing an abundance of sulphur and carbon, elements concentrated principally by biological processes.

During sedimentation it is probable that the sulphate of the sea water was reduced by bacteria forming hydrogen sulphide on the foul bottoms. This compound bound the various dissolved chalcophile elements such as silver, copper, lead, and gold into finely divided, perhaps colloidal, sulphides. Later, during diagenesis and metamorphism, these sulphides recrystallized to form pyrite, pyrrhotite, and chalcopyrite, which incorporated any minor amounts of gold and silver present in the general environment.

The geochemistry of *sulphur* and *chlorine* are discussed in detail in the next section and only the significant features will be considered here. In the rocks nearly all of the sulphur is bound in sulphides, but small amounts may be present in apatite and other minerals as the sulphate radical. The basic rocks and sediments contain the bulk of the sulphur, and the granitic rocks are relatively low in the element. The tuffs, slates, and other graphitic sediments contain high amounts of sulphur as a result of biological activity. The porphyries are also enriched in sulphur which is a syngenetic element in these rocks and not introduced subsequently.

The chlorine content of the rocks is contained principally in apatite. Small amounts are also present in carbonates and in liquid inclusions where the element is held as sodium or potassium chloride.

Numerous other elements, in addition to those given in Table 15, can be detected in the various rock types. These include F, Sc, Ga, Ge, Se, Te, Ta, Tl, Cd, Bi, In, Th, and U. With the exception of fluorine and perhaps selenium and tellurium, the concentration of these minor elements is generally less than 5 ppm.

Two conclusions which seem significant from the viewpoint of ore genesis can be drawn from the work on the minor-element content of the rocks. The first is that the general wide distribution of the minor elements in all rock types points to a syngenetic origin for the elements. That is, they were incorporated in the rocks when they were formed and were not introduced subsequently. This point is perhaps not fully appreciated by economic geologists who often consider that metals such as copper and silver, and minerals such as the sulphides and carbonates, are epigenetic in origin and hence introduced into the rock.

The second conclusion is that the abundance of the various minor elements is related directly to the chemical processes operating at the time of formation of the various rock types. As an example we may note the case of the tuffs which have a high content of sulphur due to organic activity. During this activity various chalcophile elements such as copper, zinc, and silver were also concentrated principally as a result of the high sulphur potential.

Geochemistry of the Volatiles

A knowledge of the chemistry of the volatiles, particularly water, carbon dioxide, sulphur, 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 activating agents and catalysts. It was with both these concepts in mind that the chemistry of water, carbon dioxide, sulphur, boron, and chlorine was traced in detail in the metamorphic facies, shear zones, and gold deposits. The results of this study suggest that the volatiles were derived from the sedimentary and volcanic rocks and that their present distribution is due principally to diffusion processes.

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 analyzed to trace the migration of water, carbon dioxide, and sulphur.

Water, Carbon Dioxide, Sulphur, and Chlorine

In the rocks in their present state, most of the water is bound in amphiboles, chlorite, and the various 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. Sulphur is held principally in the sulphides with only small amounts in apatite and in the sulphates of liquid inclusions. Most of the chlorine is contained in apatite. Some is fixed in the carbonates, and small amounts occur as sodium or potassium chloride in liquid inclusions and along grain boundaries.

The original site, state, and content of the volatiles in the Yellowknife rocks can only be ascertained by analogy with similar unmetamorphosed rocks. From a knowledge of present-day lavas we can conclude that those at Yellowknife originally contained much water, carbon dioxide, sulphur, and chlorine in vesicles, and certainly some volatiles would be trapped in interstices when the lavas were crystallizing beneath the sea. The sediments, likewise, were probably highly saturated with water and would contain a certain amount of original sulphides, chlorides, etc. A further comment on the original content of volatile elements is given in the "Discussion" section, later in this chapter.

Table 16 (p. 92) records the contents of water, carbon dioxide, sulphur, and chlorine in the metamorphic facies, shear zones, and quartz lenses of the greenstone belt and sedimentary rocks. Figure 16 gives a generalized graphical representation of the content of volatiles in the metamorphic facies of the greenstone belt, and Figures 17, 18, and 19 show the variation in water, carbon dioxide, and sulphur along a traverse across the belt (line A, Figure 2, facing p. 6). Attention is called to the following features:

In the greenstone belt the contents of water and carbon dioxide along the traverse line increase toward the low-grade facies, i.e., outwards from the granodiorite. The composite analyses of the rocks in the three facies show a similar increase in the sulphur content, but this trend is not marked along the traverse line. Chlorine shows relatively little change. In the sedimentary area, water is the only volatile which 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.

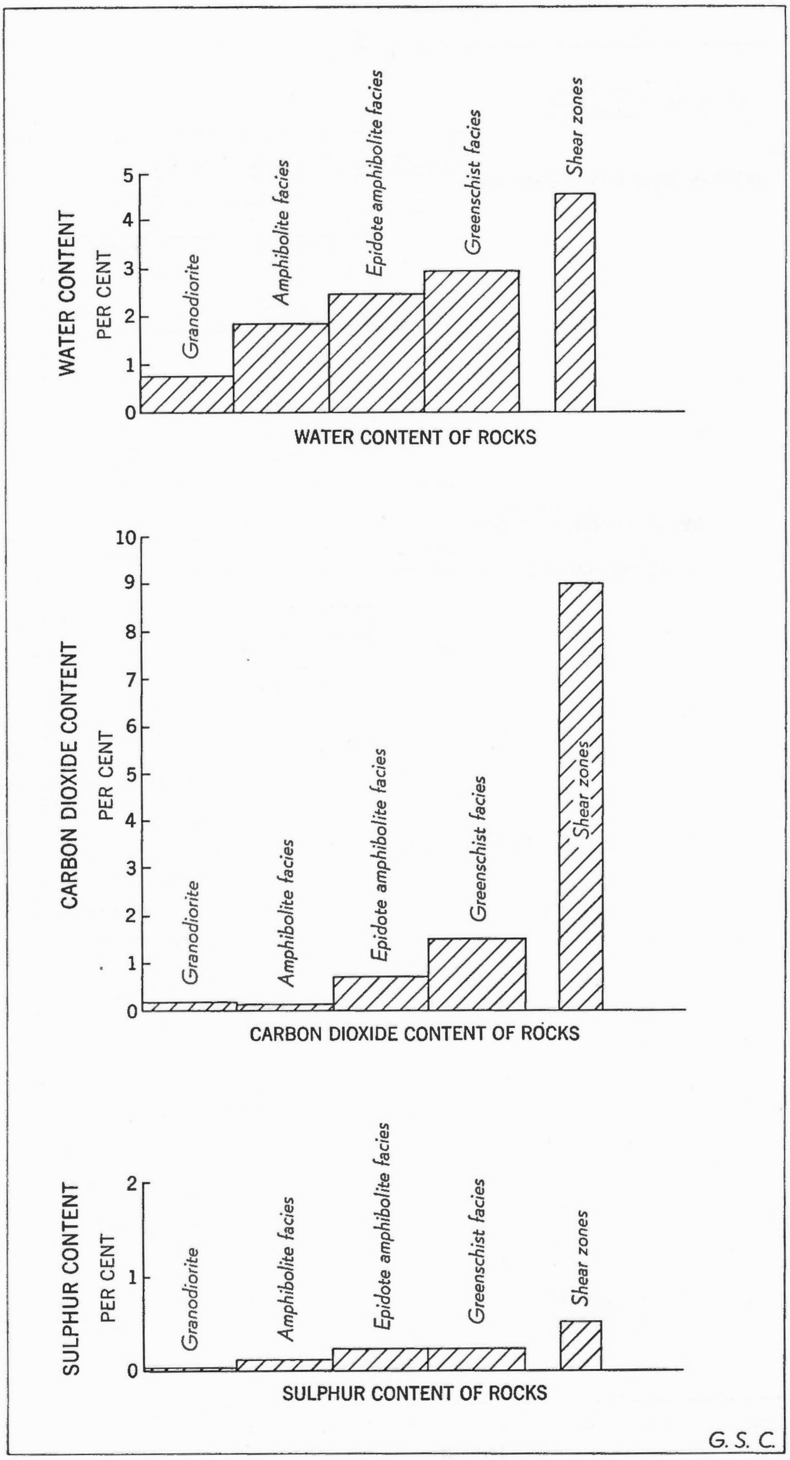

Figure 16. *Water, carbon dioxide, and sulphur content of granodiorite, metamorphic facies, and shear zones, Yellowknife greenstone belt.*

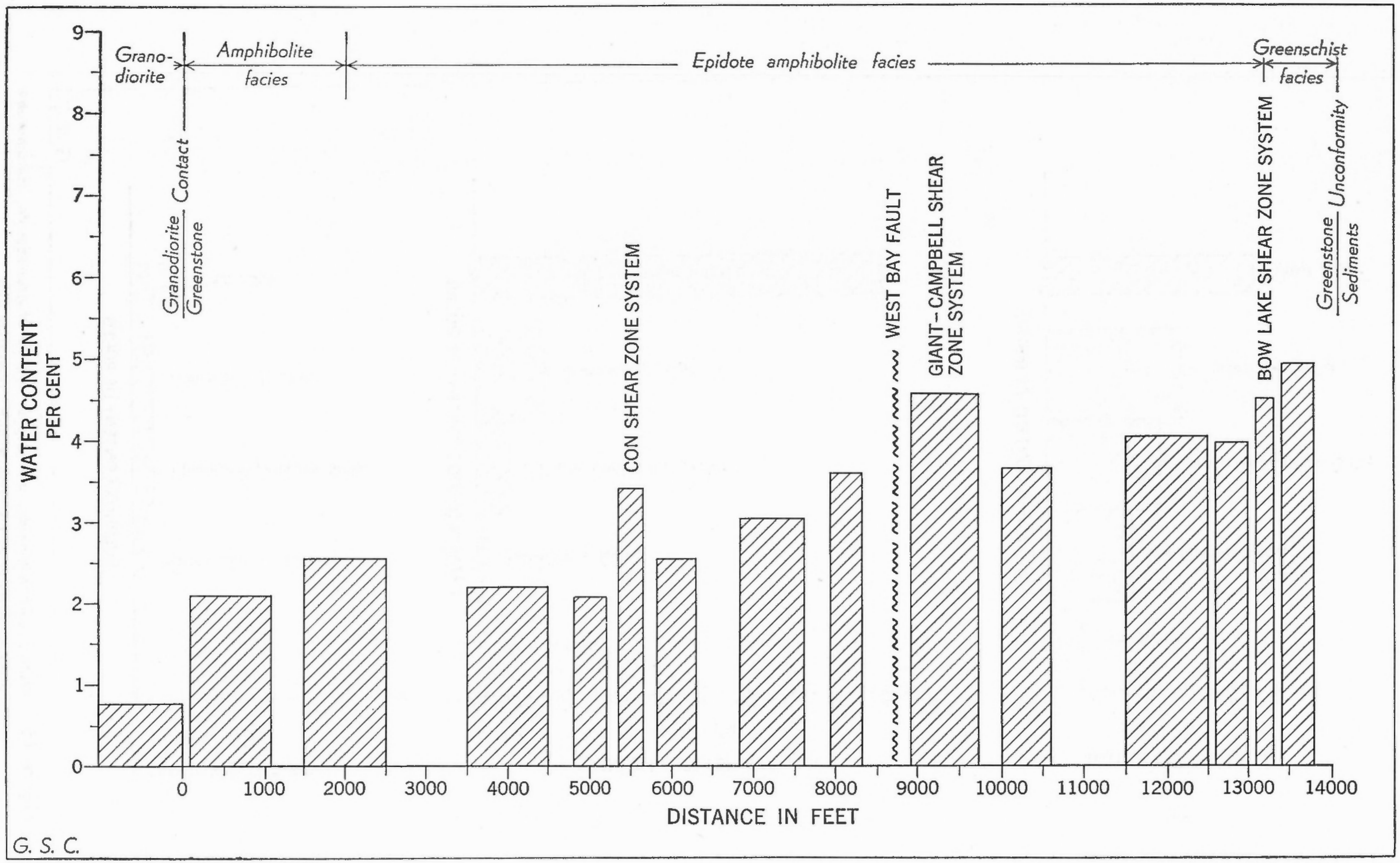

Figure 17. *Variation in total water content along line A (greenstone belt).*

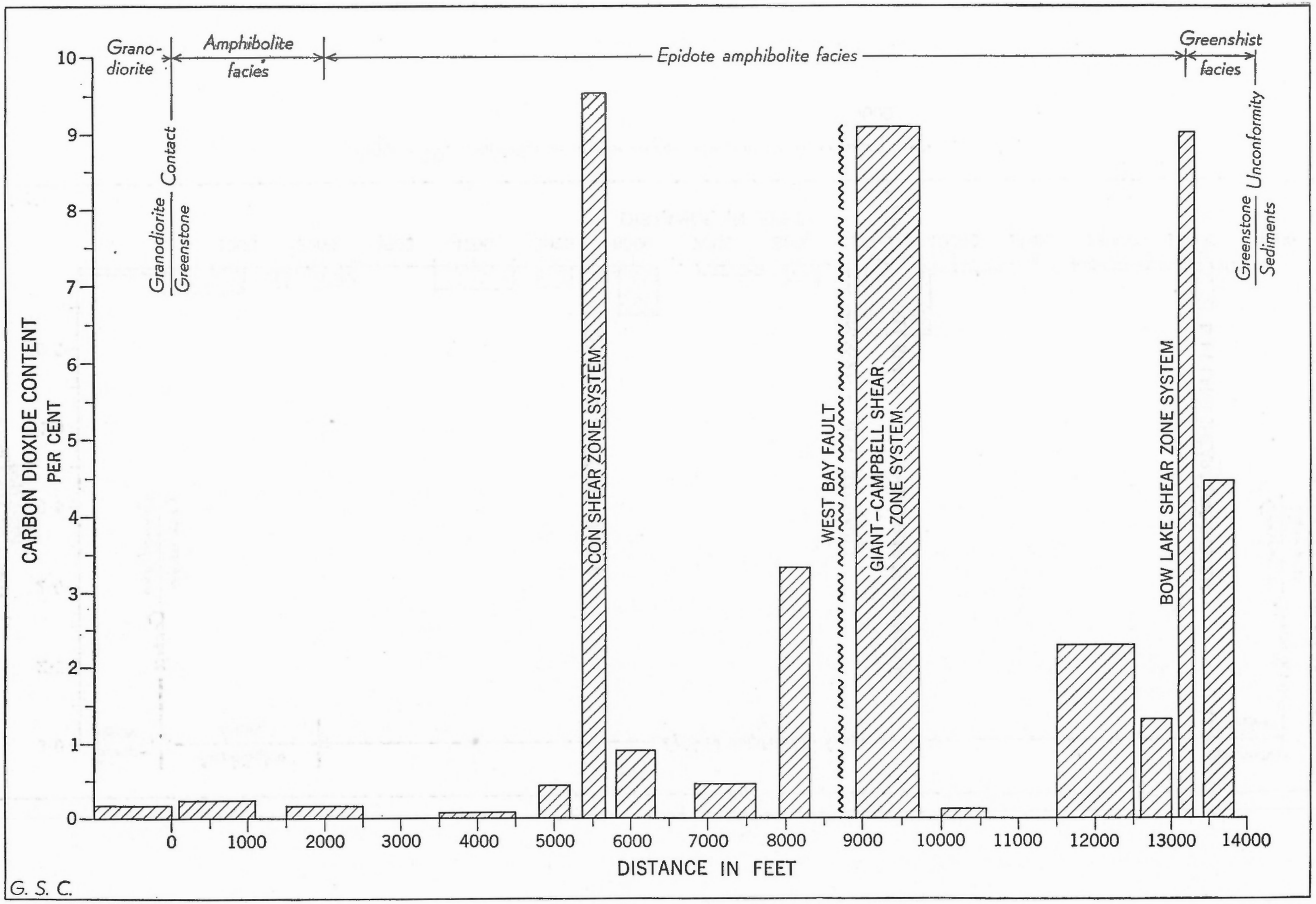

Figure 18. ***Variation in carbon-dioxide content along line A (greenstone belt).***

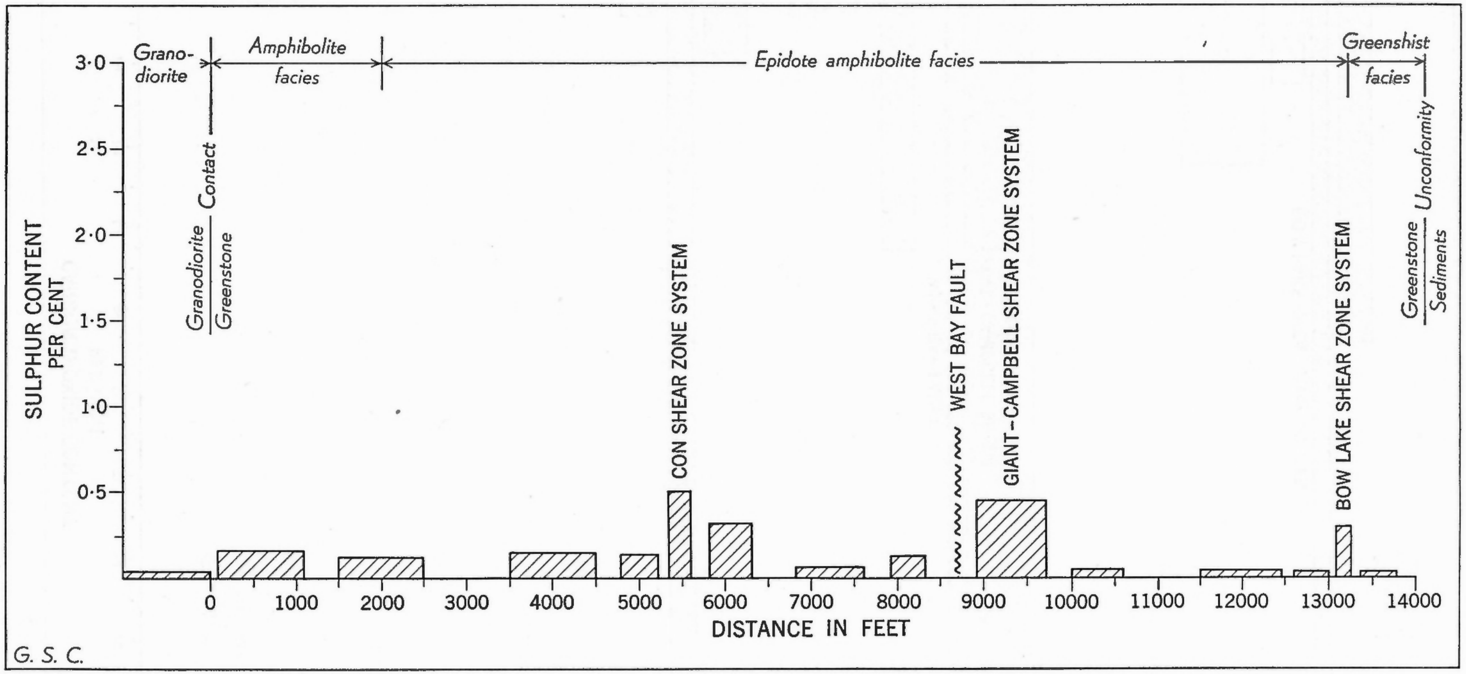

Figure 19. *Variation in sulphur content along line A (greenstone belt).*

The shear zones cutting the greenstones exhibit a marked enrichment in water, carbon dioxide, and sulphur but show a slight decrease in chlorine. The quartz-carbonate bodies in the shear zones are enriched in both carbon dioxide and water; their Cl content shows a slight increase compared with the schist of the shear zones. The pegmatites cutting the sediments show no enrichment in the volatiles nor are they surrounded by hydrous or carbonated zones. Likewise, in the sediments, the quartz veins and their alteration zones are not enriched in water or carbon dioxide, but locally they have higher-than-average amounts of sulphur.

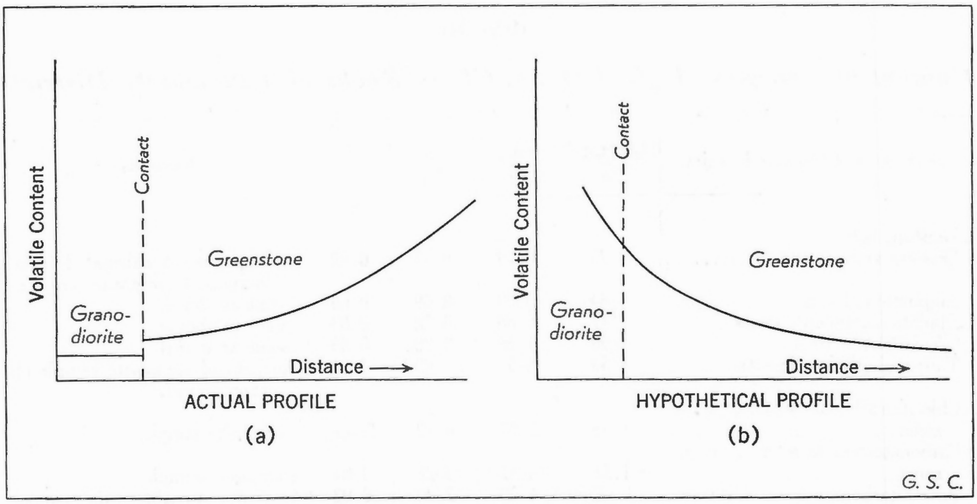

Figure 20. *Comparison of actual and hypothetical profiles of volatile contents of greenstone rocks.*

The profiles of water, carbon dioxide, and sulphur are instructive in determining the trend of migration of these compounds and their probable source. Ideally the profiles rise toward the lower-grade facies and simulate diffusion profiles (Figure 20a). 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 that shown in Figure 20b. That is, the concentration should be greatest in the rocks adjacent to the source and 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 note carefully certain phase relationships between the granitic rocks and the amphibolite facies of the greenstones. Muscovite and chlorite are stable in the last phases of the western granodiorite. These minerals are also stable in the greenschist facies and in the shear zones where the volatile content is high. From thermodynamic considerations it follows that if muscovite and chlorite were stable in the granodiorite during its final crystallization, they should also have been stable in the adjacent amphibolite facies, provided of course that 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 granitic rocks and added to the adjacent amphibolite zone. If the volatiles had migrated in quantity into the greenstone rocks adjacent to the granodiorite, extensive carbonated, sericitized, and chloritized zones would have been developed, and large concentrations of sulphides would be expected.

Table 16

Content of Volatiles (H_2O, CO_2, S, Cl) in Rocks of Yellowknife District

Description of Rock and Facies	H_2O (total) %	CO_2 %	S %	Cl %	Remarks
Greenstone belt					
Western granodiorite	0.75	0.14	0.03	0.02	Average values calculated from analyses of composite samples.
Amphibolite facies	1.84	0.09	0.09	0.03	(same as above)
Epidote amphibolite facies	2.47	0.68	0.20	0.03	(same as above)
Greenschist facies	3.00	1.28	0.20	0.03	(same as above)
Tuffs and other sediments	1.56	5.55	1.45	0.03	Analysis of composite sample of graphitic tuff.
Chlorite-carbonate schist in shear zones	5.33	8.03	0.12	Trace	Composite sample.
Carbonate-sericite schist in shear zones	1.26	15.57	3.26	0.01	Composite sample.
Quartz-carbonate lenses and veins	0.50	4.00	2.30	0.02	Contents variable; approximations only.
Sedimentary area					
Prosperous Lake granite	0.43	0.18	Trace	0.02	Average values calculated from analyses of composite samples.
Knotted quartz-mica schist and hornfels	2.38	0.12	0.13	0.04	(same as above)
Relatively unaltered slate, phyllite, greywacke, and argillite	3.35	0.07	0.12	0.015	(same as above)
Pegmatites	0.50	0.10	Trace	Trace	(same as above)
Quartz veins	0.50	0.10	0.50	0.02	Contents variable; approximations only.

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

To further strengthen the argument that the granitic rocks were not the source of the volatiles, one should note the field fact that subsequent phases of granitic bodies do not visibly affect previous consolidated phases. If the classical concept is correct, namely that with continuing crystallization successively greater concentrations of volatiles are produced, one would expect that the last phases would be especially rich in these components. In the granitic bodies at Yellowknife, no such concentration of volatiles occurs in the last phases nor are there any alteration zones containing marked concentrations of volatiles in the adjacent earlier phases which they cut.

In the sedimentary rocks similar features are present. There are no hydrated, carbonated, or sulphurized 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 approximately 1 per cent of their water when compared with the average water content of a normal series of shale, argillite, and greywacke.*

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 17. The following points are evident.

The sedimentary rocks contain much higher contents of boron than the basic volcanic and dyke rocks. In this respect they are in sympathetic agreement with the geochemical averages of unmetamorphosed rocks, and one can conclude, therefore, that the differences were inherited during the formation of the rocks, and are not the result of additions from magmatic solutions. Similar conclusions were reached by Goldschmidt and Peters (1932) as a result of their research on boron

Table 17

Boron Content of the Rocks of Yellowknife District Compared with Geochemical Averages of Similar 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		
Epidote amphibolite facies	<10		
Greenschist facies	<10	Basalts and gabbros	1.6-3
Meta-diorite and gabbro dykes	<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, greywacke, slate, etc.	50–100	Quartzites	9-31
Miscellaneous			
Quartz-feldspar porphyry	20–60		
Diabase dykes	<10	Basalts and gabbros	1.6-3

[1] Analyses by Spectrographic Laboratory, Geological Survey of Canada.

[2] Data from Rankama, K. and Sahama, Th. G.: Geochemistry; University of Chicago Press, 1949.

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* The average water content of a normal sedimentary series of shale, argillite, and greywacke, as compiled from various sources, lies close to 3.5%. Daly (Igneous Rocks and Depths of the Earth, McGraw-Hill, New York, 1933, p. 478) gives 1.64% H_2O as an average for sandstones and 5.02% H_2O for shales.

in rocks. It should also be noted that there is no major enrichment of boron in the high-grade metamorphic facies of either the greenstone belt or sedimentary area, a feature which further indicates that the granites were not the source of the boron.

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 the element. Similarly the pegmatites in the Prosperous Lake granite (average boron content, 170 ppm) carry significant concentrations of boron held in tourmaline, whereas those present in 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 the 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 the observed 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, pegmatites, etc., 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 before metamorphic reconstitution they would contain one-half per cent of water (average for basalts). Sulphur, carbon dioxide, and chlorine would likewise be present. Many of the greenstones are amygdular indicating a considerable volcanic gas content (H_2O, HCl, CO_2, H_2S, SO_2, etc.). The boron content would be low judging from the known geochemical averages of basic rocks. Furthermore, 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 water together with the other volatiles in the sea water. 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 we may note that normal shales, argillites, etc., contain an abundance of water held both interstitially and in hydrous minerals. Sulphur, carbon dioxide, and chlorine are also normal original constituents of sediments and are often present in considerable concentrations. Boron would be initially present in the tourmaline of the resistates and also as adsorbed ions.

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 which enable one to map the metamorphic facies. While only the horizontal plane has been investigated in this study it can be inferred that similar equilibrium adjustments have also taken place in the vertical plane.

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 metamorphism of the Yellowknife rocks took place, 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 the volatiles 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 of many constituents. This thesis will be further amplified in the chapters to follow.

Summary

The geological and geochemical investigation of the country rocks, pegmatites, and porphyries at Yellowknife can be summarized briefly as follows:

1. The majority of the rocks in the Yellowknife greenstone belt were probably originally basalts, poured out under the sea. Some flows were andesitic and others had a dacitic composition. All have undergone regional metamorphism with relatively little change in their major components. Their water, carbon-dioxide, and sulphur contents increase toward the lower-grade facies, i.e., outwards from the granodiorite. There is no apparent change in the chlorine content.

2. The tuffs are interbedded with the greenstones and represent a pause in the outpouring of lavas when sedimentary conditions prevailed. Most of the matrix material of the tuffs was probably volcanic ash, dust, and comminuted mineral fragments. The high contents of sulphur, carbon, silica, and carbonates in these rocks is probably due to biogenic processes operating at the time of their formation.

3. The greenstone rocks contain numerous meta-gabbro and meta-diorite sills and are cut by dykes of similar composition. The origin of these bodies is uncertain, but they may represent basic material expelled during granitization of sediments and greenstones.

4. The Yellowknife sediments were originally shales, argillites, greywackes, and conglomerates. These have been regionally metamorphosed with relatively little change in their major components. Of the volatiles only water shows an increase outward from the granites.

5. Many problems exist in ascertaining the origin of the granitic bodies. Both intrusive and granitization features are present, but no definite basic front appears to exist in either the greenstone belt or Yellowknife sediments. The western granitic body is thought to have originated by granitization of a great mass of sedimentary strata that once lay stratigraphically below the greenstones. The Prosperous Lake granite is thought to have originated by the granitization of large parts of the Yellowknife sediments.

6. Pegmatites are abundant in the Prosperous Lake granite and in the high-grade metamorphic aureole surrounding it. They are thought to have been derived by diffusion of their constituent components from the high-grade facies of the Yellowknife sediments and from the Prosperous Lake granite after this body was completely crystallized and solid. Pegmatites are rare or absent in the greenstone belt and western granitic body.

7. Quartz-feldspar porphyry dykes are restricted mainly to the greenstone belt. These dykes are thought to represent concentrations of various constituents mobilized during granitization at depth. The porphyries were completely crystallized solid bodies before the orebodies were formed and hence could not have given rise to mineralizing solutions.

8. Most of the late diabase dykes and sills have a gabbroic composition and originated by crystallization from basic magmas.

9. The geochemistry of a suite of minor elements in the Yellowknife rocks has been discussed in detail. The country rocks contain all the elements present in the orebodies.

10. The geochemistry of water, carbon dioxide, sulphur, chlorine, and boron has been discussed. It is suggested that these components were original constituents of the country rocks and that their present distribution is due to processes of regional metamorphism and metamorphic differentiation. It is doubtful if any of the volatiles were introduced from the granitic bodies by hydrothermal solutions.

Chapter VI

ALTERATION OF MINERALIZED SHEAR ZONES, FAULTS, AND FRACTURES

The first part of this chapter describes the alteration zones in mineralized shear zones, faults, and fractures. The second part is devoted to an interpretation of the features present in the alteration zones and to a discussion of the geochemistry of the alteration processes. This part of the chapter is particularly important in understanding the numerous mineral transformations and the factors promoting the mobility, migration, concentration, and dispersion of many elements.

Alteration Zones in Structures Cutting the Greenstones, Quartz-feldspar Porphyries, and Western Granodiorite

Early Quartz Lenses Cut by Shear Zones

In the western granodiorite the quartz lenses in early fractures abut the fresh rock and no alteration zones, with the exception of a slight sericitization of the plagioclase, are observable either in hand specimens or thin sections.

In the greenstones the alteration zones adjacent to the early quartz lenses are nowhere marked. All quartz lenses have knife-sharp contacts with their narrow alteration zones or unaltered wall-rocks (Plate VI, facing p. 12). Some quartz lenses in the amphibolite facies lack alteration zones, and the quartz abuts the amphibolite rock; others have an alteration zone limited to a few tenths of an inch wide. In this zone, salmon-coloured albite containing shreds of sericite, chloritized amphibole, and wisps of chlorite occur. Other minor constituents are epidote, apatite, leucoxene, ilmenite, and carbonates.

The early quartz lenses in the epidote amphibolite facies have alteration zones similar to those described above in the amphibolite facies. In most lenses, chloritized amphibole, chlorite, and some albite are developed in a narrow zone at their contacts.

Shear Zones

A few narrow shear zones cut the western granodiorite. Some of these contain small quartz lenses and veins with a few scattered pyrite crystals. The alteration zones enveloping the quartz lenses are insignificant and are only a few inches in width. They are composed of crushed quartz and sericitized plagioclase in a matrix of sericite and chlorite containing a few epidote, sphene, and pyrite crystals and some irregular patches of leucoxene. Carbonates are generally absent.

Some shear zones of the Handle Lake, Stock Lake, and Crestaurum systems cut granite dykes, stocks, and granitized rocks along their length. The granites, where cut by the shear zones, have been altered to a quartz-sericite schist containing a few quartz veinlets. The quartz-sericite schist in thin sections is composed of a foliated mass of sericite with oriented rutile inclusions, quartz grains, altered plagioclase, epidote, pyrite, sphene, and a few small patches of carbonate. In hand specimens the schist has a waxy yellow colour and is mottled by clear quartz grains and albite patches. In some localities it is cut by salmon-pink albite veinlets.

Quartz-feldspar porphyry dykes, containing quartz, sericitized plagioclase, chloritized biotite, muscovite, pyrite, pyrrhotite, apatite, leucoxene, epidote, and small amounts of carbonate, are cut in several places by the shear zones of the Negus-Rycon system. Where quartz veins are present in the shear zones, an alteration zoning outward from them is common. The outer halo, commonly only a few inches wide, contains quartz, sericitized and carbonatized feldspar, sericite, bleached biotite, and pyrite. Towards the quartz veins, this halo grades imperceptibly into a narrow inner zone where all original minerals, with the exception of quartz, are obliterated. The resulting rock is waxy yellow in colour and consists of a foliated mass of sericite containing oriented rutile inclusions, quartz, pyrite, chlorite, and small amounts of carbonates and apatite.

Similar quartz-feldspar porphyry dykes and irregular bodies are cut by shear zones of the Giant-Campbell system north of Vee Lake. Within the confines of the shear zones the altered porphyries contain essentially sericite, quartz, albite, carbonate, chlorite, and pyrite.

Most shear zones in the amphibolite facies of the greenstone belt contain quartz lenses and stringers which are flanked by characteristic alteration zones. The shear zones of the Handle Lake and Stock Lake systems exhibit alteration features which are typical for the amphibolite facies. The wall-rocks are predominantly amphibolites, containing hornblende, oligoclase-andesine, quartz, magnetite, sphene, ilmenite, and small amounts of epidote, pyrite, and pyrrhotite. These minerals are destroyed in the shear zones, and a weakly schistose aggregate of chlorite, albite, sericite, and leucoxene are present. Adjacent to quartz lenses, the chlorite schist of the shear zones grades imperceptibly into a chlorite-albite-sericite schist containing quartz, leucoxene and/or sphene, and small amounts of calcite. Pyrite, pyrrhotite, and arsenopyrite are present and may make up one-half per cent of the schistose rock. The shear zones are rarely more than 3 feet wide, and the alteration zones adjacent to quartz lenses are a foot or so wide.

The rocks of the epidote amphibolite and greenschist facies are cut by the shear zones of the four ore-bearing systems. There is relatively little difference in the internal arrangement of the alteration haloes in these four systems, and the following description applies to all shear zones in these two facies.

In most of the shear zones of the Giant-Campbell, Con, Negus-Rycon, and Crestaurum systems the six alteration phases listed in Table 18 can be recognized. The widths of the phases vary extensively throughout the systems; in some places all six phases may be compressed into a zone a few inches in width; in other places individual phases may be tens and even hundreds of feet wide. All phases are not necessarily present within a shear zone. All shear zones are marked by a development of phases 1 and 2 and locally by a mild development of phase 3. Where orebodies and mineralized zones are present, all phases are generally present, but some orebodies lack an adjacent pronounced sericite-carbonate phase.

The location of the more intensely altered phases (3 to 6) of the shear zones is controlled in most places by the same structural features that have localized the quartz veins and lenses, namely, shear-zone junctures and flexures and dragged parts of schist zones.

Table 18

Phases of Alteration in the Shear Zones of the Giant-Campbell, Con, Negus-Rycon, and Crestaurum Systems

Phase	Minerals Present (in order of relative abundance)	Remarks
Country rock	Fibrous amphibole, oligoclase, epidote, quartz, magnetite, leucoxene, sphene, chlorite, carbonates, pyrite, pyrrhotite, apatite, minor reticulating epidote-carbonate veinlets.	Massive to slightly schistose greenstone country rock.
1.	Chlorite, fibrous amphibole, oligoclase, epidote, quartz, magnetite, ilmenite, leucoxene, sphene, carbonates, pyrite, pyrrhotite, apatite, reticulating epidote-carbonate veinlets, hematite on slips in some places.	Wall-rock adjacent to shear zones; rock is weakly schistose.
2.	Chlorite, albite, ankerite, quartz, leucoxene, pyrite, small amounts of fibrous amphibole, apatite and epidote in some places, pyrrhotite locally, rare reticulating epidote-carbonate veinlets.	Shear zone; chlorite schist; marked foliation.
3.	Chlorite, ankerite, albite, quartz, leucoxene, pyrite, colourless to faintly greenish mica, rare occurrences of tourmaline, apatite, and pyrrhotite.	Shear zone; chlorite-carbonate schist; strong foliation.
4.	Ankerite, chlorite, sericite, quartz, albite, leucoxene, pyrite, arsenopyrite, rare occurrences of tourmaline and apatite.	Shear zone; carbonate-chlorite-sericite schist; strong foliation.
5.	Ankerite, sericite, quartz, chlorite, pyrite, arsenopyrite, rutile needles, rare occurrences of tourmaline and apatite.	Shear zone; carbonate-sericite schist; strong foliation.
6.	Quartz, sericite, ankerite, pyrite, arsenopyrite, sulphosalts, gold, sphalerite, etc., rutile needles, rare occurrences of tourmaline.	Mineralized zones; orebodies in some cases.
Quartz bodies	Quartz, arsenopyrite, pyrite, sulphosalts, sericite, ankerite, gold, rare occurrences of tourmaline and apatite, scheelite in some quartz lenses.	Quartz lenses and veins; orebodies.

The country rocks are predominantly epidote amphibolites, but some shear zones of the Giant-Campbell system intersect dacites along part of their length. The amphibolites contain fibrous amphibole (probably actinolite), albite-oligoclase, epidote, quartz, magnetite, ilmenite, leucoxene, chlorite, carbonate, pyrite, and pyrrhotite in that order of abundance. These minerals are highly intergrown with one another, and the rock has a poorly developed schistose texture in thin sections. In hand specimens the rock is massive and breaks with a blocky-to-irregular fracture. The dacites contain phenocrysts of plagioclase (albite-oligoclase) and quartz in a fine-grained matrix of plagioclase, quartz, amphibole, chlorite, biotite, carbonate, sericite, epidote, apatite, magnetite, and pyrite, in that order of abundance. The fresh dacite has a granulitic texture in thin sections and is massive in hand specimens.

Phase 1 marks a transition between the epidote amphibolite country rock and the shear zones, and only a slight schistosity has been impressed on the rocks. The main feature of this phase is the occurrence of reticulating pinkish buff and pistachio-green epidote-carbonate veinlets. In most occurrences these veinlets contain a dense intergrowth of epidote, calcite or ankerite, quartz, albite, tremolite, leucoxene, chlorite, hematite and pyrite. In other occurrences quartz-carbonate stringers form a central core flanked by a narrow epidote-carbonate alteration zone containing the minerals listed above. Seams and joints coated with hematite occur in this phase in many places especially in the shear zones of the Giant system.

Phase 2 constitutes the chlorite schist phase of the shear zones. The rock is dark green in colour and is highly foliated both in hand specimens and thin sections. Constituent minerals include, in order of abundance, green chlorite, albite, ankerite, quartz, leucoxene, pyrite, and epidote. In some places a few small reticulating carbonate-epidote veinlets are present. The albite and quartz commonly occur in small elongated lenses and in bands in the highly foliated chlorite masses. The leucoxene occurs as small buff to white, optically opaque masses with a linear arrangement along the foliated chlorite masses. Narrow quartz and carbonate veinlets cut across the schistosity in most specimens.

Phase 2 grades imperceptibly by increase in ankerite into the chlorite-carbonate schist of phase 3. In thin sections the gradation is marked by a bleaching of part of the chlorite to give a colourless to faintly greenish mica having low first order interference-colours and containing small leucoxene knots. The leucoxene is clearer than in the chlorite schist and in some thin sections small diffuse crystals of rutile can be discerned in the irregular leucoxene masses. Albite, quartz, and pyrite are generally present, and in a few localities apatite and small amounts of tourmaline may occur. In thin sections the rock shows a banded structure. Some bands contain green chlorite, light green mica, and albite. Locally ankerite occurs in small crenulations and seams which cut the bands. Quartz is commonly present in augen-like masses around pyrite crystals or in seams and veinlets parallel to or transecting the bands of other minerals. The rock is green to greenish buff in colour and is strongly foliated in hand specimens and thin sections.

In the vicinity of quartz lenses and mineralized zones the chlorite-carbonate schist phase grades by increase of ankerite, sericite, and quartz, into the carbonate-chlorite-sericite schist of phase 4. This phase in turn grades by increase in sericite, carbonate, and quartz, and decrease in chlorite, into the carbonate-sericite schist of phase 5. This latter phase grades into either mineralized zones (phase 6) or quartz veins and lenses by increase in quartz and sulphides.

The macroscopic and microscopic features of phases 4, 5, and 6 are nearly the same in all occurrences. The rock is grey to buff in colour and highly foliated in hand specimens and thin sections. Mashing and extreme contortion of the schist occurs in most shear zones, especially in those of the Giant-Campbell system. The rock contains variable amounts of ankerite, sericite, chlorite, quartz, pyrite, arsenopyrite, and leucoxene depending upon the phase in which it occurs. In phases 4 and 5 the minerals occur in bands in some localities; in others, especially in parts of the Negus-Rycon system, all minerals occur as a dense intergrowth. Toward the mineralized zones and quartz bodies there is a definite increase in pyrite and arsenopyrite. These two minerals occur principally in sericite bands, but some are scattered throughout the general groundmass. Trains of leucoxene masses, in which rutile needles are readily distinguished, occur along all the sericite bands. The leucoxene is a marked feature of these phases of alteration and gives the rock its distinctive buff colour. Small quartz and carbonate veinlets intersect the highly altered phases throughout their extent.

The alteration phases described above are general in the Giant-Campbell, Con, Crestaurum, and some of the shear zones of the Negus-Rycon systems. In a few shear zones of the latter system and in the Shaft zone of the Con system, however, there are a few differences, mainly in the textures of the zones. In these shear zones alteration phases 3 to 6, are compressed into a zone rarely more than a foot wide. This composite zone consists of a dense intergrowth of microcrystalline ankerite, bleached chlorite, quartz, albite, sericite, chlorite, trains and disseminated masses of leucoxene, and abundant pyrite and arsenopyrite. The rock of this zone is only slightly foliated and appears as a narrow buff- to grey-coloured dyke-like zone (Plate VII, facing p. 12) adjacent to the quartz lenses. The transition to the chlorite schist phase, which also shows only a limited degree of foliation, is sharp. In many places there is a zoning of the sulphides outward from the quartz. Arsenopyrite occurs adjacent to the quartz veins, pyrite farther out but within the highly altered phase, and pyrrhotite in the chlorite schist phase. In all occurrences small quartz-carbonate and albite-quartz veinlets ramify through the highly altered phase.

Where the shear zones of the Giant-Campbell system cut dacite, extensive widths of chlorite-carbonate-sericite schist and carbonate-sericite schist are formed. The minerals present in the alteration zones are chlorite, ankerite, quartz, albite, sericite, leucoxene, pyrite, pyrrhotite, and arsenopyrite.

Quartz-carbonate Lenses and Stringers that Cut the Shear Zones and Gold-bearing Quartz Lenses

These quartz-carbonate lenses and stringers occur in all parts of the shear zones, but are concentrated principally in the highly altered, and mineralized parts.

In most occurrences the quartz-carbonate stringers abut the rock in which they occur without any observable alteration zone (Plates XV and XVI, facing pp. 44 and 45). In a few places the stringers are flanked by a zone a few tenths of an inch wide consisting of sericite schist containing leucoxene.

Post-diabase Faults and Fractures

Along most of their length the post-diabase faults consist of zones of brecciated and comminuted rock fragments, rarely more than a few feet wide. Locally, the faults contain irregular lenses of quartz exhibiting both massive and comb features, and a 'giant quartz vein' occurs at the junction of the West Bay and Akaitcho faults. Small amounts of chalcopyrite and pyrite occur in the fault zones, generally in the quartz lenses or adjacent wall-rock. Hematite is widespread and occurs in the fault breccia, quartz lenses, and in seams and joint planes in the wall-rocks of the faults.

Where the faults cut greenstones the fragments constituting the fault breccia have been mildly altered to non-foliated masses of chlorite, epidote, albite, amphibole, and leucoxene; in granitic rocks the breccia fragments are altered to masses of quartz, albite-oligoclase, sericite, and chlorite. The fragments in some places are cemented by carbonate, in others by albite. Albite, prehnite, and epidote veinlets are abundant in the walls of most faults, and hematite accompanied by albite and quartz occurs in vuggy parts of the breccia and in seams, fractures, and veinlets in the fault zone and adjacent wall-rock.

In the fault zones bordered by greenstones, an irregular alteration zone is present around quartz lenses. In the outer part of this zone the original breccia fragments retain their outlines in detail but have been highly altered to an intergrown mass of oligoclase or albite, chlorite, quartz, leucoxene, and small amounts of carbonate. Massive quartz cements the fragments in places, and cockade structures of comb quartz surrounding the fragments are abundant. Inward, the fragments are obliterated, and there is an imperceptible gradation into relatively pure quartz lenses composed of much intergrown comb quartz with some massive quartz containing wisps and shreds of chlorite and leucoxene.

The alteration zone bordering the 'giant quartz vein' at the junction of the West Bay and Akaitcho faults is a hundred feet or more in width in the granite. The outer part of the zone is marked by veinlets and seams of quartz and albite containing hematite. This part grades into an inner part which consists of highly altered fragments of granite containing fine-grained albite-oligoclase, shreds of chlorite, leucoxene, quartz, altered biotite, hematite, colourless mica, and an amorphous unidentified brown material, probably limonite. The fragments are cemented by both massive and comb quartz containing hematite. The inner zone grades imperceptibly into the 'giant quartz vein' which contains numerous ghost fragments of breccia consisting of microcrystalline quartz and albite with small amounts of leucoxene and chlorite. In some places a red or a black jasper rock containing highly replaced fragments of granite impregnated with hematite is present. Both the irregular silicified ghost fragments and the jasper are cemented and seamed by massive and comb quartz containing hematite.

Many late fractures contain finely ground rock which has been leached of some of its components. Others contain earthy calcite along the fractures and slips, and in open spaces, scalenohedra of calcite and cubes of pyrite are present. In two cases prehnite has been identified, one in fractures cutting the Con diabase dyke, and the other in fractures associated with the Negus fault. In another fracture cutting the Con diabase dyke, asbestiform amphibole, chlorite, calcite, and small amounts of axinite were observed as alteration minerals.

Wall-rock Alteration Zones in Sedimentary Rocks and Prosperous Lake Granite

Pre-diabase Faults and Fractures in Relatively Unaltered Sediments

The rocks cut by these faults and fractures are greywacke, argillite, slate, arkose, and conglomerate; their constituent minerals include in order of abundance, oligoclase or andesite, quartz, sericite, biotite, chlorite, pyrite, pyrrhotite, ilmenite, and minor amounts of carbonate, carbon, and tourmaline.

Most quartz veins and lenses in the relatively unaltered sediments lack a bordering alteration zone or have a weakly developed one. Thin sections of the weakly altered zones reveal the development of some albite, chlorite, and shreds of sericite in the original feldspars. In most places, however, the quartz lenses abut a thin selvedge of chloritic schist or unaltered sedimentary rock in which the original clastic nature is preserved.

The alteration zones at the Burwash prospect are typical of a few gold-quartz lenses in the relatively unaltered sediments. At this prospect the quartz lenses occur in small faults or fractures. They are rarely more than a foot wide and their alteration zones rarely exceed 6 inches in width. On weathered surfaces these zones present a bleached, peach-coloured, dyke-like zone. The minerals present in the altered zones include quartz, albite, altered biotite, chlorite, sericite, pyrite, arsenopyrite, leucoxene, pyrrhotite, rutile needles, apatite, carbonaceous matter, and carbonates, in that order of abundance. In some thin sections these minerals exhibit a marked foliation, in others the clastic texture of the original rock is preserved. Both the alteration zones and adjacent wall-rocks are seamed by veinlets of quartz and albite.

Pre-diabase Faults and Fractures in Knotted Quartz-mica Schists

The rocks in this zone of metamorphism include nodular quartz-mica schist, hornfels, and slate which contain oligoclase or andesine, quartz, biotite, pyrrhotite, ilmenite, graphite, garnet, andalusite, cordierite, sillimanite, staurolite, white mica, tourmaline, apatite, zircon, and rarely carbonate minerals.

The quartz veins and lenses, in these highly metamorphosed sediments, either have no alteration zones or narrow ones which are inconspicuous on both weathered and fresh surfaces. The alteration effects in the wall-rocks of the Ptarmigan veins appear to be typical.

The wall-rocks adjacent to the main Ptarmigan vein are knotted quartz-mica schists which possess a granular to moderately schistose texture and contain ovoid segregations of quartz, biotite, sericite and graphite. In most places the textures of the altered zones are similar to those of the country rock, but in a few places a strong schistosity is developed in the alteration zone adjacent to the quartz lenses.

The altered zones contain a foliated mass of quartz, albite-oligoclase, biotite, muscovite, chlorite, and some pyrrhotite, arsenopyrite, apatite, and graphite. Brown tourmaline, generally associated with biotite, occurs in some places in the alteration zones adjacent to the quartz lenses. Carbonate minerals are rare. Quartz and albite veinlets ramify throughout the alteration zones and adjacent country rock.

The highly metamorphosed sediments next to the Prosperous Lake granite contain many irregular quartz lenses bordered by a poorly developed alteration zone somewhat similar to that described for the Ptarmigan vein. Tourmaline is often present both in the veins and in the adjacent wall-rocks. Andalusite (in some places chiastolite) occurs in the narrow alteration zones of many of these lenses.

Numerous pegmatite dykes and irregular masses cut the knotted quartz-mica schists and the Prosperous Lake granite. In most places these dykes have no observable alteration zones; in others the development of brown tourmaline in the wall-rocks at the pegmatite contacts is a marked feature.

Post-diabase Faults and Fractures

The post-diabase faults that cut the Yellowknife sediments and Prosperous Lake granite are poorly exposed in most places, and only a few alteration zones have been observed. In outcrops of the faults the breccia is little altered except where quartz lenses occur. In these localities the granite and sedimentary rock is slightly sericitized, albite has formed, and chlorite and some carbonate minerals occur locally. In the Prosperous Lake granite the walls of the faults are impregnated with hematite near quartz stockworks. Tourmaline was not observed in any of the late faults or in the adjacent wall-rocks where they cut granite or sediments.

Geochemistry of the Alteration Zones and a Discussion of the Alteration Processes

Chemical analyses have been made of the typical alteration phases in the shear zones of the greenstone belt where they intersect epidote amphibolite and quartz-feldspar porphyry rocks. Similar analyses have been made on samples collected adjacent to a gold-bearing quartz vein in the relatively unaltered sedimentary rocks of the Yellowknife group.

Tables 19, 20, and 23 record the percentage of each constituent, the adjusted percentage after volume calculations, the gains and losses, and the percentage gains and losses for samples taken across well-defined alteration zones in two shear-zone systems of the greenstone belt. Table 24 records the same data for the alteration zones adjacent to the gold-bearing quartz veins at the Burwash prospect in the Yellowknife sediments. Table 21 shows the results of analyses of large composite samples from the two major phases of alteration in shear zones that cut greenstones. These samples were selected with great care from all shear zones investigated and probably give the best data on the general overall trend of the chemical changes.

Alteration Processes in the Greenstone Belt

The alteration zoning in the Con, Negus-Rycon, and Giant-Campbell systems was studied in detail by thin sections and chemical and spectrographic analyses. The alteration features of these systems, while slightly different in a few respects from those of other systems, are typical and illustrate the trend in all shear zones cutting the greenstones.

For purposes of discussion the various phases given in Table 18 may be grouped into three general phases—the country rock (greenstone), chlorite and chlorite-carbonate schist phase, and the carbonate-sericite schist phase.

The microscope reveals that the amphibole of the country rock was altered first to chlorite and ankerite, and in the more intense phases the chlorite in turn was altered to sericite. The plagioclase may have lost calcium to form albite in the chlorite phase, but it has been generally obliterated in the sericite phase, and sericite and ankerite have formed at its expense. Epidote has been altered to chlorite or to carbonate depending upon the intensity of alteration. Ilmenite, magnetite, and sphene have been generally obliterated, and pyrite, arsenopyrite, rutile, and leucoxene have formed from some of the components of these minerals. Quartz and carbonate minerals have formed throughout the highly altered phases.

It has been shown in the foregoing chapter that the carbon dioxide, water, and sulphur were probably derived from the greenstone country rocks, and that these compounds diffused into the dilatant shear-zone systems. Here they reacted with the minerals present producing new minerals stable under the existing conditions. To maintain the equilibrium, various chemical exchanges, as shown by the profiles in Figures 21, 22, and 23, have taken place. For purposes of discussion let us examine the results as shown by the profiles drawn from the analyses of the composite samples (Figure 23). Local variations will be reflected in the profiles from the individual shear zones.

The profile for SiO_2 shows a marked decrease in the chlorite-carbonate and sericite schist phases of the shear zones compared with the greenstone. This decrease is attended by an increase in CO_2 in both phases, by H_2O in the chlorite-carbonate phase, and by S in the carbonate-sericite phase. This suggests that these gaseous components displaced and liberated SiO_2 to maintain the chemical equilibrium. The profiles from all shear zones show similar features and we may, therefore, conclude that as the volatiles were added to the system, silica was liberated and migrated away into dilatant zones to form the quartz veins and lenses. More will be said about this in the sections to follow and in the next chapter.

The content of Al_2O_3 in the composite samples shows a decrease in the chlorite-carbonate phase and an increase in the carbonate-sericite phase as compared with the greenstone. Similar features are shown by the profile of the Negus-Rycon system, but in the Campbell system the Al_2O_3 content of the carbonate-sericite phase is lower than both the greenstone and chlorite-carbonate phase. This anomaly can perhaps be explained by the degree of carbonatization. The Campbell system shows much higher percentage gains in CO_2 than the Negus-Rycon system and more carbonate has formed at the expense of the aluminous silicates. Hence, the greater migration of Al_2O_3 to maintain the chemical equilibrium.

Table 19

Chemical Changes Produced by Alteration of Greenstone, Negus-Rycon System

Constituent	YC-16[1] %	YC-17[2] %	Adjusted[4] %	Gains and Losses in Constituents	Percentage Gains and Losses	YC-16 %	YC-18[3] %	Adjusted[4] %	Gains and Losses in Constituents	Percentage Gains and Losses
SiO_2	49.18	45.40	43.54	−5.64	− 11.45	49.18	34.96	35.30	−13.88	− 28.20
Al_2O_3	10.59	7.35	7.05	−3.54	− 33.50	10.59	12.21	12.33	+ 1.74	+ 16.45
Fe_2O_3	7.20	3.56	3.41	−3.79	− 52.65	7.20	3.01	3.04	− 4.16	− 57.80
FeO	9.87	9.16	8.78	−1.09	− 11.05	9.87	8.93	9.02	− 0.85	− 8.60
CaO	11.01	10.99	10.54	−0.47	− 4.25	11.01	10.42	10.52	− 0.49	− 4.45
MgO	5.63	4.18	4.01	−1.62	− 28.80	5.63	4.40	4.44	− 1.19	− 21.16
Na_2O	1.16	0.50	0.48	−0.68	− 58.75	1.16	1.11	1.12	− 0.04	− 3.44
K_2O	0.24	1.02	0.98	+0.74	+308.00	0.24	2.48	2.50	+ 2.26	+941.00
H_2O^+	1.46	3.26	3.13	+1.67	+114.50	1.46	0.80	0.81	− 0.65	− 44.50
H_2O^-	0.07	0.14	0.13	—	—	0.07	0.31	0.31	—	—
TiO_2	0.84	1.05	1.01	+0.17	+ 20.20	0.84	1.79	1.81	+ 0.97	+115.75
P_2O_5	0.18	0.38	0.36	+0.18	+100.00	0.18	0.70	0.71	+ 0.53	+294.50
MnO	0.22	0.11	0.10	−0.12	− 55.50	0.22	0.08	0.08	− 0.14	− 63.60
CO_2	1.39	9.56	9.17	+7.78	+560.00	1.39	12.13	12.30	+10.91	+785.00
S	0.85	2.17	2.08	+1.23	+145.00	0.85	6.47	6.55	+ 5.70	+670.00

As_2O_3	trace	1.57	1.50	+1.50	—	trace	1.93	1.95	+ 1.95	—
Total	99.89	100.30	—	—	—	99.89	101.73	—	—	—
Specific Gravity	2.97	2.85	—	—	—	2.97	3.01	—	—	—

(All analyses by R. J. C. Fabry, Geological Survey of Canada)

[1] YC-16—Greenstone, chip sample across 80 feet, 11th level, Negus mine, Negus-Rycon system.

[2] YC-17—Chlorite and chlorite-carbonate schist, chip and channel sample across 2 feet, 11th level, Negus mine, Negus-Rycon system.

[3] YC-18—Carbonate-chlorite and carbonate-sericite schist, chip and channel sample across 1 foot, 11th level, Negus mine, Negus-Rycon system.

[4] Adjusted %=percentages of YC-17 and YC-18 multiplied by the factors 2.85/2.97 and 3.01/2.97 respectively, to reduce to a common volume.

Table 20

Chemical Changes Produced by Alteration of Greenstone, Campbell System

Constituent	YC-19[1] %	YC-20[2] %	Adjusted[4] %	Gains and Losses in Constituents	Percentage Gains and Losses	YC-19 %	YC-21[3] %	Adjusted[4] %	Gains and Losses in Constituents	Percentage Gains and Losses
SiO_2	51.53	43.91	40.92	−10.61	−20.59	51.53	49.29	49.29	−2.24	−4.35
Al_2O_3	16.31	14.72	13.71	− 2.60	−15.90	16.31	13.10	13.10	−3.21	−19.65
Fe_2O_3	0.94	0.30	0.28	− 0.66	−70.10	0.94	1.21	1.21	+0.27	+28.75
FeO	9.65	6.87	6.40	− 3.25	−33.70	9.65	5.67	5.67	−3.98	−41.25
CaO	8.59	9.43	8.78	+ 0.19	+ 2.22	8.59	7.99	7.99	−0.60	− 7.00
MgO	6.23	7.69	7.17	+ 0.94	+15.10	6.23	3.81	3.81	−2.42	−38.95
Na_2O	2.49	1.63	1.52	− 0.97	−38.90	2.49	0.33	0.33	−2.16	−86.60
K_2O	0.11	0.70	0.65	+ 0.54	+491.00	0.11	1.59	1.59	+1.48	+1,345.50
H_2O^+	2.11	3.55	3.31	+ 1.20	+56.80	2.11	1.45	1.45	−0.66	−31.30
H_2O^-	0.10	0.46	0.43	—	—	0.10	0.10	0.10	—	—
TiO_2	0.84	0.58	0.54	− 0.30	−35.75	0.84	0.26	0.26	−0.58	−69.00
P_2O_5	0.22	0.33	0.31	+ 0.09	+40.95	0.22	0.14	0.14	−0.07	−31.80
MnO	0.16	0.22	0.20	+ 0.04	+25.00	0.16	0.08	0.08	−0.08	−50.00
CO_2	0.55	9.60	8.95	+ 8.40	+1,529.00	0.55	10.48	10.48	+9.93	+1,800.00
S	0.28	0.43	0.40	+ 0.12	+42.80	0.28	3.67	3.67	+3.39	+1,210.00

As_2O_3..............	—	—	—	—	—	—	2.87	2.87	+2.87	—
Total............	100.11	100.42	—	—	—	100.11	102.04	—	—	—
Specific Gravity...	2.95	2.75	—	—	—	2.95	2.94	—	—	—

(All analyses by R. J. C. Fabry, Geological Survey of Canada)

[1] YC-19—Greenstone wall-rock, chip sample across 250 feet, 13th level, Negus mine, Campbell system.

[2] YC-20—Chlorite and chlorite-carbonate schist, chip sample across 70 feet, 13th level, Negus mine, Campbell system.

[3] YC-21—Carbonate-chlorite and carbonate-sericite schist, quartz stringers and small lenses. Chip and channel sample across 8 feet, 13th level, Negus mine, Campbell system.

[4] Adjusted % = percentages of YC-20 and YC-21 multiplied by the factors 2.75/2.95 and 2.94/2.95 respectively, to reduce to a common volume.

Table 21

Chemical Changes Produced by Alteration of Greenstone, Composite Samples of all Shear-zone Systems

Constituent	A-76[1] %	A-251[2] %	Adjusted[4] %	Gains and Losses in Constituents	Percentage Gains and Losses	A-76 %	A-250[3] %	Adjusted[4] %	Gains and Losses in Constituents	Percentage Gains and Losses
SiO_2	50.45	40.36	37.12	− 13.33	− 26.42	50.45	38.19	38.30	− 12.15	− 24.08
Al_2O_3	13.96	12.87	11.84	− 2.12	− 15.19	13.96	16.26	16.31	+ 2.35	+ 16.83
Fe_2O_3	2.00	1.06	0.97	− 1.03	− 51.50	2.00	0.38	0.38	− 1.62	− 81.00
FeO	9.61	12.00	11.04	+ 1.43	+ 14.88	9.61	3.49	3.50	− 6.11	− 63.58
CaO	10.23	8.94	8.22	− 2.01	− 19.65	10.23	11.02	11.05	+ 0.82	+ 8.02
MgO	6.53	8.43	7.75	+ 1.22	+ 18.68	6.53	5.77	5.79	− 0.74	− 11.33
Na_2O	1.85	0.90	0.83	− 1.02	− 55.14	1.85	0.29	0.29	− 1.56	− 84.32
K_2O	0.39	0.41	0.38	− 0.01	− 2.56	0.39	2.82	2.83	+ 2.44	+ 622.64
H_2O^+	2.36	5.20	4.78	+ 2.42	+102.54	2.36	1.16	1.16	− 1.20	− 50.85
H_2O^-	0.11	0.13	0.12	+ 0.01	+ 9.09	0.11	0.10	0.10	− 0.01	− 9.09
TiO_2	1.02	1.05	0.97	− 0.05	− 4.90	1.02	0.82	0.82	− 0.20	− 19.61
P_2O_5	0.13	0.11	0.10	− 0.03	− 23.08	0.13	0.21	0.21	+ 0.08	+ 61.54
MnO	0.21	0.22	0.20	− 0.01	− 4.76	0.21	0.17	0.17	− 0.04	− 19.05
CO_2	0.68	8.03	7.39	+ 6.71	+986.76	0.68	15.57	15.62	+14.94	+2,197.06
S	0.22	0.12	0.11	− 0.11	− 50.00	0.22	3.26	3.27	+ 3.05	+1,386.36
Cl	0.02	0.00	0.00	− 0.02	−100.00	0.02	0.01	0.01	− 0.01	− 50.00

Cr_2O_3	0.03	0.03	0.03	0.00	0.00	0.03	0.00	0.00	− 0.03	− 100.00
C	0.04	0.12	0.11	+ 0.07	+175.00	0.04	0.04	0.04	0.00	0.00
As_2O_3	—	trace	—	—	—	—	1.50	1.50	—	—
Total	99.84	99.98	—	—	—	99.84	101.06	—	—	—
Less O=S, Cl	0.10	0.05	—	—	—	0.10	1.22	—	—	—
Net Total	99.74	99.93	—	—	—	99.74	99.84	—	—	—
Specific Gravity	2.99	2.75	—	—	—	2.99	3.00	—	—	—
Analyst	J. A. Maxwell	S. Courville	—	—	—	J. A. Maxwell	S. Courville	—	—	—

[1] A-76 —Composite sample from 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%=percentage 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.

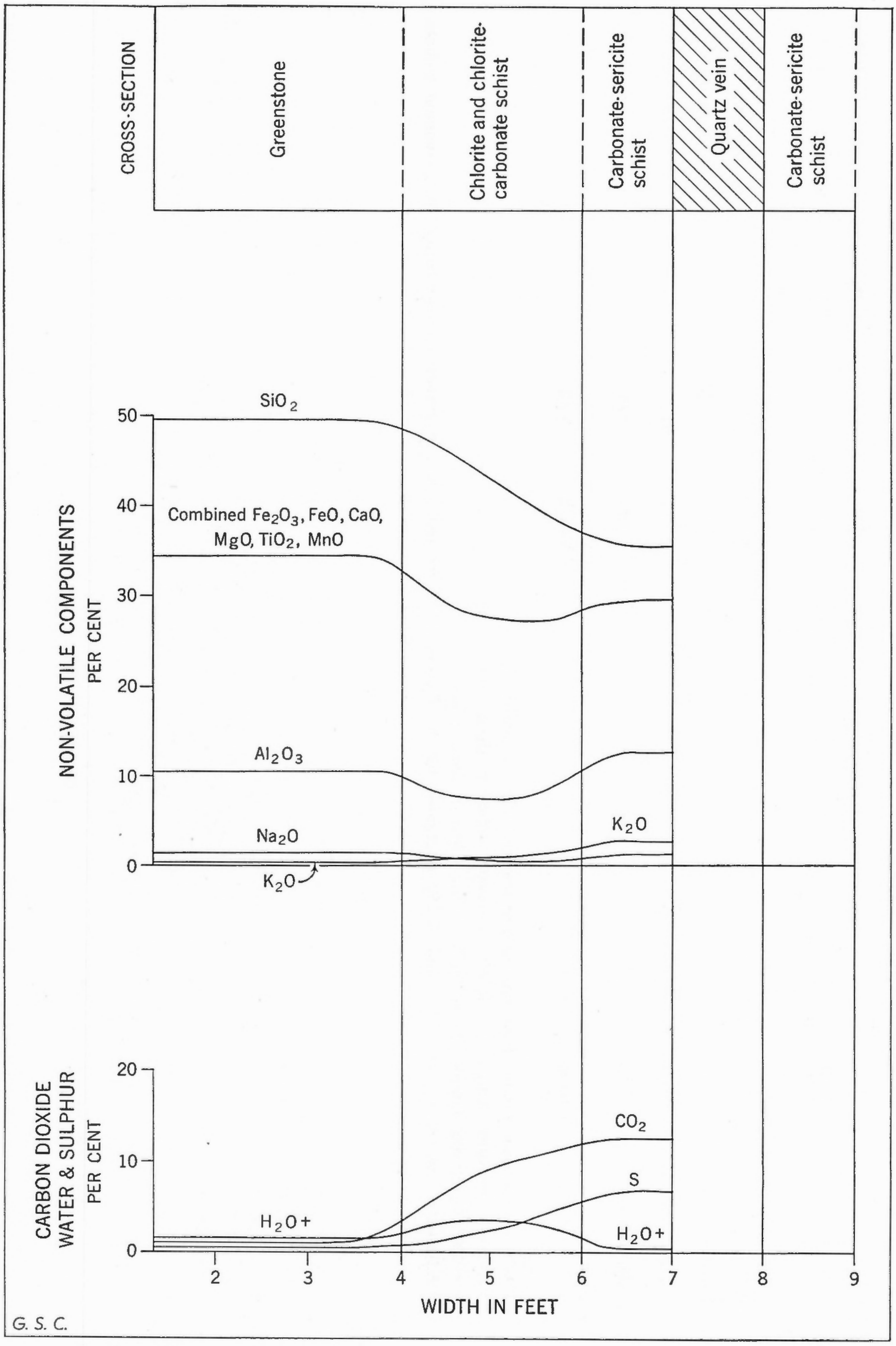


Figure 21. *Chemical changes produced by alteration of greenstone, Negus-Rycon system.*

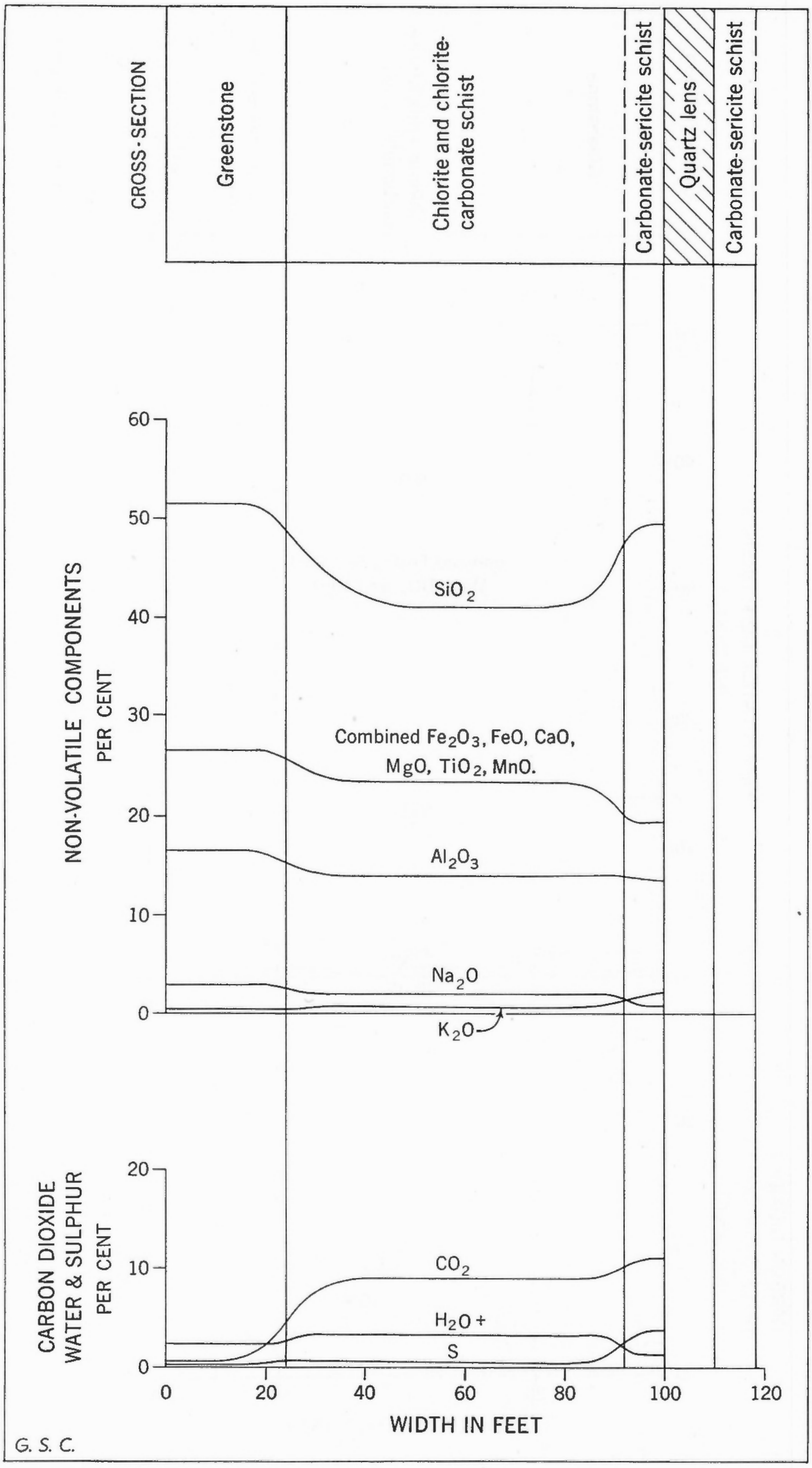


Figure 22. *Chemical changes produced by alteration of greenstone, Campbell system.*

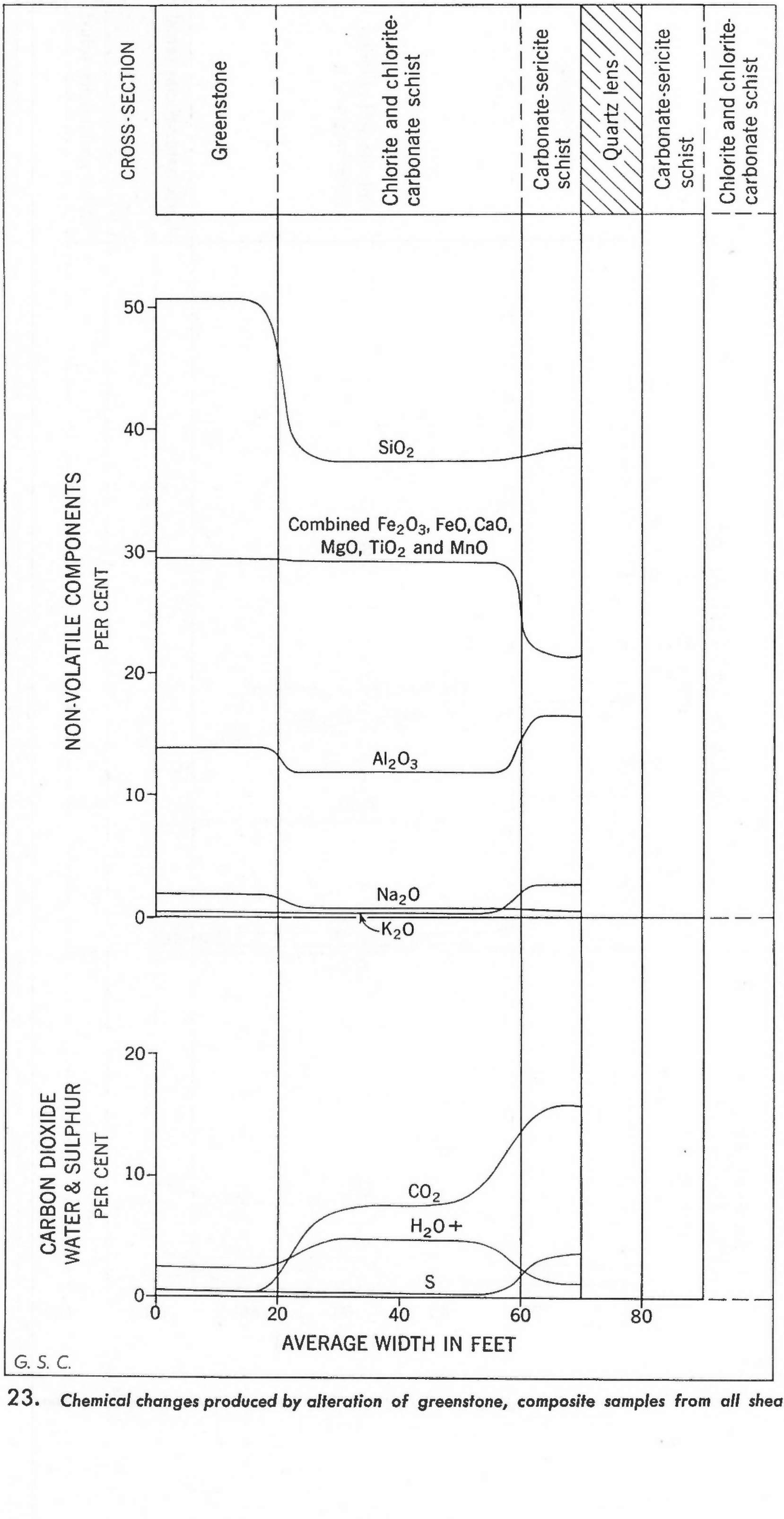


Figure 23. *Chemical changes produced by alteration of greenstone, composite samples from all shear zones.*

The Fe_2O_3, FeO, CaO, MgO, TiO_2, and MnO contents of the composite samples show individual trends in the alteration phases, but their combined content shows an overall decrease in both alteration phases compared to the greenstone. This tendency is also shown by the analyses from the individual shear zones and appears to be a general one.

The Na_2O content decreases consistently in the two alteration phases compared with the greenstone. This loss of soda is also shown by the analyses from the two specific shear-zone systems.

Compared with the greenstone, the K_2O content of the composite samples is relatively constant in the chlorite-carbonate phase but increases many times in the carbonate-sericite phase. In specific shear zones the K_2O content may increase significantly in the chlorite-carbonate phase.

The profiles of H_2O as shown by the analyses of both the composite samples and those from individual systems behave consistently. The water content increases in the chlorite-carbonate phase and decreases in the carbonate-sericite phase compared to the greenstone.

In all cases the profiles for CO_2 clearly indicate an increase in this constituent in all the alteration phases of the shear zones as compared with the greenstone. The greatest amounts are present in the carbonate-sericite phase with lesser amounts in the chlorite-carbonate phase.

The sulphur profiles of the alteration phases of the shear zones provide some interesting data on the origin of the sulphides in the orebodies and carbonate-sericite phase. As shown by the analyses of composite samples, the content of sulphur is less in the chlorite-carbonate phase than in the greenstone. In the carbonate-sericite phase the content is high, a feature which is common to all shear zones. Considering the profiles of the two specific shear-zone systems, however, it will be noted that the sulphur content is higher in both phases of the shear zones than in the greenstones. This apparent anomaly in the two results may be due to different sampling procedures. In the case of the individual shear zones, continuous samples were taken across the shear zones. Since the chlorite-carbonate zones always contain small seams of carbonate-sericite-pyrite schist these were unavoidably included with the chlorite-carbonate schist samples. In other words no separation on strictly petrographic grounds was made. In the case of the composite samples petrographic control was rigidly adhered to, and the samples of the two phases of alteration were prepared to exclude mutual contamination. It is evident from the results of the composite samples that where chlorite-carbonate schist was formed from greenstone the process led to a decrease in the sulphur content of the rock. The sulphur liberated probably migrated together with other components into the carbonate-sericite phase or to dilatant zones where it was precipitated as pyrite and other sulphides. This concept is amplified further in Chapter IX.

To summarize the chemical features displayed by the profiles, it can be said that the principal agents responsible for the alteration are carbon dioxide and water, and to a lesser extent sulphur and arsenic. These volatiles have reacted differently with the various mineral constituents of the greenstone rocks, and the alteration minerals formed reflect the chemical equilibrium attained under the conditions of pressure, temperature, and concentration that prevailed during the formation of the shear zones. As carbon dioxide and water were added, silica was abstracted together with some iron, calcium, magnesium, titanium, and manganese. Soda was leached from all alteration phases, and potash was enriched in the sericite phase. Sulphur was evidently mobilized in the chlorite-carbonate phase and migrated into the carbonate-sericite phase or into the site of the quartz lenses.

The mineral transformations and elemental migrations inferred from thin sections and chemical and spectrographic analyses provide much data on the geochemistry and relative mobilities of the elements during the alteration processes. These are interpreted in the following sections according to well-established crystallochemical principles.

The amphiboles of the greenstone in the presence of CO_2 and H_2O have yielded either ankerite or chlorite or both depending upon the concentration of the two volatiles. To form chlorite the elemental constituents of the amphibole must have undergone a major structural rearrangement. During this process some of the Mg, Fe, Mn, Al_2O_3, and SiO_2 was bound by OH into the chlorite structure. The Ca and the remainder of the Fe, Mg, and Mn were liberated and bound by CO_2 into the ankerite structure. The K and Na contained in the original amphibole were liberated during the process.

In the more highly carbonated parts of the shear zones the process has gone farther and the chlorite was attacked by the CO_2, and its Mg, Fe, and Mn were bound into ankerite. This has liberated SiO_2 and Al_2O_3.

The plagioclase has undergone a similar alteration—its Ca content was bound into ankerite, and the K, Na, Al_2O_3, and SiO_2 formed albite in certain circumstances or migrated. In the same manner the Ca, Fe, Mn, Al_2O_3, and SiO_2 of the epidote minerals were incorporated into chlorite which was ultimately attacked by CO_2 to form ankerite with the liberation of SiO_2 and Al_2O_3.

Sulphur and arsenic diffusing through the shear zones have bound some iron liberated by the alteration of amphibole, chlorite, and epidote into pyrite and arsenopyrite. Polished sections also show that the pyrite and arsenopyrite contain irregular unreplaced nuclei of magnetite and ilmenite suggesting that the iron in these minerals was also bound by sulphur and arsenic. Titanium was liberated during the alteration of the magnetite and ilmenite, the carbonatization of the amphibole and chlorite, and the sericitization of the chlorite. This element was not readily accommodated in the carbonate, sericite, or sulphide structures and hence formed an independent mineral phase which now appears as irregular white leucoxene patches or aggregates of yellow rutile needles.

Potassium is enriched in the shear zones especially in the carbonate-sericite phase, adjacent to quartz lenses. It is often assumed that such a potash metasomatism is due to the introduction of potassium by magmatic solutions. Such an assumption neglects the pertinent facts that a ready source of potassium exists in the greenstones, and that the element has a high mobility where differential pressure and shearing prevails, and where water and carbon dioxide are present. The greenstone contains an average content of 0.52 per cent K_2O, held principally in the plagioclase and amphiboles. During the carbonatization and hydration of these minerals the K^+ was liberated because large amounts could not be readily accommodated in the chlorite or carbonate structures. In the shear zones enormous masses of rock have been carbonatized and hydrated, and it follows that large amounts of potassium must have been set free.

Potassium shows large percentage gains in most of the alteration phases and is strongly enriched in the sericite schist adjacent to quartz lenses. From thin-section studies it is apparent that the sericite is formed at the expense of both chlorite and plagioclase. These observations taken together with the chemical considerations discussed above suggest that the geochemical history of potassium during the alteration processes was as follows:

1. Release as K^+ or as a hydrated ion from its initial host minerals such as plagioclase and amphibole during carbonatization and hydration.
2. Diffusion of K^+ ions from zones of intense shearing into zones of lower pressure where reactions with chlorite and plagioclase or combination with alumina and silica took place to form sericite.

Sodium is bound principally in the plagioclase, but small amounts are also present in the amphiboles. During the carbonatization of these two minerals most of the sodium was liberated. Recombination may have taken place with alumina and silica to form albite locally, but much sodium has been leached and probably migrated to higher levels or was ultimately dispersed at the surface.

The percentage gains and losses for sodium are lower than for potassium, suggesting that sodium has the lower mobility of the two elements.

Alumina is fixed in the plagioclase, amphibole, and epidote of the greenstone. During alteration of these minerals the alumina was redistributed among the chlorite, plagioclase, and sericite of the alteration zones. Some parts of the shear zones are leached and others enriched, but the percentage gains and losses are low, suggesting that Al_2O_3 had a relatively low mobility during the alteration processes.

During the alteration of the greenstone most of its Ca, Mg, Mn, and Fe content has been bound by carbon dioxide into ankerite; some iron has been bound by sulphur and arsenic into pyrite and arsenopyrite. The remainder of this group of elements, as shown by the profiles of their combined oxides, has been leached suggesting migration into low-pressure zones such as the vein sites. There, much of the Ca, Mg, Mn, and Fe was bound by CO_2, S, and As into the ankerite, pyrite, and arsenopyrite of the quartz lenses. Some of these elements, however, may have migrated upward along the shear zones and were dispersed at the surface.

The content of individual minor elements in the alteration phases shows extreme and often erratic variations making a tabulation of average values virtually impossible. However, certain qualitative statements can be made with some assurance.

Rubidium, cesium, beryllium, boron, and the rare earths show an enrichment in the alteration phases. Rubidium follows potassium in its geochemistry, and its enrichment is to be expected. Cesium follows rubidium and potassium closely, accounting for its enrichment. Spectrographic analyses of separated minerals from the alteration phases show that beryllium and boron are concentrated in the sericite, and the content of these two elements appears to vary with the amount of sericite developed. In places a few minute crystals of tourmaline occur scattered throughout the sericite and chlorite schist accounting for a local enrichment of boron.

Copper, zinc, lead, antimony, silver, and gold are enriched principally in the carbonate-sericite phase. The amounts of these elements vary directly with the content of sulphur and arsenic indicating that they are bound principally in the sulphides.

The rare-earth elements show a moderate enrichment in some zones especially in the phases containing an abundance of carbonate.

In places chlorine is enriched in the carbonate-sericite phase where it is bound principally in carbonates and apatite.

Other minor elements have a rather constant concentration in both the greenstone and alteration zones. There are, however, many local exceptions and much work would be required to determine whether or not there has been any marked overall depletion or enrichment. As an example the variation of titanium may be cited. Locally, in certain alteration phases titanium is enriched, in others depleted. Over all, however, there appears to be little significant change.

The partition of the minor elements among the various minerals of the greenstones has been discussed previously (Chapter V). During alteration of the greenstones certain reactions have taken place resulting in a redistribution of the minor elements as shown by spectrographic analyses of separated minerals. Table 22 gives the probable substitution of some minor elements for the major elements in the minerals of the greenstone and altered zones and is intended as a guide in following the transformations discussed below.

As shown by spectrographic analyses, the breakdown of the amphiboles to yield chlorite has not been marked by an extensive liberation of the minor elements because the chlorite structure will apparently tolerate nearly all of the minor elements present in the amphibole. The partition of the minor elements from this point onward as the alteration intensifies follows two courses depending upon whether the amphibole has been carbonatized or sericitized.

Where the chlorite has been carbonatized, the Ti, V, Cr, Li, Ni, and Co were liberated because the carbonate lattice has a low tolerance for these elements, as shown by the spectrographic analyses of carbonates (Table 32, Chapter VIII). The elements V, Cr, Ni, and Co have a widespread distribution in pyrite (Table 34, Chapter IX), and it is probable that the largest amounts of these elements have been bound by sulphur into this mineral. The remainder were fixed in sericite or leucoxene.

In the second case, sericite has formed from the chlorite, and V, Ni, Cr, and Li were accommodated in the sericite as shown by spectrographic analyses of this mineral. Ti, however, could not be accommodated in this mineral in any quantity, and it now appears bound as rutile which forms knots and small trains of microscopic crystals in the sericite schist.

Strontium and barium substitute for potassium and probably calcium in the plagioclase structure, and some is present in amphibole and chlorite. Carbonatization and sericitization of these minerals would not liberate large amounts of either Sr or Ba because they can be readily accommodated in either carbonate minerals or sericite.

Table 22

Substitution of Minor Elements for Major Elements in Mineral Structures

Minor Element	Radii Å	Probable Substitution in Mineral Structures
Ti^{3+}	0.76	For Fe^{2+} (.74Å) in amphibole and Al^{3+} (.51Å) in chlorite
V^{4+}	0.63	For Al^{3+} (.51Å) in amphibole, chlorite, and sericite For Ti^{4+} (.68Å) in sphene, rutile, ilmenite, and magnetite For Fe^{3+} (.64Å) in magnetite
V^{5+}	0.59	For P^{5+} (.35Å) in apatite
Cr^{3+}	0.63	For Fe^{3+} (.64Å) and Al^{3+} (.51Å) in amphibole, chlorite, sericite, and magnetite For Fe^{2+} (.74Å) and Mg^{2+} (.66Å) in amphibole, chlorite, and sericite
Ni^{2+} Co^{2+}	0.69 0.72	Primarily for Mg^{2+} (.66Å) in amphibole, chlorite, and magnetite; also for Fe^{2+} (.74Å) in these minerals
Sr^{2+} Ba^{2+}	1.12 1.34	For Ca^{2+} (.99Å) in feldspars and carbonates; also for K^{+} (1.33Å) in feldspars and sericite
Ga^{3+}	0.62	For Al^{3+} (.51Å) in silicate minerals; also for Cr^{3+} (.63Å) and Fe^{3+} (.64Å) in magnetite and ilmenite
Li^{+}	0.68	For Al^{3+} (.51Å) and Mg^{2+} (.66Å) in amphibole, chlorite, and sericite

The elements in the ilmenite and magnetite can be traced by spectrographic methods with some certainty through the alteration process. During the disintegration of these two minerals to form leucoxene and rutile, the elements liberated include Fe, Mg, Zn, Mn, Ni, Co, Al, Cr, V, and Ga. Of these Fe, Zn, Ni, Co, Ga, and V would in most cases be bound by sulphur into pyrite and by sulphur and arsenic into arsenopyrite. Tables 34 and 35 (Chapter IX) show that all these elements are present in pyrite and arsenopyrite but whether the greatest proportion occurs in structural sites or in residual unreplaced nuclei of magnetite and ilmenite cannot be determined in most cases.

The history of other minor elements, such as silver, gold, copper, etc., during the alteration processes is discussed in detail in the chapters to follow.

Origin of the Alteration Zones in Greenstones

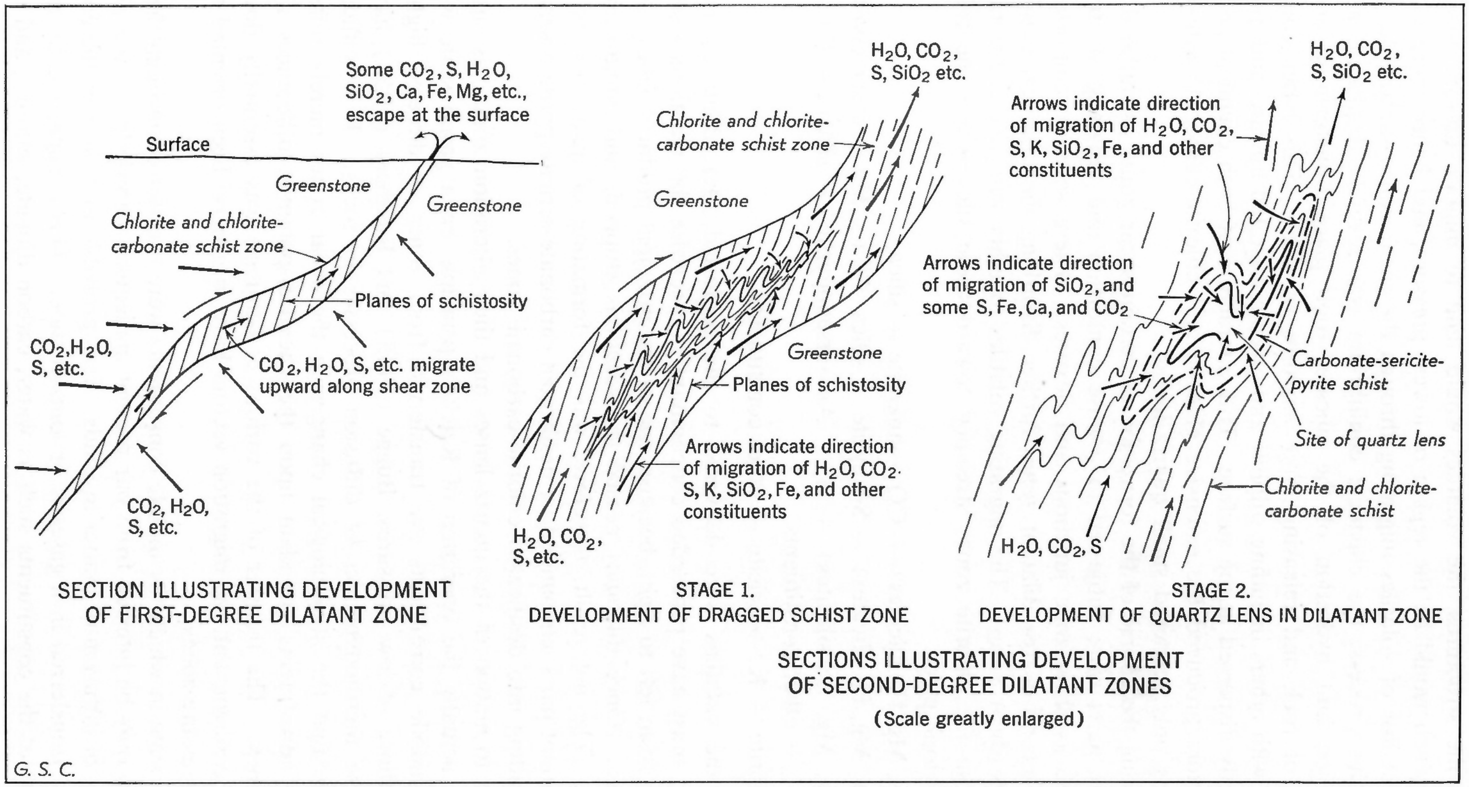
In the classical sense, the gold-quartz lenses and their alteration haloes in the shear zones at Yellowknife would be interpreted as the result of deposition from flowing solutions which travelled along certain channels. This, however, is unlikely in view of the many facts opposing such a concept. Perhaps the best argument against the flowing-solution idea is the observation that the lenses and their alteration zones appear to be isolated bodies in great volumes of chlorite and chlorite-carbonate schists, rocks which have a compact texture and in which there is no clear evidence of interconnecting channelways. On the contrary, the chemical effects in the shear zones are so pervasive and the transformations so complete over great widths and depths that diffusion of matter through infinitely small fractures and along grain boundaries would seem to have been the main process in the formation of the chlorite schist, alteration haloes, and quartz lenses.

The main facts bearing directly on the origin of the chlorite schist zones, quartz lenses, and their alteration haloes may be summarized as follows:

1. The shear zones are thrust zones formed by great compression and shearing.
2. The main body of the shear zones consists of chlorite and chlorite-carbonate schist which is strongly foliated but not necessarily highly contorted.
3. The quartz lenses and their carbonate-sericite schist haloes generally occur in areas of extreme contortion as at shear-zone junctions or at sites in the shear zones where movement of the walls has produced open spaces or dragged zones in the chlorite schist. All these sites were low-pressure zones as well as zones of low-chemical potential for certain specific elements (ions).
4. During the formation of the shear zones the principal constituents added have been carbon dioxide and water. Silica has been removed in large quantities and sulphur appears to have been depleted in the chlorite and chlorite-carbonate zones. Alumina has generally been decreased in the chlorite and chlorite-carbonate phases but shows a varied habit in the carbonate-sericite phase. Soda has been depleted in both alteration phases and potash has been enriched in the carbonate-sericite phase. Some rearrangement of calcium, iron, magnesium, and titanium has taken place within the zones, but in general there has been a removal of these elements from the highly altered zones.
5. In the discussion on the origin of the quartz veins in the next chapter it is shown that during alteration processes in the shear zones, much more silica has been removed than is now present in the quartz veins. This may also apply to sulphur, suggesting that the chemical system was an open one and that much material has migrated upward where it was ultimately dispersed at the surface.

The field and laboratory investigations suggest that the schist of the shear zones and the early gold-quartz lenses were formed simultaneously as the result of intense shearing which triggered and promoted the chemical effects characteristic of the shear zones.

When the shear zones were first formed, they constituted first-degree dilatant zones into which the volatiles were drawn from the surrounding rocks (Figure 24).



SECTION ILLUSTRATING DEVELOPMENT
OF FIRST-DEGREE DILATANT ZONE

STAGE 1.
DEVELOPMENT OF DRAGGED SCHIST ZONE

STAGE 2.
DEVELOPMENT OF QUARTZ LENS IN DILATANT ZONE

SECTIONS ILLUSTRATING DEVELOPMENT
OF SECOND-DEGREE DILATANT ZONES

(Scale greatly enlarged)

Figure 24. ***Diagrams illustrating the development of first- and second-degree dilatant zones, alteration zones, and quartz lenses.***

Once in the structures, the volatiles would tend to migrate upward toward the surface which would be the region of lowest pressure, and hence there would be a constant flux of volatiles migrating through the shear zones toward the surface. During this process, the chemical equilibrium was severely displaced, and carbonatization and hydration of the silicates took place transforming enormous volumes of rock and releasing large amounts of silica. This latter constituent together with others including sulphur and arsenic migrated upward and may have been partly dispersed at the surface. This interaction of both chemical and structural factors produced the extensive chlorite and chlorite-carbonate schist zones containing only scattered small quartz lenses.

During the course of the formation of certain shear zones as outlined above, particular parts were subjected to intense contortion and dragging at structural sites such as shear-zone junctions and flexures. These severely contorted sites marked second-degree dilatant zones further disturbing the chemical equilibrium within the shear zones. The migrating volatiles together with released potash and silica from the chlorite zones streamed toward these sites where the following reactions took place.

(Ca, Mg, Fe silicates) + CO_2→ankerite + silica

(Ca, Mg, Fe silicates) + S→pyrite + silica +Ca+ Mg + other constituents

(Ca, Mg, Fe silicates) + S + As→arsenopyrite + silica + Ca + Mg + other constituents

Chlorite + K^+→sericite + other constituents

As the volatiles were delivered to the contorted sites, dilatancy (volume increase) must have proceeded concomitantly, otherwise the reactions would not have run from left to right, because one of the principal products, silica, must be withdrawn. Once dilatancy ceased the reactions stopped, and equilibrium was restored. The net result, therefore, was the formation of quartz lenses in the more dilatant parts surrounded by desilicated carbonate-sericite-pyrite-arsenopyrite zones grading into desilicated chlorite-carbonate zones.

The formation of the quartz lenses and their alteration zones, as suggested above is actually the operation of Reicke's principle on a grand scale whereby various mobile constituents are transferred from zones of directed high pressure to those of low pressures. Bugge (1945) and Ramberg (1952) have discussed the thermodynamics of diffusion processes in rocks. It is sufficient to state here that the mineralogical changes in the shear zones merely reflect the chemical adjustments attendant upon the chemical-potential differences induced by dilatancy. The transfer of the various constituents was essentially down the pressure gradient, and the migration vectors have in general been oriented toward the low-pressure zones.

The state in which the mobile constituents were transferred through the shear zones can only be inferred from our present inadequate knowledge of the physical chemistry of diffusion of matter in solids. It is probable that most of the constituents were transferred in a gaseous or ionized state. This is suggested by the fact that many of the constituents such as water, carbon dioxide, sulphur, and arsenic pass readily into the gaseous state. Furthermore it is well known that gases at high temperatures and pressures diffuse more readily than liquids through solids. Another important consideration is that silica and other oxides have a marked solubility in gaseous water at high temperatures as shown by the investigations of Kennedy (1944, 1950) and Morey (1957).

Water was undoubtedly the main catalyst in the processes whereby numerous constituents were transferred through both the country rocks and shear zones. Under the deep-seated conditions of formation of the gold-quartz lenses the state of the water was probably gaseous, as noted above, and it may have been partly ionized as H^+, H_3O^+, and OH^-. Carbon dioxide probably existed as the ionized components of carbonic acid, H^+, HCO_3^-, and CO_3^{2-} and sulphur was probably present as H_2S or the ionized components of this gas, H^+ and HS^-. Silica was probably hydrated as $Si(OH)_4 \cdot nH_2O$ but may also have migrated as hydrated sodium and potassium complexes. Numerous other constituents were probably transferred as hydrated complexes.

There seems to be little justification for assuming that the migration of the constituents through the shear zones required the movement of large volumes of water. Ions, especially when hydrated, diffuse readily through gaseous water at high temperatures. This mechanism, therefore, provides an adequate means of transport, and in the author's opinion the migration of the elements took place through a nearly stationary flux of gaseous water which permeated both the country rocks and shear zones. The density of the hydrous flux was probably controlled in part by the thermal gradient and also by the dilatancy of the structures. Such a mechanism of transport is actually analogous to the diffusion of ions in liquid water, a phenomenon well known to chemists and shown to be applicable to geological processes by Duffell (1937).

The relative rates of migration of the various constituents through the shear zones is a problem which requires much experimental data for an adequate solution. The main factors bearing on the problem can, however, be stated and an attempt at an interpretation of some of the chemical features of the shear zones can be made.

Shearing was undoubtedly one of the most important factors. It is well known that shearing strains mineral lattices and promotes diffusion (Mott, 1955) In addition, extreme contortion also comminutes the minerals increasing chemical reaction. Furthermore, the effects of directed pressure, such as shearing, on the mobility of the elements, must also be considered. Bridgman (1931) has shown that all atoms can be compressed at high pressures, and that the compressibilities of the alkali metals are greater than those of other elements. It can also be shown from lattice theory that the greater the compressibility of an element the weaker is its bonding energy. It follows, therefore, that under great shearing stress, the more compressible an element the easier it will be detached from its lattice. As Bugge (1945) has suggested, this phenomena is a plausible explanation for the relatively high mobility of the alkalis compared with calcium, magnesium etc., in zones of intense shearing. In the shear zones, excepting the volatiles, soda and potash exhibit the largest percentage gains and losses, attesting to their higher mobility compared with other constituents. This higher mobility can probably be attributed in part to the action of shearing in view of the theoretical concepts mentioned above.

When water is present in the system, consideration must also be given to the effect of the ionic potential[1] on the migration of the elements. Elements such as potassium, sodium, calcium, and magnesium have a relatively low ionic potential and form easily soluble cations that are not readily precipitated by changes in pH. Elements like iron and aluminum have an intermediate ionic potential, are readily hydrolyzed and their solubilities are largely pH dependent. Silicon, sulphur, phosphorous, etc. with high electrostatic charges and high ionic potentials, form oxy-acid anions whose solubilities may depend in part on the pH of the environment. As noted above, sodium and potassium have low ionic potentials, and their cations are readily soluble. Transfer of these elements through a pervasive water gas would, therefore, be relatively easy and hence their mobility in the shear zones was high. Calcium and magnesium, on the other hand, have higher ionic potentials and their mobility was lower as shown rather conclusively by their smaller percentage gains and losses in the shear zones as compared to sodium and potassium. Silica forms complex ions whose solubilities vary only slightly with pH near the neutral point; at high pH's their solubilities increase. The percentage gains and losses for silica in the shear zones are not high suggesting that the pH of the environment was close to the neutral point. For alumina the percentage gains and losses are relatively low indicating a low mobility for this constituent. Aluminum is an amphoteric element with a relatively high ionic potential, and alumina has solubility maxima at pH 4 and 10. The iron oxides show intermediate values in their percentage gains and losses indicating a moderate mobility. This means that the pH of the environment during the migration of iron must have been on the acid side because the mobility of iron above pH 7 is relatively low. Correlating these observations on silica, alumina, and iron, it seems logical to conclude that an acidic condition prevailed during the main stages of the alteration processes.

The effects of carbon dioxide, sulphur, and arsenic have not been considered. Their presence has without question modified the course of the reactions and the mobility of many elements. It would be expected that carbon dioxide would have increased the acidity and hence promoted the migration of Ca, Fe, Mg, and Mn, and perhaps K and Na. The presence of sulphur and arsenic, especially in a gaseous hydrated form, would certainly have promoted the migration of many of the trace elements such as Cu, Zn, Au, Ag, etc. As the volatile constituents were used up, the pH of the environment probably became alkaline permitting a greater migration of silica and perhaps alumina.

It is apparent, therefore, that the mobility and transfer of the elements in the shear zones has depended upon several interacting factors. Chief among these was shearing which comminuted the rock, permitting extensive chemical reaction

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[1] The ionic potential is the charge of an ion divided by its radius, and is a measure of the behaviour of an ion towards water.

to proceed. It also promoted diffusion, and because of the intrinsic feature of compressibility, certain elements such as Na and K were more readily detached from their constituent minerals than others. Once free the elements migrated in accordance with their ionic potentials. Those with low ionic potentials migrated freely; those with high potentials less so. The pH of the environment was critical for the migration of some elements especially aluminum and iron. The influence of carbon dioxide, sulphur, and arsenic was marked not only in promoting the migration of Ca, Mg, Fe, etc., but also the metallic trace elements, and finally in fixing many of the elements in the carbonate and sulphide minerals of the shear zones.

Alteration Processes in Quartz-feldspar Porphyry

Fresh quartz-feldspar porphyry contains essentially quartz, plagioclase, chloritized biotite, and muscovite. Accessory minerals are pyrite, pyrrhotite, leucoxene, epidote, and carbonate. The microscope shows that alteration of the rock results in the development of sericite from the plagioclase and biotite and a general recrystallization of the quartz and sulphides. In places an increase in sulphides is apparent.

Table 23

Chemical Changes Produced by Alteration of Quartz-feldspar Porphyry, Negus-Rycon System

Constituent	A-23[1] %	A-24[2] %	Adjusted[3] %	Gains and Losses in Constituents	Percentage Gains and Losses
SiO_2	73.09	72.46	73.80	+0.71	+ 1.06
Al_2O_3	14.01	16.26	16.56	+2.55	+ 18.30
Fe_2O_3	0.32	0.34	0.35	+0.03	+ 9.36
FeO	0.89	0.45	0.46	−0.43	− 48.50
CaO	2.05	0.94	0.96	−1.09	− 53.20
MgO	0.37	0.77	0.78	+0.41	+111.00
Na_2O	4.15	0.63	0.64	−3.51	− 84.50
K_2O	1.63	3.94	4.01	+2.38	+146.00
H_2O^+	0.72	1.93	1.97	+1.25	+174.00
H_2O^-	0.05	0.12	0.12	+0.07	+140.00
TiO_2	0.20	0.25	0.26	+0.06	+ 30.00
P_2O_5	0.05	0.10	0.10	+0.05	+100.00
MnO	0.02	0.01	0.01	−0.01	− 50.00
CO_2	1.80	0.97	0.99	−0.81	− 45.00
S	0.80	1.27	1.29	+0.49	+ 61.20
Cl	trace	0.01	0.01	—	—
Cr_2O_3	0.04	trace	—	—	—
Total	100.19	100.45	—	—	—
Less O=S,Cl	0.34	0.55	—	—	—
Net Total	99.85	99.90	—	—	—
Specific Gravity	2.69	2.74	—	—	—

(Analyst—J. A. Maxwell, Geological Survey of Canada.)

[1] A-23—Composite sample of massive quartz-feldspar porphyry, Con mine.

[2] A-24—Composite sample of altered quartz-feldspar porphyry adjacent to quartz veins, Negus-Rycon system.

[3] Adjusted % = percentages in A-24 multiplied by the factor 2.74/2.69 to reduce to a common volume.

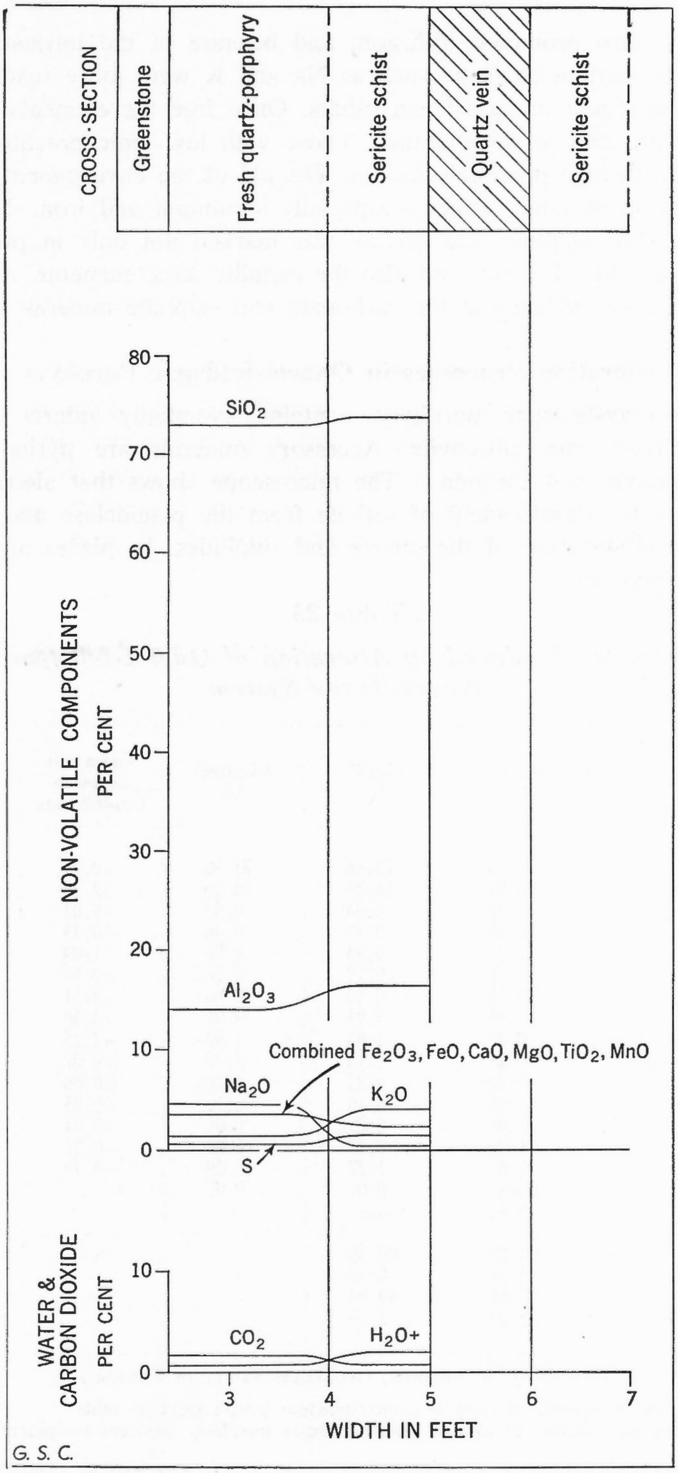


Figure 25. *Chemical changes produced by alteration of quartz-feldspar porphyry, Negus-Rycon system.*

The chemical analyses of the fresh and altered porphyry are given in Table 23 and graphed in Figure 25. They indicate relatively little change in the SiO_2, Fe_2O_3, TiO_2, P_2O_5 and MnO during the alteration process. Much calcium and carbon dioxide have migrated out of the sericite zone together with sodium and some iron. Potassium, alumina, water, and sulphur were added.

The alteration processes, therefore, were mainly an exchange of potassium for sodium during hydration, and to balance the equilibrium, alumina was added and calcium abstracted. This calcium together with carbon dioxide probably formed carbonates in the quartz lenses. Some of the iron was fixed by sulphur in the alteration zones, and the remainder migrated to the site of the quartz lenses where it was probably fixed as pyrite.

Alteration Processes in Sedimentary Rocks

As already noted, the majority of quartz veins and pegmatites enclosed by sedimentary rocks have no well-defined alteration zones. Some pegmatites and quartz veins, however, are marked along their borders by a development of tourmaline indicating an introduction of boron. A few quartz veins such as those at the Burwash prospect have a thin alteration zone. An analysis of a composite sample from this type of alteration zone is given in Table 24. Figure 26 shows the

Table 24

Chemical Changes Produced by Alteration of Greywacke, Burwash Prospect

Constituent	Composite Sample of Greywacke	Composite Sample of Alteration Zone	Gains and Losses in Constituents
SiO_2	62.61	64.48	+1.87
Al_2O_3	16.78	16.22	−0.56
Fe_2O_3	0.38	0.84	+0.46
FeO	5.81	4.95	−0.86
CaO	2.80	0.50	−2.30
MgO	2.99	3.09	+0.10
Na_2O	3.79	3.69	−0.10
K_2O	1.56	2.12	+0.56
H_2O^+	1.94	2.77	+0.83
H_2O^-	0.12	0.15	+0.03
TiO_2	0.68	0.66	−0.02
P_2O_5	0.16	0.14	−0.02
MnO	0.08	0.06	−0.02
CO_2	0.10	0.00	−0.10
S	0.14	0.20	+0.06
Cl	0.02	0.02	+0.00
Cr_2O_3	0.01	0.03	+0.02
C	0.13	0.10	−0.03
Total	100.10	100.02	—
Less O=S,Cl	0.06	0.09	—
Net Total	100.04	99.93	—
Specific Gravity	2.73	2.73	—

(Analyst—J. A. Maxwell, Geological Survey of Canada.)

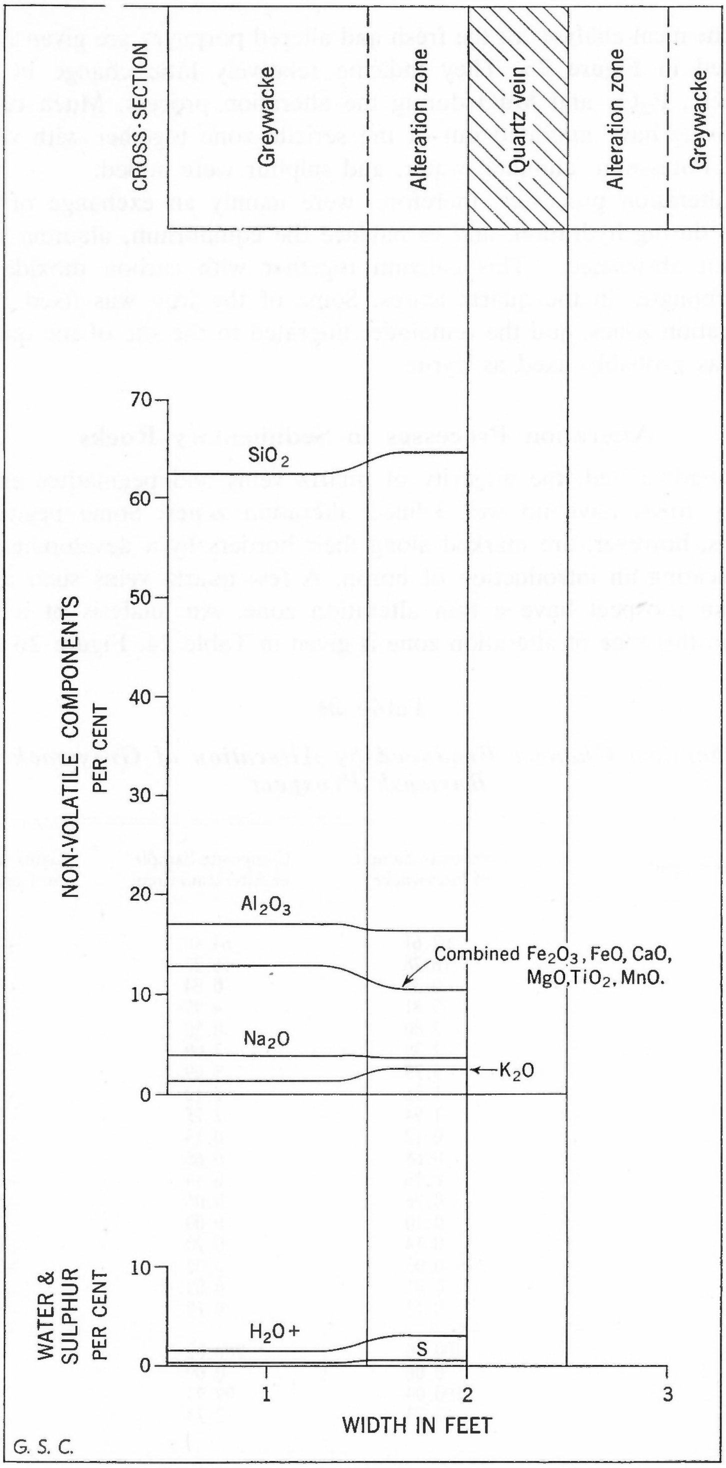


Figure 26. *Chemical changes produced by alteration of greywacke, Burwash prospect.*

differences graphically. It should be emphasized that this type of alteration is unusual in the sediments and should not be considered as a general one.

The alteration of the greywacke has resulted in the introduction of some silica, water, potash, and sulphur and the removal of some alumina, calcium, ferrous iron, and carbon dioxide.

Alteration Processes along Post-diabase Faults

In the greenstone rocks chloritization of the breccia of the post-diabase faults accompanied by the development of epidote, albite, hematite, leucoxene, and prehnite are the principal alteration effects. Carbonates have a widespread distribution in the faults, but are nowhere abundant. Locally, the fault breccia is silicified and irregular quartz lenses are present.

The detailed progressive changes in the mineral constituents of the fault zones during alteration are not clear because of the highly friable nature of the breccia and gouge, making it difficult to cut good thin sections. It is apparent, however, that the amphibole, plagioclase, magnetite, and ilmenite of the greenstone are completely altered to chlorite, epidote, albite, leucoxene, and small amounts of carbonate; in some places prehnite is present. The geochemistry of this alteration process is undoubtedly similar to that described for the formation of the chlorite phase in the shear zones and need not be repeated in detail. The main points of interest are the formation of quartz and hematite in or near the faults.

The analyses of the greenstone compared with the chlorite-schist phase of the shear zones show a loss of silica. In the late faults the formation of chlorite and the other minerals would, likewise, liberate silica which probably migrated into dilatant zones within the faults where it was precipitated as quartz.

In the granite at the junction of the West Bay and Akaitcho faults, a series of large quartz stockworks has formed. The principal alteration effects associated with these stockworks are silicification, hydration as characterized by sericitization and chloritization of feldspars and ferromagnesian minerals, and the formation of hematite.

Water has been the principal agent responsible for the alteration. Introduction of this compound has led to a complete breakdown of the feldspars and ferromagnesian minerals with the liberation of silica, alumina, the alkalis, iron oxides, and calcium, magnesium, and iron. Part of the silica, alumina, and alkalis is bound in sericite, part in chlorite and albite. The excess silica was probably delivered to fractures in which it migrated upward and laterally to dilatant zones where it was precipitated as quartz lenses. The other elements not required to establish equilibrium were probably distributed through the quartz lenses as sericite, hematite, and carbonates.

Of particular interest is the origin of hematite, a mineral common to all late faults, especially where the faults cut greenstones and granite. During chloritization of the greenstones, much iron was liberated. Alteration of granite also released iron because biotite, hornblende, and other ferromagnesian minerals were attacked and altered to sericite, an iron-free mineral. The iron released during these alteration processes probably found its way into quartz lenses and seams or fractures in the rocks where it was precipitated as hematite. The presence of hematite emphasizes the high oxidation potential of the environment of deposition; if sulphur and carbon dioxide had been present, as they were during the formation of the shear zones, iron sulphides and carbonates would have been developed extensively.

Little detailed work was done on the alteration effects in sediments along late faults because they are covered with drift in nearly all areas. Where exposures occur, a mild degree of chloritization and sericitization with local silicification and the formation of small quartz lenses have taken place. Hematite was not noted in any quantity in any of the exposures, and tourmaline was absent.

Chapter VII

GEOCHEMISTRY AND ORIGIN OF QUARTZ VEINS AND LENSES

This chapter discusses the detailed interrelationship of structural and chemical processes which have led to the formation of the quartz veins and lenses in the Yellowknife district. In the greenstone belt, the available facts suggest that the early gold-quartz lenses in the shear zones have originated mainly by chemical exchanges during the alteration of the shear zones. Carbon dioxide and water were introduced and silica and other components transferred to the vein sites. Other quartz lenses and veins in the greenstones, and those in the sediments are the result of metamorphic differentiation or local secretion processes.

Dilatancy, resulting from structural adjustments, was the prime mover in concentrating the veins and lenses. It is doubtful if any of the veins or lenses were deposited by magmatic solutions because of the general isolated nature of the bodies in the country rock and in the great body of schist composing the shear zones. Furthermore, the field facts suggest that the quartz veins and lenses were not connected by any series of master channelways to a magmatic source. In view of these and other considerations to follow, the conclusion is forced upon the investigator that diffusion has been the principal process in the concentration of the quartz bodies.

Chemical Composition

The early quartz lenses in greenstones and granites are nearly pure silica and contain only small amounts of other elements generally held in sericite, carbonates, or sulphides.

The gold-bearing lenses and late quartz-carbonate stringers are impure and contain much sericite, chlorite, carbonate, and various sulphides. Such bodies vary widely in their silica content, averaging about 90 per cent.

Quartz bodies in the sediments are relatively pure silica and contain only small amounts of sericite, carbonate, and sulphides.

Most of the quartz in the late faults is intimately intergrown with chlorite, hematite, and other minerals. Even the crystalline material in the late faults contains much sericite, kaolin, etc. in thin sections.

Table 25 lists chemical and semi-quantitative spectrographic analyses of quartz from all types of deposits. The contents of minor elements are extremely erratic and generally have a wide range from sample to sample in the same setting. It is very doubtful if the contents of minor elements reflect anything but the degree of contamination by sericite, sulphides, carbonates, etc. It is nearly impossible to remove these extraneous minerals by leaching and other treatment because they

Table 25

Spectrographic Analyses of Quartz from Characteristic Occurrences

Key: M—Major constituent
T—Trace; less than 20 ppm
P—present in sample
N.F.—not found
—, not determined

Constituent	Early Quartz Lens in Western Granite (ppm)	Early Quartz Lens in Amphibolite Facies (ppm)	Early Quartz, Con Shear System (ore quartz) (ppm)	Early White Quartz, Negus-Rycon System (ore quartz) (ppm)	Black Quartz, Negus-Rycon System (ore quartz) (ppm)	Ore Quartz, Campbell System (ppm)	Ore Quartz, Giant System (ppm)	Ore Quartz, Crestaurum System (ppm)	Quartz in Fractures Cutting Ore Quartz, Con System (ppm)
Si	M	M	M	M	M	M	M	M	M
Al	10–200	10–200	50–500	50–500	50–500	50–500	50–500	50–500	50–500
Mn	1*	1–10	10–50	1–10	1*	1–10	1–10	1–10	1–10
Fe	20*	10–50	20–50	20–50	45*	20–50	20–50	20–50	10–50
Ti	3*	1–10	1–10	1–10	1*	1–10	1–10	1–10	1–10
Mg	10–100	10–100	20–50	10–100	10–80	10–100	10–100	10–100	10–100
Ca	10–100	10–100	50–150	50–150	10–100	50–150	50–150	50–150	10–100
Na	100–400	100–400	100–400	100–400	100–400	100–400	100–400	100–400	100–400
Li	5–25	5–25	5–50	5–50	5–50	5–50	5–50	5–50	5–20
K	10–100	10–100	10–100	10–100	10–100	10–100	10–100	10–100	10–100
Ba	10–100	10–100	10–100	T	T	T	T	T	10–100

Sr	T	T	T	T	T	T	T	T	10–100
Cu	T	T	T	T	T	T	T	T	T
B	—	—	—	—	T	—	—	—	—
Cr	—	—	—	—	T	—	—	—	—
C	N.F.	N.F.	P	N.F.	P	N.F.	P	P	N.F.

NOTES: 1. All samples were ground, screened, leached with aqua regia, washed with distilled water, and dried before analysis.
2. (*) Chemical determinations by S. Abbey.
3. Semi-quantitative spectrographic analyses by Spectrographic Laboratory, Geological Survey of Canada.
4. Carbon analyses by R. W. Boyle.

Table 25 (cont'd)

Spectrographic Analyses of Quartz from Characteristic Occurrences

Key: M—Major constituent
T—Trace; less than 20 ppm
P—present in sample
N.F.—not found
—, not determined

Constituent	Quartz in Fractures Cutting Campbell System (ppm)	Quartz in Fractures Cutting Giant System (ppm)	Smoky Quartz in Pegmatite, Prosperous Lake Granite (ppm)	Grey Quartz, Ptarmigan Vein (ore quartz) (ppm)	White Quartz Cutting Grey Ore Quartz, Ptarmigan Vein (ppm)	White Quartz, 'Giant Quartz Vein' (ppm)	Quartz Crystal, Late Fault (ppm)	Amethyst Quartz in Late Fault (ppm)
Si	M	M	M	M	M	M	M	M
Al	50–500	50–200	10–100	10–100	10–100	10–100	10–100	10–100
Mn	1*	1*	1–2*	1–10	1–10	1–10	1–10	4*
Fe	10–30*	24*	15*	10–50	10–50	10–50	10–50	100*
Ti	1–3*	1*	7*	1–10	1–10	1–10	1–10	49*
Mg	10–100	10–100	10–100	10–100	10–100	10–100	10–100	10–100
Ca	10–100	10–100	10–100	10–100	10–100	10–100	10–100	10–100
Na	100–400	100–400	100–400	100–400	100–400	100–400	100–400	100–400
Li	5–25	5–25	5–50	5–25	5–25	5–25	5–25	5–25
K	10–100	10–100	10–100	10–100	10–100	10–100	10–100	10–100

Ba	10–100	T	—	T	T	T	T	T
Sr	10–100	T	—	T	T	T	T	T
Cu	T	T	T	T	T	T	T	T
B	—	—	T	T	T	—	—	—
C	N.F.	N.F.	N.F.	P	N.F.	N.F.	N.F.	N.F.

NOTES: 1. All samples were ground, screened, leached with aqua regia, washed with distilled water, and dried before analysis.
2. (*) Chemical determinations by S. Abbey.
3. Semi-quantitative spectrographic analyses by Spectrographic Laboratory, Geological Survey of Canada.
4. Carbon analyses by R. W. Boyle.

are so intimately intergrown with the quartz. It follows, therefore, that contamination by the elements present in intergrown minerals masks any systematic variations in the substitution of elements in the quartz lattice or any variations in the elements in the salts present in the crystal cavities.

Some lenses contain grey or black quartz. The nature of the coloration of this quartz has been examined chemically by the author (Boyle, 1953a). In most lenses the black and grey colour is caused primarily by carbon or graphite distributed along planes or disseminated through the quartz. Grey sulphides may serve to deepen the colour in certain cases, but the effect is not notable unless the sulphides are present in large amounts.

Origin

Early Quartz Lenses Cut by the Shear Zones

These lenses are isolated bodies, occurring mainly in tension fractures in massive flows and sills in the greenstone belt. They are short and narrow, and are unconnected to any system of faults or fractures along which solutions could have travelled.

Silica analyses of a meta-gabbro sill have been made on traverses outward from two of these lenses. The results are given in Table 26.

Table 26

Silica Content of Meta-gabbro Sill on Traverses Across Early Quartz Lenses

Description of samples and location with respect to quartz lens	SiO_2 %	Specific gravity of rock
Lens No. 1 (width 6 inches)		
Chip sample across interval, 0-3 feet from lens	49.43	3.02
Chip sample across interval, 3-13 feet from lens	50.66	3.03
Chip sample across interval, 13-120 feet from lens	50.76	2.99
Lens No. 2 (width 6 inches)		
Chip sample across interval, 0-3 feet from lens	49.28	3.00
Chip sample across interval, 3-13 feet from lens	49.84	3.00
Chip sample across interval, 13-130 feet from lens	50.18	3.04

(All analyses by J. A. Maxwell, Geological Survey of Canada.)

The analyses show a small, but significant decrease in silica in the zones adjacent to the lenses. It might be argued that these differences represent original inhomogeneities in the rock, but this seems unlikely, because the sill from which the samples were taken shows no marked mineralogical differences.

The conclusion seems valid, therefore, that the silica lost from the greenstones has migrated and concentrated in the tension fractures as quartz lenses. When the tension fractures formed, they set up marked low-pressure zones, and chemical equilibrium was established by the migration of silica to fill these zones.

Early Gold-quartz Lenses in Shear Zones

In Chapter VI it was emphasized that as carbon dioxide, water, and sulphur were added, silica was abstracted in large quantities. Here, further data are given to show that it is highly probable that the silica liberated during the alteration has formed the present gold-quartz lenses and veins.

Chemical analyses (Tables 27, 28, 29, 30) have been made to determine the SiO_2 content of the country rock, chlorite schist, and other alteration phases within several shear zones. These should be studied in conjunction with the analyses given in Tables 19, 20, and 21 (Chapter VI), and graphed in Figures 21, 22, 23 (Chapter VI). All samples represent chip or channel samples taken across the shear zones at different levels in the various mines.

Table 27

Total SiO_2 Analyses—Negus-Rycon System

Sample No.	Description	Total % SiO_2
3rd level, 300 feet, Negus Mine		
YC–22	Greenstone. Chip sample across 50 feet	51.71
YC–23	Chlorite schist. Channel sample across 1 foot	44.53
YC–24	Carbonate-chlorite schist and carbonate-sericite schist. Composite channel sample across 1 foot	41.74
	Analyst, J. A. Maxwell.	
11th level, 1,425 feet, Negus Mine		
YC–1	Greenstone. Chip sample across 250 feet	48.46
YC–2	Chlorite schist. Channel sample across total width of chlorite schist zone—1 foot 6 inches	44.27
YC–3	Carbonate-chlorite and carbonate-sericite zone. Composite channel sample across total width of 6 inches	40.97
	Analyst, R. J. C. Fabry.	

Table 28

Total SiO_2 Analyses—Campbell System

Sample No.	Description	Total % SiO_2
11th level, 1,425 feet, Negus Mine		
YC–4	Greenstone. Chip sample across 250 feet	47.97
YC–5	Chlorite schist, some chlorite-carbonate schist. Chip sample across 70 feet	41.93
YC–6	Carbonate-chlorite and carbonate-sericite schist, small quartz lenses and stringers. Chip sample across 2 feet	43.35
	Analyst, R. J. C. Fabry.	
13th level, 1,775 feet, Negus Mine		
YC–7	Greenstone. Chip sample across 250 feet	47.72
YC–8	Chlorite schist, some chlorite-carbonate schist. Chip sample across 50 feet	43.91
YC–9	Carbonate-chlorite and carbonate-sericite schist. Composite chip sample across 3 feet	42.93
	Analyst, R. J. C. Fabry.	

Table 29

Total SiO_2 Analyses—Giant System

Sample No.	Description	Total % SiO_2
1st level, 100 feet, Giant Mine		
YC–10	Chloritized greenstone. Chip sample across 20 feet	44.86
YC–11	Chlorite schist, some chlorite-carbonate schist. Chip sample across 40 feet	46.07
YC–12	Carbonate-chlorite and carbonate-sericite schist. Composite chip sample across 20 feet	45.47
Analysts: R. J. C. Fabry, samples YC-11 and YC-12; J. A. Maxwell, sample YC-10		
3rd level, 425 feet, Giant Mine		
YC–13	Greenstone. Chip sample across 100 feet	47.52
YC–14	Chlorite schist, some chlorite-carbonate schist. Chip sample across 100 feet	45.48
YC–15	Carbonate-chlorite and carbonate-sericite schist. Composite chip sample across 20 feet	37.71
Analyst, R. J. C. Fabry.		

Table 30

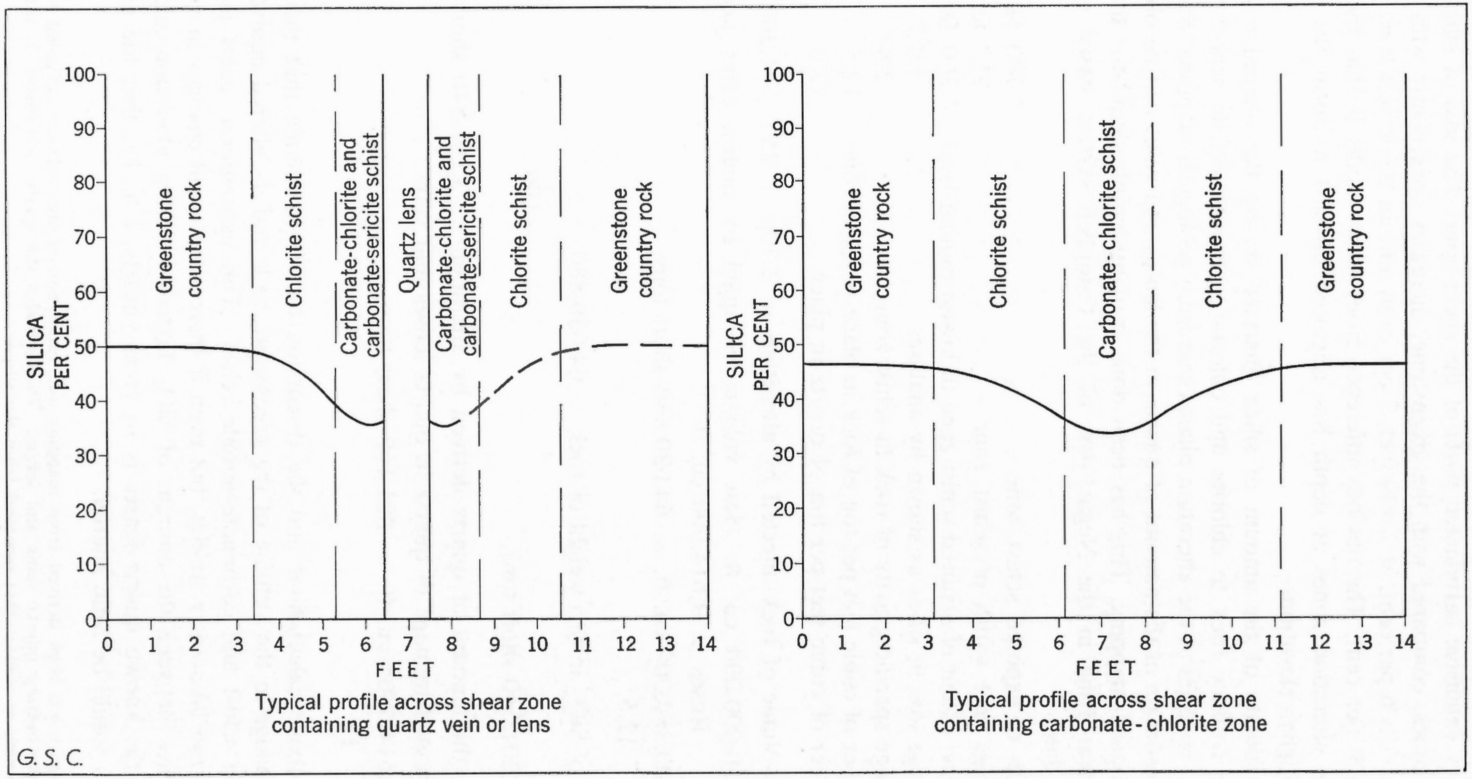
Total SiO_2 Analyses—Con System

Greenstone	Shear Zone
Meta-basalt and meta-andesite	Composite samples of chlorite schist, carbonate-chlorite and carbonate-sericite schist
500-foot level Channel chip sample across 60 feet 44.0 % SiO_2	Channel chip sample across 15 feet. 38.0 % SiO_2
1,400-foot level Channel chip sample across 30 feet 42.8 % SiO_2.	Channel chip sample across 10 feet. 35.6 % SiO_2
2,300-foot level Channel chip sample across 40 feet 49.0 % SiO_2	Channel chip sample across 20 feet. 29.0 % SiO_2

(Analyses courtesy the Consolidated Mining and Smelting Co., Trail, B.C. Samples were obtained and submitted by Dr. C. G. Cheriton.)

Figure 27 summarizes diagrammatically the behaviour of SiO_2 in all shear zones where the alteration zones are distinct. The profile on the left shows clearly that there is a consistent decrease in the SiO_2 content of the alteration halo as the quartz lenses are approached. The one on the right shows a distinct loss of SiO_2 in the carbonate-chlorite parts of the shear zones, when compared with the country rock and the chlorite schist phase of the shear zone.

Table 30 shows the results of a series of chemical analyses of samples taken across the total width of the alteration phases of the shear zones at different levels in the Con system. In this system (*see also* Figure 5, in pocket), the quartz lenses



Typical profile across shear zone containing quartz vein or lens

Typical profile across shear zone containing carbonate-chlorite zone

G. S. C.

Figure 27. *Profiles illustrating the behaviour of SiO_2 across the alteration zones.*

occur above extensive carbonated parts of the shear zone. The loss of silica from the shear zones, compared with the greenstone, increases consistently with depth; at 500 feet it is 6 per cent, at 1,400 feet, 7 per cent, and on the lowest level, 2,300 feet, it is 20 per cent. The obvious inference from these results is that the silica lost in the alteration zones at depth has migrated upward to form the quartz lenses at higher elevations.

An estimate of the amount of silica liberated during the alteration of the greenstone country rock to chlorite and chlorite-carbonate-sericite schist can be made from analyses of the alteration phases and from geological mapping. Similarly a reliable estimate of the amount of quartz in the lenses and veins can be obtained from geological mapping. This has been done in considerable detail for the productive shear zone in the Negus part of the Campbell system based on the following data.

Length of exposed schist zone	2,700 feet
Average true width of schist zone	250 feet
Vertical extent of exposed schist zone to lowest mining level	1,200 feet
Average loss in silica as shown by analyses	5.0%
Average specific gravity of rock in schist zone	2.85
Number of cubic feet per ton of rock in place in schist zone	12.5
Number of cubic feet per ton of quartz in place	12.0

The total volume of rock affected by alteration = 2,700 × 250 × 1,200

= 810,000,000 cu. ft. (less volume occupied by quartz veins and lenses = 9,614,000 cu. ft.*)

$$= \frac{800{,}386{,}000 \text{ cu. ft.}}{12.5} = 64{,}030{,}880 \text{ short tons.}$$

Total loss of SiO_2 in this weight of rock $= 64{,}030{,}880 \times \frac{5}{100}$

= 3,201,540 short tons.

Therefore, the amount of quartz derived by alteration = 3,201,540 short tons.
Total calculated tonnage of quartz in quartz lenses and veins

$$= \frac{9{,}614{,}000^{*} \text{ cu. ft.}}{12} = 801{,}160 \text{ short tons.}$$

The above calculations and the discussion to follow assume that there has been no change in the volume of the greenstone rock and its altered equivalents, the chlorite schist and carbonate-sericite schist. This assumption seems justified from field and laboratory studies, but even if there were small changes in volume the difference between the amount of SiO_2 liberated during alteration and that present in the known quartz lenses is so great (nearly 4 to 1), that the general conclusions would be little altered.

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* This figure has been derived from mapping and estimation of the volumes occupied by both barren and ore-bearing quartz veins and lenses. This includes the quartz remaining in the shear zone after mining as well as that removed from the stopes.

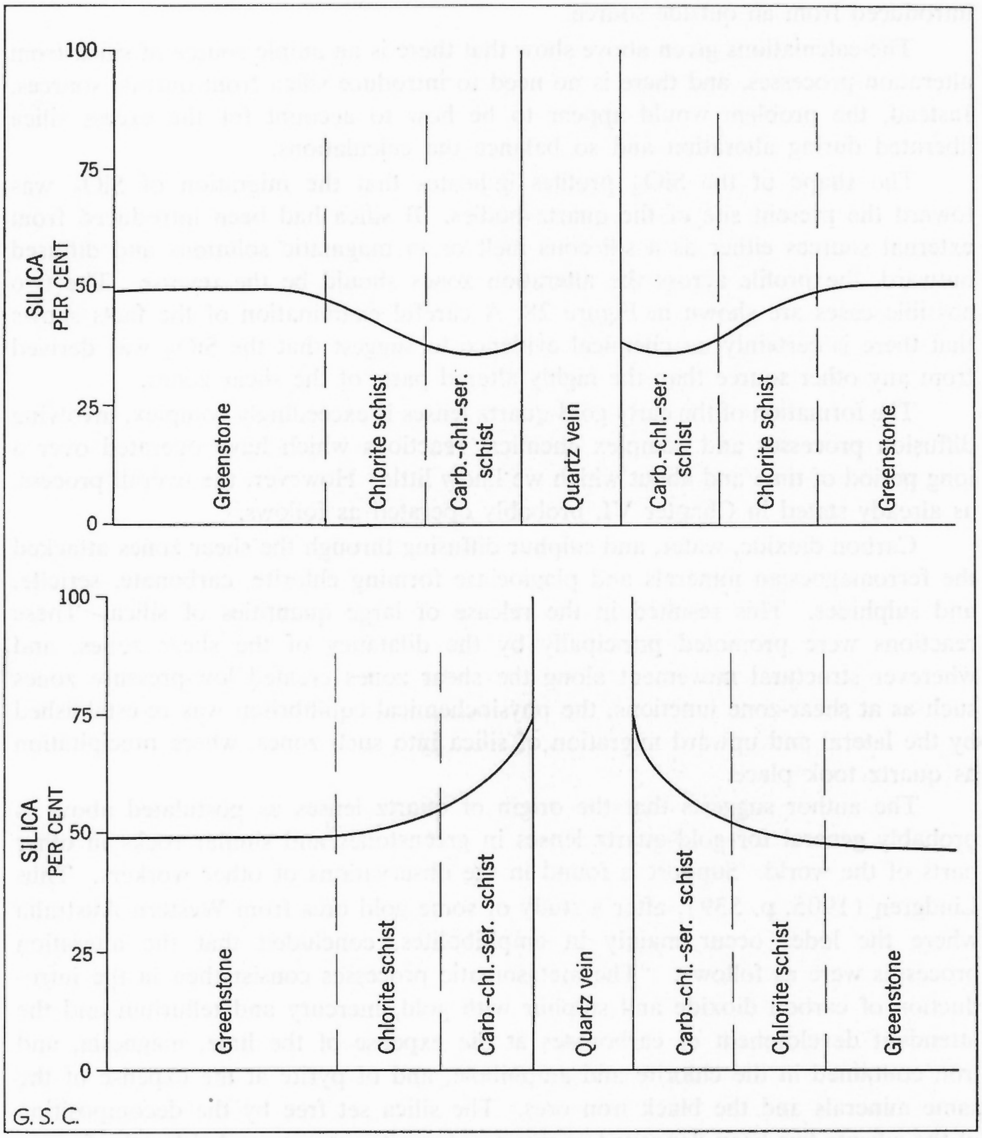

Figure 28 *(Upper) Actual per cent SiO_2 profile across alteration zones. Profile suggests diffusion of SiO_2 toward present site of quartz vein. (Lower) Expected per cent SiO_2 profile across alteration zones, if SiO_2 had been introduced and diffused outward from present site of quartz vein.*

From the evidence presented it seems probable that the SiO_2 in the quartz lenses was derived from alteration processes that took place within the shear zones. That is, the quartz of the quartz lenses came from the shear zone itself; it was not introduced from an outside source.

The calculations given above show that there is an ample source of silica from alteration processes, and there is no need to introduce silica from outside sources. Instead, the problem would appear to be how to account for the excess silica liberated during alteration and so balance the calculations.

The shape of the SiO_2 profiles indicates that the migration of SiO_2 was toward the present site of the quartz bodies. If silica had been introduced from external sources either as a siliceous melt or in magmatic solutions and diffused outward, the profile across the alteration zones should be the reverse. The two possible cases are shown in Figure 28. A careful examination of the facts shows that there is certainly no chemical evidence to suggest that the SiO_2 was derived from any other source than the highly altered parts of the shear zones.

The formation of the early gold-quartz lenses is exceedingly complex, involving diffusion processes and complex chemical reactions which have operated over a long period of time and about which we know little. However, the overall process, as already stated in Chapter VI, probably operated as follows.

Carbon dioxide, water, and sulphur diffusing through the shear zones attacked the ferromagnesian minerals and plagioclase forming chlorite, carbonate, sericite, and sulphides. This resulted in the release of large quantities of silica. These reactions were promoted principally by the dilatancy of the shear zones, and wherever structural movement along the shear zones created low-pressure zones such as at shear-zone junctions, the physiochemical equilibrium was re-established by the lateral and upward migration of silica into such zones, where precipitation as quartz took place.

The author suggests that the origin of quartz lenses as postulated above is probably general for gold-quartz lenses in greenstones and similar rocks in other parts of the world. Support is found in the observations of other workers. Thus Lindgren (1905, p. 539), after a study of some gold ores from Western Australia where the lodes occur mainly in amphibolites, concluded that the alteration processes were as follows: "The metasomatic processes consist then in the introduction of carbon dioxide and sulphur with gold, mercury and tellurium and the attendant development of carbonates at the expense of the lime, magnesia, and iron contained in the chlorite and amphibole, and of pyrite at the expense of the same minerals and the black iron ores. The silica set free by the decomposition of the silicate has been deposited as quartz where it was not needed for the formation of the new silicates sericite and albite."

Finlayson (1909), in his description of the alteration of andesite and dacite lavas and tuffs in the vicinity of the gold orebodies of the Hauraki gold fields, New Zealand, gives analyses of fresh and altered hornblende andesite which indicate that during chloritization and carbonatization processes silica is lost in the chloritized parts of the alteration zones.

Simpson and Gibson (1912) give a series of analyses of typical Kalgoorlie rocks in which the propylites (chlorite-carbonate schist) and carbonated parts show substantial losses of silica when compared with the amphibolites, gabbros, and epidiorites from which they were derived. The analyses given by Feldtmann (1916) substantiate the above conclusions. A suite of analyses of specimens from Ora Banda (40 miles northwest of Kalgoorlie) given by Clarke and Ellis (1939) however, show an increase in the silica content as the veins are approached. The specimens were, however, not in a complete sequence from one crosscut.

Moore (1912), in a study of the alteration of a Precambrian granite at the St. Anthony gold mine, Sturgeon Lake area, Ontario, found a decrease in the amount of silica as the quartz veins were approached and concluded from the analyses (page 756), ". . . a comparison of the analyses shows a regular decrease in the silica content of the granite indicating a transfer to the veins."

McCann (1922), in his study of the gold-quartz veins of the Bridge River district, British Columbia, where the veins occur in augite diorite, found a strong desilication of the adjacent wall-rocks. He made comparisons with the Grass Valley and Juneau Alaska gold deposits and found a similar phenomenon. About the silica he says (page 364), "the silica which has been lost has probably contributed to the vein filling. . . ."

Knopf (1929) in his description of the Mother Lode system in California observed (page 47), "the carbon dioxide liberated immense quantities of silica from the wall rocks, and this silica was delivered to the vein channels, where it was in part precipitated as quartz."

At Porcupine, Hurst (1935) found that during the alteration processes of the dacite, pillow lava (greenstone), and quartz porphyry in which the orebodies occur, the content of silica was decreased substantially in the altered equivalents of these rocks adjacent to the quartz bodies.

Bateman (1940), in his description of the character of the wall-rock alteration in the Uchi Lake greenstones, gives analyses and remarks on the desilication of the alteration zones adjacent to the gold veins and orebodies.

Davidson and Banfield (1944), describing the alteration associated with the Beattie gold deposits which occur in syenite porphyry and greenstones, give analyses showing a desilication of the syenite porphyry as the vein is approached. The andesite greenstone, however, shows an increase in silica as the orebody is approached. Only two analyses are given and it is difficult to draw conclusions. The andesite (dark greenstone) does not appear to be a normal sample of greenstone country rock since it contains 29.70 per cent SiO_2 and 18.75 per cent $CaCO_3$. It probably represents a phase in the alteration zones.

Cooke (1947), after a study of the Sixteen to One gold-quartz vein, Alleghany, California, which occurs in a sedimentary sequence with serpentinite bodies, suggested that the silica released as a result of chloritization, sericitization, and carbonatization from adjacent and deeper wall-rock may have formed the vein quartz.

Schmidt (1954) has dealt in some detail with the source of silica in ore deposits. He has concluded that most of the silica is derived from the desilication of alumino-silicate wall-rocks and thinks that it has been transported for distances often measured in inches, and rarely more than hundreds of feet.

Quartz-carbonate Veins and Lenses Cutting Early Gold-quartz Lenses

These veins are developed principally in the vicinity of the early gold-quartz lenses or in the more highly altered parts of the shear zones. The structural and chemical facts bearing on their origin are as follows:

1. They are structurally isolated bodies developed in tension fractures. They can be completely removed by mining and have no obvious feeder channels.
2. They contain elements and compounds such as SiO_2, CO_2, S, Ca, Mg, Fe, Cu, Sb, and Au, all which are available in large amounts in the early gold-quartz lenses and altered zones which they cut.
3. They have no obvious alteration zones and hence could not have resulted from alteration processes.

In view of these considerations it seems probable that these veins and stringers were formed by lateral and vertical secretion of their constituents from the mineralized parts of the shear zones in which they occur. The secretion processes were triggered by the dilatancy of the tension fractures, and equilibrium was re-established by the filling of the fractures with the mobile constituents from the zones which they cut, namely silica, the components of the carbonates, and locally small amounts of antimony, sulphur, arsenic, copper, and gold.

Quartz Lenses and Veins in Sedimentary Rocks

The majority of gold-quartz lenses in the sedimentary rocks have no characteristic wall-rock alteration zones, and they did not originate in the same way as those in the shear zones of the greenstones. Briefly the facts bearing on their origin are these—

1. Structurally they are isolated bodies—that is, they are in fractures, drag-folds, and faults which are local in origin. These structures are not connected to any master fractures which might have tapped magmas existing at one time thousands of feet away.
2. They are located in greywackes and slates and their metamorphic equivalents, rocks which originally had an abundance of free silica either as quartz or in a colloidal form.
3. They are in rocks which have undergone a considerable degree of metamorphism.

It is well known that silica is a very mobile compound during low-grade metamorphism. The silicification of fossils and wood and the formation of authigenic quartz serve as excellent examples of its marked mobility in such circumstances. There is, therefore, every reason to suspect that the gold-quartz lenses in the sediments are the result of metamorphic differentiation caused by (1) the formation of local dilatant zones, and (2) the consequent vertical and horizontal migration of silica into these zones during metamorphism. In no case is there a logical argument for the derivation of the silica, or indeed for the other components of the quartz lenses, from magmatic solutions.

Quartz Lenses in Late Faults

These bodies have already been explained (Chapter VI) as the result of desilication of greenstones or granites during the hydration of ferromagnesian and feldspar minerals. The liberated silica has apparently migrated upward and laterally to dilatant zones in the late faults, where it has been precipitated as quartz.

It is particularly significant that these quartz deposits occur in faults that cut the youngest igneous rocks (late diabase), and that no granitic rocks of later Precambrian age occur in their vicinity. A source of magmatic solutions is, therefore absent, and it is difficult to see how the quartz deposits could have any magmatic affiliations.

Chapter VIII

GEOCHEMISTRY AND ORIGIN OF CARBONATES

In this chapter the trends in the major and minor elemental contents of the carbonates are outlined and the variations are discussed.

With the exception of a few calcareous sedimentary lenses, most of the carbonates in the country rocks and epigenetic deposits have been derived by metamorphic or alteration processes involving the redistribution of carbon dioxide originally present in the country rocks.

Carbonates in Country Rocks

The carbonate minerals in the greenstone country rocks are calcite and ankerite. The amount of carbonate minerals differs across the metamorphic facies, being greatest in the greenschist facies with progressively lesser amounts in the epidote amphibolite and amphibolite facies respectively. This difference has been interpreted (*see* Chapter V) as the result of the redistribution during regional metamorphism of carbon dioxide originally present in the lavas.

The carbonate minerals in the sedimentary rocks are calcite with smaller amounts of ankerite. There is relatively little difference in the amounts of these two carbonates in the metamorphic facies, but the contents are generally so low that variations on a regional scale are difficult to detect either by analyses for carbon dioxide or by thin-section studies. In some localities skarn lenses containing essentially amphiboles, pyroxene, epidote, garnet, quartz, and calcite are present. Such skarn lenses are developed principally in the knotted quartz-mica schists but also in the relatively unaltered sediments, and are undoubtedly due to metamorphism of impure sedimentary calcareous lenses.

The content of carbonates in the granitic rocks and pegmatites is low compared with that in the greenstones and sediments. Calcite is the principal carbonate mineral in the granitic rocks, and in most occurrences it is secondary, appearing in seams and as a diffuse alteration of plagioclase or amphibole.

Chemistry of Carbonates in Shear Zones, Late Faults, Etc.

Chemical analyses of the three distinct ages of carbonates in the shear zones are given in Table 31. The first age constitutes the carbonate in the highly altered parts of the shear zones. This carbonate is ankerite with a high magnesium and iron content. The second age is ankerite or calcite and is present in the cross-cutting quartz-carbonate veins. This age is generally characterized by a higher calcium content and lower iron and magnesium contents. The third age occurs in late fractures and in places is being precipitated from flowing underground waters. This carbonate is generally calcite with a low iron and magnesium content.

Table 31

Analyses of Carbonates from Shear Zones of Yellowknife Greenstone Belt

Constituent	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9
CaO..........	30.44	28.57	31.10	37.49	23.25	28.05	55.20	53.85	54.91
MgO.........	18.43	15.48	5.56	11.78	11.62	11.65	0.26	0.69	0.45
FeO..........	3.27	7.37	–	–	–	6.41	0.43	0.72	0.46
Fe (Total)....	–	–	7.25	2.35	5.24				
MnO.........	0.42	0.56				0.21	0.75	0.83	0.89
Mn (Total)....			0.50	0.05	0.35				
SiO_2..........				1.50					
Loss on ignition.....				43.81					
X-ray powder pattern	ankerite	ankerite	ankerite	ankerite	ankerite	ankerite	calcite	calcite	calcite

Key

C–1. Early alteration carbonate, Giant-Campbell system, Vee Lake. (Analysis by R. J. C. Fabry.)
C–2. Early carbonate veinlets cutting early alteration carbonate, Giant-Campbell system, Vee Lake. (Analysis by R. J. C. Fabry.)
C–3. Early alteration carbonate, Negus-Rycon system. (Analysis by R. W. Boyle.)
C–4. Early alteration carbonate, Con system. (Analysis by S. Abbey.)
C–5. Early alteration carbonate, Negus-Rycon system. (Analysis by Mines Branch, Ottawa.)
C–6. Second age of carbonate in crosscutting quartz-carbonate veins, Negus mine, Campbell system. (Analysis by R. J. C. Fabry.)
C–7. Second age of carbonate in crosscutting quartz-carbonate veins, Negus mine, Campbell system. (Analysis by R. J. C. Fabry.)
C–8. Second age of carbonate in crosscutting quartz-carbonate veins, Negus mine, Campbell system. (Analysis by R. J. C. Fabry.)
C–9. Third age of carbonate (calcite scalenohedra) in late fractures, Rycon mine, Negus-Rycon system. (Analysis by R. J. C. Fabry.)

Only small amounts of calcite and ankerite occur in the gold-quartz lenses in the sedimentary rocks. Most of this carbonate is secondary, occurring in seams and small vugs in the quartz.

The content of carbonates in the late faults is relatively low compared to that present in the shear zones. Only small amounts of calcite and ankerite occur in the small lenses and seams in the breccia of the faults.

Table 32 lists spectrographic analyses of the principal ages of carbonates from characteristic occurrences. The principal minor elements in the carbonates are Si, Al, Ba, Sr, Ti, V, Sc, Y, Yb, and La.

Aluminum, silicon and sodium are present in nearly all samples analyzed. The bulk of these three elements is probably present in minute inclusions of sericite and quartz which are nearly always present in thin sections of the carbonates.

Strontium is a common minor element in all of the carbonates investigated. Barium occurs less commonly in detectable amounts but is present in most of the early alteration carbonates in the shear zones. Both these elements are commonly found in carbonates and it is probable that they occupy lattice sites and substitute for Ca^{2+}.

The more common occurrence of strontium than barium in the carbonates is probably due to the difference in ionic radii of the two elements. Sr^{2+} (1.12Å) is considerably smaller than Ba^{2+} (1.34Å) thus permitting a greater degree of substitution for Ca^{2+} (0.99Å) in the calcite and ankerite lattices.

Titanium and vanadium may be present in minute rutile or sericite inclusions in some carbonates. In others, however, this habit is unlikely because these extraneous minerals cannot be seen in any quantity in thin sections. In these

Table 32

Spectrographic Analyses of Carbonates

Description of Sample	Per-cent Concentration of Elements				
	100–10%	10–1%	1–.1%	.1–.01%	.01–.001%
Ankerite in alteration zone, Con system	Ca, Mg	Fe, Al, Si	Mn	Na, Sr, Ti	V, Ba, Cu
Ankerite in alteration zone, Giant-Campbell system, Vee Lake	Ca, Mg	Fe	Mn	Si, Cu, Sr Pb, Al	V, Ba
Ankerite in alteration zone, Negus-Rycon system	Ca	Fe, Mg, Al	Mn	Na	Cu, Sr, Ti
Calcite in quartz-calcite stringers cutting gold-quartz lenses, Campbell system, Negus mine	Ca	Mg	Fe, Mn, Si	Y, Yb, Sc, Sr	Al, Ba, V, Pb Cu
Ankerite in vug in early gold-bearing quartz, Negus-Rycon system	Ca, Mg	Fe	Si, Mn	Al	Y, Yb, La Sr
Black calcite in stringers cutting gold-quartz lenses, Giant mine	Ca		Fe, Mg	Mn, Sr	Si, Al, Cu
Late calcite scalenohedra in fracture, Con system	Ca		Mn, Fe, Y	Si, Na, Yb Mg, Sr, La Al	
Late calcite scalenohedra in fracture, Negus-Rycon system	Ca		Mn, Mg, Fe	Sr, La	Ba, Al, Si Y
Late calcite scalenohedra in fracture, Campbell system	Ca	Mn	Fe, Mg	Y, Yb, Sc Cu	Al, Sr, Si V
Late calcite scalenohedra in fracture, Giant system	Ca		Mn	Fe, Mg, Ni Ba	Si, Al, Ti, Cu, Sr
Ankerite in vug in breccia of post-diabase fault (Pud fault)	Ca, Mg	Fe	Mn	Si	Al, Sr, V
Calcite in vug in breccia of post-diabase fault (Townsite fault)	Ca	Fe	Mn, Mg	Al, Si, Y Yb, Sc	Cu, Sr, V
Ankerite in vug in giant quartz vein, West Bay fault	Ca, Mg Si	Fe	Mn	Al	Yb, Y, La, Sr

(*Semi-quantitative spectrographic analyses by Spectrographic Laboratory, Geological Survey of Canada*).

carbonates it is probable that these two elements substitute for iron in the carbonate lattice as a result of the similarity of the ionic radii of the three elements, Fe^{2+} (0.74Å); Ti^{4+} (0.68Å), Ti^{3+} (0.76Å); V^{4+} (0.63Å), V^{3+} (0.74Å). Because of the marked charge difference of the titanium and vanadium ions the substitution is, however, never extensive.

Scandium is present in the late ages of carbonates but has a general erratic distribution. The element Sc^{3+} (0.81Å) probably substitutes for Fe^{2+} (0.74Å) because of the close similarity of their ionic radii.

The spectrographic analyses suggest that yttrium and other rare earths prefer the carbonates with a high calcium content, and these elements are, therefore, enriched in the late ages of the carbonates in the shear zones. This would seem to indicate a higher mobility for these elements during low-temperature processes. The general enrichment of the yttrium earths in the carbonates, in contrast to the low and erratic contents of the cerium earths, is probably due to the easier capture of the yttrium earths to replace Ca^{2+} because of closer similarity in radii as shown below:

$$Ca^{2+}\text{—0.99Å}$$

$$\left.\begin{array}{l} Y^{3+}\text{ —0.92Å} \\ Yb^{2+}\text{—1.03Å} \end{array}\right\} \text{ Yttrium earths}$$

$$\left.\begin{array}{l} La^{3+}\text{—1.14Å} \\ Ce^{3+}\text{—1.07Å} \end{array}\right\} \text{ Cerium earths}$$

In the carbonates of the shear zones, chloride ion is a common constituent, especially in the second and third ages as shown in the following tabulation:

Type of Carbonate	*Cl (ppm)*
Ankerite in carbonate-sericite alteration zones	50[1]
Calcite and ankerite in cross cutting quartz-carbonate veins	900[2]
Scalenohedral calcite in late fractures	100[2]

[1] Analysis by R. W. Boyle.
[2] Analysis by S. Courville.

Much of the chloride ion is extractable by pulverizing the carbonate and leaching with distilled water. This suggests that the chloride ion is contained in minute inclusions of sodium or potassium chloride in the carbonates, or in these salts in crystal cavities.

Origin of the Carbonates

The amount of carbonates in the country rocks varies with the rock type and metamorphic facies. By comparison the greenstones are relatively high in carbonates whereas the sediments and granitic rocks are low. In the greenstone belt the amount of carbonates increases outward from the granodiorite contact. Thus the amphibolite facies is low in carbonates, and the amounts increase consistently across the epidote amphibolite and greenschist facies. This variation has been interpreted as due to the migration of carbon dioxide during regional metamorphism. In the sediments there is no apparent difference in the content of carbonates in the metamorphic facies.

The amount of carbonates in the epigenetic deposits differs. By comparison the shear zones in the greenstones are high in carbonates whereas the quartz lenses, shear zones, and faults in the sediments and granitic rocks are markedly low in the minerals. Carbonates are concentrated in the shear zones cutting the epidote amphibolite and greenschist facies, but those cutting the amphibolite facies contain only small amounts of carbonate minerals. There is no marked difference in the carbonate content of the quartz lenses cutting the different metamorphic facies of sedimentary rocks. Carbonates are present in small amounts in late faults cutting greenstones but are absent or present in very small amounts where they cut granitic rocks and sediments.

The foregoing facts show that the quantity of carbonates in the epigenetic deposits varies nearly directly with the amounts present in the host rocks. From this it can be inferred that the country rocks supplied the constituents of the carbonates, and it seems unlikely that magmatic hydrothermal solutions played any part in their genesis.

It has been shown in Chapter VI that the calcium, iron, magnesium, and manganese contents of the altered rocks of the shear zones remain rather constant or decrease slightly suggesting a transfer of these elements toward the quartz lenses. It follows, therefore, that none of the cationic constituents of the carbonates have been introduced by solutions or other processes. The alteration profiles across the shear zones show that carbon dioxide has been introduced, and it is apparent that this compound has diffused through the schist of the shear zones and has fixed some of the calcium, iron, magnesium, and manganese of the schist to form the early alteration carbonates. The rest of the calcium, iron etc., transferred to the quartz lenses, has been fixed by CO_2 and appears as ankerite or calcite in seams and patches in the early gold-quartz lenses.

The second age of carbonate has been precipitated nearly simultaneously with quartz in the tension fractures cutting the early carbonatized zones. As noted previously the quartz-carbonate lenses in these structures are isolated, and it seems obvious that they owe their origin to local secretion processes promoted by the dilatancy of the tension fractures. The fact that the carbonates are high in calcium and low in iron and magnesium suggests that the latter two elements were relatively immobile during these processes.

The carbonates in late fractures have been precipitated from underground waters which flow along the fractures and contain all of the elements present in the carbonates (*see* Chapter XI). The precipitation is taking place in some fractures at the present time.

The small amounts of carbonates in the late faults have probably been derived locally by diffusion processes. It seems particularly significant that these carbonates occur mainly in the faults cutting greenstones (rocks relatively high in CO_2), whereas they are almost absent in those cutting granitic bodies (rocks low in CO_2).

Chapter IX

GEOCHEMISTRY AND ORIGIN OF SULPHIDES

This chapter outlines the geochemistry of the sulphide mineralization of the Yellowknife district and discusses the paragenesis and origin of the various types and ages of sulphides.

Sulphur, arsenic, and antimony were original constituents of the host rocks, and were present in sufficient quantities to supply the amounts concentrated in the deposits. The epigenetic sulphides in the shear zones originated partly by a redistribution of sulphophile elements during regional metamorphism of the greenstones, and partly as a result of the alteration processes which formed the extensive schist zones. The sulphides in the quartz lenses in the sedimentary rocks are the result of metamorphic differentiation processes, and their migration and concentration were promoted principally by the dilatancy of the structures in which they occur.

The successive ages of sulphides in the shear zones of the greenstones and quartz lenses of the sediments are thought to be the result of two processes—(1) exsolution of certain elements from an early suite of sulphides, and (2) local secretion processes which concentrated the exsolved elements. Both these processes operated simultaneously and were promoted by shearing, fracturing, and recrystallization after the deposition of the early sulphides. There is little evidence to support the thesis that successive ages of sulphides represent separate introductions from hydrothermal solutions.

Sulphides in Country Rocks

The sulphur content of the greenstones (*see* Tables 9, 15, and 16, pp. 67, 78, and 92) is held mainly in pyrite with smaller amounts in pyrrhotite and chalcopyrite. The arsenic and antimony are contained mainly in pyrite with smaller amounts in pyrrhotite. These elements accompanied the magmas which formed the lava rocks of the greenstone belt and are therefore, syngenetic. As shown by the analyses of the greenstones (Table 16) there is a general but small increase in the content of sulphur toward the lower-grade facies. This increase has been interpreted as due to the effects of regional metamorphism. The original sulphur, together with other chalcophile elements, was mobilized and migrated from high- to low-temperature regions.

The sulphur, arsenic, and antimony contents of the sedimentary rocks (Tables 10 and 15, pp. 69 and 78) are contained principally in pyrite and pyrrhotite. These three elements were deposited during sedimentation processes and are, therefore, syngenetic. There is no apparent difference in the content of sulphur across the metamorphic facies, indicating relatively little migration on a broad scale during regional metamorphism.

Certain slates and argillites in the sedimentary area, and tuffs in the greenstones contain much graphitic material and are relatively high in sulphur compared with the other sedimentary rocks. The presence of both carbon and sulphur, two elements essential for life, suggests that organic processes have played a large part in concentrating sulphur in these rocks. It is well known that sulphur is markedly concentrated in black sediments, and in fact such a concentration is normal in present day sapropels and other organic muds in foul bottoms of seas and lakes. In such reducing environments sulphur bacteria play a major part by reducing sulphates and producing H_2S which binds any available iron and other chalcophile elements into sulphides. During metamorphism these sulphides may be recrystallized, and some of their components may be mobilized and swept into fractures, faults, and other dilatant zones.

All granitic rocks are low in sulphides (*see* Tables 12 and 13, pp. 71 and 72). Some porphyries, on the other hand, are enriched in sulphur which is present mainly in pyrite or pyrrhotite. These sulphides appear to be syngenetic and not introduced subsequently into the porphyries.

The late diabase (*see* Table 14, p. 77) contains on an average 700 ppm, sulphur. This value is also probably indicative of the original content of sulphur in the lavas of the greenstone belt.

Chemistry of Sulphides in Epigenetic Deposits

The principal sulphides in the epigenetic deposits in the greenstones are pyrite and arsenopyrite. Small amounts of chalcopyrite, sphalerite, pyrrhotite, stibnite, sulphosalts, galena, and molybdenite are present in the various deposits, but large concentrations of these sulphides are uncommon.

In the quartz lenses in the sediments the principal sulphides are pyrite, sphalerite, and galena with smaller amounts of pyrrhotite and chalcopyrite.

Analyses of ores from the greenstone belt and from one deposit in the sediments are given in Table 33. These analyses serve to emphasize that pyrite and arsenopyrite are the most abundant sulphides in the ores of the greenstone belt, and that pyrite, sphalerite, and galena are the most abundant in those of the sediments. Despite the presence of stibnite and sulphosalts in most polished sections of the ores from the greenstone belt, the content of antimony is never high as shown by the analyses. The orebodies near A shaft in the Giant system have a low antimony content as shown by the analyses. This is, however, not typical of all ores in this system. Those at B and C shafts contain more sulphosalts, and the antimony content would equal or exceed that present in the Con and Negus-Rycon systems. Recent metallurgical work also indicates that the antimony and arsenic contents of the Giant ores increase with depth.[1] The content of Zn, Cu, and Pb in the ores of the greenstones is generally small, attesting to the general low content of sphalerite, chalcopyrite, and galena.

Spectrographic analyses of the principal sulphides are given in Tables 34 to 42 inclusive. The following interesting features are shown by these analyses.

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[1] A. S. Dadson, personal communication.

Table 33

Analyses of Gold Ores, Yellowknife District

Key: Dash indicates content not determined.
N.D.—not detected.

Constituent	Con Mine[1] (Con System)	Negus Mine[2] (Negus-Rycon System)	Giant Mine[3]	Giant Mine[4]	Giant Mine[5]	Prosperous Lake[6]
Au (oz./ton)	0.57	4.09	0.42	0.65	0.92	0.53
Ag (oz./ton)	0.19	4.38	0.085	0.10	1.21	0.26
Fe (total) (%)	5.53	2.10	7.64	7.75	6.84	2.49
S (%)	1.22	0.65	3.64	3.12	3.07	1.93
As (%)	0.49	0.10	1.56	1.29	3.31	N.D.
Sb (%)	0.14	0.19	—	N.D.	trace	—
Cu (%)	trace	0.12	—	0.03	trace	0.015
Zn (%)	0.35	0.41	—	0.08	nil	1.32
Pb (%)	trace	trace	—	N.D.	0.05	0.12

[1] Analysis made on 120 pounds of mill feed; Mines Branch, Ottawa, Investigation No. 867.

[2] Analysis made on 587 pounds of high-grade gold ore; Mines Branch, Ottawa, Investigation No. 742.

[3] Analysis made on 11,180 pounds of gold ore, A shaft, Giant mine; Mines Branch, Ottawa, Investigation No. 2,100.

[4] Analysis made on 2,513 pounds of gold ore, A shaft, 200-level, Giant mine; Mines Branch, Ottawa, Investigation No. 2,078.

[5] Analysis made on 110 pounds of gold ore, A shaft, surface, Giant mine; Mines Branch, Ottawa, Investigation No. 1,788.

[6] Analysis made on 330 pounds of gold ore, Tin claims located in sediments south of Prosperous Lake; Mines Branch, Ottawa, Investigation No. 1,231.

Pyrite from all occurrences tends to collect most of the chalcophile elements among which Ni, Co, Cu, Zn, Mn, Pb, As, Sb, Ga, Sn, In, V, Ag and Au are most common. All these elements probably occur in the lattice of the pyrite. The Al, Ti, Cr, Mg, and some of the V and Mn may be present in small specks of ilmenite and magnetite which can often be seen in polished sections. The Si, Ca, Sr, Ba, and some of the Al are present in quartz, sericite or carbonate inclusions.

Like pyrite, arsenopyrite tends to collect many chalcophile elements especially Co and Ni. In nearly all arsenopyrite Sb is present as shown by qualitative chemical analyses. This element has a high volatility in the arc and may not always report in spectrographic analyses. Ag and Au are also present in most occurrences of arsenopyrite as shown by assay. In the spectrograph, however, gold has a low sensitivity and may not be detected unless present in significant amounts.

Pyrrhotite appears to have a relatively low tolerance for extraneous chalcophile elements. With the exception of Ni, Co, and Cu, the other common chalcophile elements are either absent or present in amounts less than 10 ppm.

Stibnite and the various sulphosalts are generally so intimately mixed with one another and with sphalerite and other minerals that few generalizations can be made. Te, Ag, and Au are common minor elements in these sulphides and probably occupy lattice sites.

The principal minor elements in sphalerite are Cd, Ag, and Pb. In chalcopyrite, Ag, Zn, and Pb are common. Te appears to be concentrated in galena. Tin occurs sporadically in some ores and has been mentioned by Jolliffe (1938). Most of the tin is probably in stannite which has been identified mineralogically. Minor trace amounts also occur in pyrite, galena, and sphalerite.

At one stage in the investigation, attempts were made to relate the content of minor elements in various sulphides to depth below the surface and to pyrite geothermometer readings (Smith, 1947). Other attempts were made to correlate the minor elements with the gold content of the lodes. None of these investigations were successful because it is nearly impossible to obtain pure samples of individual sulphides. Furthermore there is often a very erratic distribution of

Table 34

Spectrographic Analyses of Pyrite from Characteristic Occurrences

Description of Sample	Per cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
In quartz-feldspar porphyry, vicinity of Negus and Rycon mines	Fe		Al, Si, Ti	Ni, Cu, Zr, Zn, Ca	Mg, Mn, Pb, Y, Yb, Ba, Ag
Cubes in chlorite schist, Campbell system	Fe			Si, Al, Ca Ba	Mn, Mg, As, Ni, Cu, Ag, Ti, Co, Sr, Cr, Ga, Sb
In carbonate-sericite schist, Campbell system	Fe			Mg, As, Al, Au, Ca	Si, Mn, Ni, Cu, Ag, Ti, Co, Sr, Ba, Cr
Cubes in chlorite schist, Giant system	Fe		Al, Ti	Si	Mg, Mn, Ca, Ni, Co, Cu, V, Sr
In carbonate-sericite schist, Giant system	Fe			Si	As, Pb, Cu, Bi, Ag, Ti, Au, Mg, Mn, Ni, Co
In quartz lenses, Negus-Rycon system	Fe			As, Au, Ca	Sb, Si, Mn, Pb, Mg, Ni, Al, Cu, Ag, Co, Cr, Ga, Sn, In, V, Ti, Zn
In quartz lenses, Ptarmigan mine	Fe			As, Ni	Si, Mg, Cu, Ag, Co, Ga, Pb
Splendent, in late fracture, Negus-Rycon system	Fe			As	Sb, Si, Mg, Sn, Ni, Al, Cu, Ca
Dull reniform, from late fracture, Negus-Rycon system	Fe			As, Sb, Co, Ni, Si, Ca, Mn, Cu, Pb, Ag, Mg	Ga, Al, V, In, Ti, Cr, Sr

(Semi-quantitative Spectrographic analyses by Spectrographic Laboratory, Geological Survey of Canada.)

minor elements in the sulphides. Whether this is due to analytical errors or to erratic natural variations is not clear. Perhaps statistical methods could be adapted to work of this kind with better results.

Table 35

Spectrographic Analyses of Arsenopyrite from Characteristic Occurrences

Description of Sample	Per cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
In alteration zone adjacent to gold-quartz lens, Con system	Fe, As		Si	Al, Sb, Ti, Pb, Ni	Mg, Ca, Mn, Cu, Cr, Co, Ag, Bi, Au
In alteration zone adjacent to gold-quartz lens, Campbell system	Fe, As		Al, Ti	Si, Ni, Mn, Co	Mg, Ca, Cu, Au
In alteration zone adjacent to gold-quartz lens, Giant system	Fe, As	Si, Al Mg, Ca	Na, Ti, Cr	Mn, V, Ni, Ba	Co, Be, Sc, Cu, Zr, Ag, Au
In white quartz lenses cutting early gold veins, Con system	Fe, As		Si, Al	Co, Ca, Ti, Ni, Mg, Cr, Ba	V, Ag, Mn, B, Cu, Sb, Pb, Be
In quartz-carbonate stringers cutting early mineralized zones, Campbell system	Fe, As			Si, Ni, Mn, Al, Co, Ti	Mg, Ca, Cr, Cu
From Burwash prospect; vein cuts sediments	Fe, As		Si, Al, Mg	Ni, Ti, Ca, Ba	Mn, Pb, V, Ag, Cu, Co

(Semi-quantitative Spectrographic Analyses by Spectrographic Laboratory, Geological Survey of Canada.)

Table 36

Spectrographic Analyses of Pyrrhotite from Characteristic Occurrences

Description of Sample	Per cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
In fractures, Negus-Rycon system (age uncertain)	Fe			Ni, Cu	Co, Mn, Mg, Si, Ca, Ba
In fractures, Crestaurum mine	Fe			Ni	Mg, Si, Ca, Cu, Co
Associated with pyrite in tuff bed, Giant mine	Fe		Al, Si	As, Ca	Mn, Mg, Ni, Co, Cu
In tuff, Ranney system	Fe			Si, Al	Mn, Mg, Ti, Ni, Cu, Co, Ca

(Semi-quantitative Spectrographic Analyses by Spectrographic Laboratory, Geological Survey of Canada.)

Table 37

Spectrographic Analyses of Stibnite from Characteristic Occurrences

Description of Sample	Per cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
Massive, with minor amounts of sulphosalts, Rycon mine	Sb, Si		Fe	As, Ca, Cu	Mn, Te, Pb, Mg, Bi, Al, Ag, Au
Massive, with minor amounts of sulphosalts, Giant mine	Sb	Si		Pb, Cu, Ag	Fe, Mg, Ni, Al, Ca, Au

(Semi-quantitative Spectrographic Analyses by Spectrographic Laboratory, Geological Survey of Canada.)

Table 38

Spectrographic Analyses of Sulphosalts from Characteristic Occurrences

Description of Sample	Per cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
Composite sample from Giant mine; some admixed sphalerite	Fe, Zn	Sb, Pb	As, Si Mg	Cu	Ca, Ni, Ag, Co
Composite sample from Ranney system; some admixed sphalerite	Zn, Fe Pb	Sb	As, Si		Mg, Mn, Cu, Ag, Cd
Composite sample from Negus-Rycon system	Fe	Si, Sb	Pb, Au, Bi Cu, Ag	Zn, As	Al, Mn, Mg, Cd, Te
Freibergite in quartz-carbonate stringers; associated with chalcopyrite and gold —Campbell system	Cu, Fe	As, Sb, Ag, Fe	Si, Al, Ca, Zn	Mn, Ni, Bi Ba	Mg, Au
Composite sample from Crestaurum system	Fe, Sb	Si	Al	As, Mg, Ti Cu	Mn, Pb, Ca B

(Semi-quantitative Spectrographic Analyses by Spectrographic Laboratory, Geological Survey of Canada)

Table 39

Spectrographic Analyses of Sphalerite from Characteristic Occurrences

Description of Sample	Per cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
Dark, in vug, Rycon mine	Zn, Fe		Si,Cd	Na, Mg, Ca Ag, Al	Cu
Amber-coloured, in fracture cutting early quartz, Campbell system	Zn	Fe, Si	Cd	Na, Mg, Ca Ag, Al	Cu
Amber-coloured, in late fracture, Campbell system	Zn	Fe	Si, Cd	Sb, Cu, Ca As, Pb, Mg	Mn, Al, Sn, Ag, Ti
Dark, in vuggy quartz, Ptarmigan mine	Zn, Fe	Si	Cd	As	Mn, Pb, Mg, Bi, Al, Cu, Ag, Co

(Semi-quantitative Spectrographic Analyses by Spectrographic Laboratory, Geological Survey of Canada.)

Table 40

Spectrographic Analyses of Chalcopyrite from Characteristic Occurrences

Description of Sample	Per cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
Associated with tetrahedrite and gold in quartz-carbonate stringers, Campbell system	Cu, Fe		Pb	Zn, Ni, Bi, Al, Ag, Ca	Si, Mn, Mg, Ba
From Crestaurum system, associated with molybdenite	Cu, Fe	Si	Al	Mg, As, Ti	Mn, Pb, Mo, V, Cr, Ag, Ca, Ba
From late fault	Cu, Fe		Si	Pb, Bi, As	Mg, Ag, Zn, Al, Ti, Mn

(Semi-quantitative Spectrographic Analyses by Spectrographic Laboratory, Geological Survey of Canada.)

Table 41

Spectrographic Analyses of Galena from Characteristic Occurrences

Description of Sample	Per cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
In calcite in quartz-carbonate stringers cutting early gold-quartz lenses, Con system	Pb		Si, Fe As, Ag, Sb, Cu	Te, Mg, Bi, Zn	Mn, Al, Ca, Ti, Sn
In vuggy quartz, Ptarmigan vein	Pb	Si	Bi	As, Ag	Te, Fe, Mn, Mg, Al, Ca, Cu, Sn

(Semi-quantitative Spectrographic Analyses by Spectrographic Laboratory, Geological Survey of Canada.)

Table 42

Spectrographic Analyses of Molybdenite from Characteristic Occurrences

Description of Sample	Per cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
In quartz-feldspar porphyry matrix, Con mine	Mo	Si, Fe, Al		Mg	
In quartz lens, Crestaurum system; associated with chalcopyrite	Mo	Si	Al, Fe	Mg, Ti, As	Mn, Pb, Cu, V, Ba, Ca
In quartz lens, Crestaurum system; associated with bismuthinite	Mo	Si	Al, Fe	Mg, As, Ti	Mn, Ni, V, Cr, Ba, Ca, Cu

(Semi-quantitative Spectrographic Analyses by Spectrographic Laboratory, Geological Survey of Canada.)

Origin of Sulphides in Epigenetic Deposits

There are several features in the distribution of the chalcophile elements in the host rocks and in structures of widely differing age that bear directly on the origin of the sulphides in the epigenetic deposits. A few of these are discussed below.

The greatest quantity of sulphides is concentrated in the shear zones of the greenstones and in the quartz lenses of the sediments. By contrast the content in the late post-diabase faults is low. Another fact is that the early deposits were formed during the period of regional metamorphism of the sediments or during the last stages of metamorphism of the greenstones. When the deposits in the late faults were formed, the processes of regional metamorphism were not operative. Correlation of these facts indicates that the processes of regional metamorphism played a major part in the concentration of the sulphides. We may, therefore, infer that during regional metamorphism when the temperature was high, some of the sulphur, arsenic, antimony, and other chalcophile elements in the country rocks were mobilized and migrated into the shear zones of the greenstone belt or into the quartz lenses in the sediments. When the late faults were formed, the wave of regional metamorphism had passed and the chalcophile elements were immobile. Hence, they did not concentrate in the late structures.

In a general way the amount and type of sulphide in the epigenetic deposits seems to depend upon the content of chalcophile elements in the rocks which the deposits cut. A few examples of this feature will be given.

In the greenstone belt it is apparent from the analyses in Table 33 that the shear zones contain only small amounts of lead and zinc. On the other hand the quartz lenses in the sediments are relatively high in these two elements. Geochemically, the abundance of lead and zinc is generally lower in basic rocks than in sediments (*see* Table 15, p. 78). The inference is obvious, therefore, that the availability of lead and zinc in the host rocks has been a deciding factor in their concentration in the deposits.

Another example of this relationship is the distribution and content of molybdenite in the deposits. Acid rocks generally contain more molybdenum than basic rocks, as shown by the following values given by Rankama and Sahama (1950).

	Mo (ppm)
Gabbros and norites	3
Subsilicic rocks (U.S.A.)	2
Granite, Schwarzwald, Germany	12
Silicic rocks (U.S.A.)	2.5

At Yellowknife the porphyries are enriched in molybdenum and the content in the granitic rocks is generally higher than in other rocks. Molybdenite is not abundant in any of the deposits, but where present this sulphide occurs generally in deposits cutting porphyries, granitic rocks or in zones in or immediately adjacent to granitized rocks. This suggests that the content of molybdenum in the epigenetic deposits is dependent principally upon the original elemental content of the host rock and not on magmatic hydrothermal agencies. If the latter were responsible it is difficult to understand why molybdenum should be deposited only in structures in acidic rocks or in rocks in their near vicinity.

Finally, the control exerted by the host rocks on the content of sulphides is shown rather well in both shear zones and late faults cutting across different rock types. Shear zones and late faults are remarkably low in sulphides where they cut the sulphur-poor granitic rocks but traced into the relatively sulphur-rich greenstones or sediments they increase markedly in their sulphur content. There is, therefore, a direct relationship between the content of sulphides in the deposit and the content in the host rocks, and it is difficult to conceive of any other than secretion processes as an explanation of this phenomenon.

In the shear zones four distinct ages of sulphides are present as follows:

1. Early pyrite and arsenopyrite in alteration zones enveloping quartz lenses and in fragments and seams of schist contained in the quartz lenses. In places small amounts of chalcopyrite, sphalerite, and pyrrhotite are associated with the early pyrite and arsenopyrite and appear to have been deposited simultaneously with these minerals.

2. Stibnite, sulphosalts, sphalerite, pyrite, galena, and chalcopyrite in vugs, fractures, and crushed zones in the early quartz lenses. These sulphides are definitely later than those in 1, because they vein the early pyrite and arsenopyrite.

3. Small amounts of chalcopyrite and sulphosalts, principally tetrahedrite and bournonite in crosscutting quartz-carbonate stringers and lenses.

4. Pyrite and marcasite with minor amounts of sphalerite and sulphosalts in late fractures and small faults. These sulphides are younger than 1, 2, and 3.

Age relationships similar to the above have been repeatedly described in the literature and are nearly always explained by separate introductions of material from hydrothermal solutions. While this may be true in some deposits, the evidence for such repeated introductions is not convincing at Yellowknife. The facts bearing on the problem are as follows:

The late generations of sulphides are always concentrated in zones containing an abundance of early pyrite, arsenopyrite, sphalerite, and chalcopyrite and are especially common where pyrite and arsenopyrite have been crushed, granulated, or recrystallized. Furthermore, the later ages of sulphides contain only the elements which are concentrated in the early sulphides. Spectrographic analyses of early pyrite and arsenopyrite show conclusively that they contain As, Sb, Cu, Zn, Pb and other chalcophile elements, and these sulphides could, therefore, be a source for the elements in later generations of sulphides.

Coleman (1953, p. 516) emphasized the above relationships when he wrote:

> The sulphosalts appear to have a chemical similarity to the associated pre-existing metallic minerals. Tetrahedrite is commonly associated with chalcopyrite and appears to replace it. Chalcostibite was found only where there were older copper minerals, as was commonly bournonite. Berthierite occurs principally with abundant pyrite or arsenopyrite. These associations suggest that some of the constituent metallic elements of the sulphosalts, were present before the introduction of the solutions from which these minerals formed. Much of the sulphosalts may have been formed by reaction of pre-existing sulphides with an antimony rich fluid.

The chemical similarity of late sulphosalts and earlier sulphides, therefore, seems quite clear. The introduction of antimony from an outside source however, seems unnecessary because an adequate source would seem to be available in both early pyrite and arsenopyrite.

Considering the problem as a whole, it seems probable that the components of the late generations of sulphides merely represent redistributed material from the early sulphide minerals. The process probably took place as follows: During the formation of the shear zones, sulphur, arsenic, and antimony together with other chalcophile elements migrated into dilatant zones. Here the sulphur and arsenic reacted with the available iron to form pyrite, arsenopyrite, and locally pyrrhotite. Where the concentrations of copper and zinc were great enough, chalcopyrite and sphalerite were formed. At the high temperatures which prevailed during this period, pyrite and arsenopyrite would tolerate a high content of Sb, Cu, Zn, Pb, etc., because their structures would be expanded, disorder would be great, and hence substitution would be facilitated. As the deposits cooled, two interacting factors would come into play—repeated shearing and fracturing resulting in the crushing and recrystallization of the early sulphides and the formation of local tension fractures or faults, and exsolution of Sb, Cu, Zn, etc., because of the low tolerance of pyrite and arsenopyrite for these elements at low temperatures. The Sb, Cu, Zn, etc. thus set free, together with some sulphur, would migrate into and be precipitated in any available fractures, faults, or other open spaces.

In quartz lenses in the sediments the sulphides are generally intergrown with one another in a manner suggesting contemporaneous deposition. They appear to have originated principally by processes of metamorphic differentiation and were concentrated at the same time as the quartz. Where successive ages of sulphides are present they probably originated in a manner similar to that suggested for those in the shear zones of the greenstones.

On quantitative grounds some may question the postulate that the host rocks were the source of the sulphur 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. Table 43 gives total amounts of S, As, Sb, Cu, and Zn 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 (Table 15, p. 78), were taken as follows: S—1,500 ppm, As—3 ppm, Sb—1 ppm, Cu—50 ppm, and Zn—50 ppm. The amount of ore 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 given in Table 33, was taken as follows: S—2.34%, As—1.35%, Sb—0.15%, Cu—0.07%, and Zn—0.28%.

The author is fully aware that many factors enter into calculations such as those given in Table 43. 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 sulphur, arsenic, antimony, and chalcophile elements could have been derived solely from the sheared rock of the shear zone. This argument is further strengthened by the analyses given in Table 21 (p. 110) which suggest that during the formation of the chlorite schist zones, sulphur is liberated and probably concentrated in the carbonate-sericite zones and quartz lenses. When one considers the probable contribution of the sulphide constituents 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.

Table 43

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	0.12	0.081	64.8
Sb	0.04	0.009	22.5
Cu	2.0	0.004	0.20
Zn	2.0	0.017	0.85

The results of an extensive sulphur isotopic investigation of the sulphides are reported elsewhere, (Wanless, Boyle, and Lowdon, in press). Briefly, the isotopic work confirms the conclusion that the sulphides in the deposits were derived from the country rocks (greenstones and sediments) and that their present sulphur isotopic distribution was determined by temperature, pressure, and chemical potential gradients.

Chapter X

GEOCHEMISTRY AND ORIGIN OF GOLD AND SILVER

This chapter discusses the distribution of gold and silver in the country rocks and deposits of the district, and outlines the geochemistry of the two elements and their origin in the epigenetic deposits.

Both gold and silver are constituents of all rocks in the Yellowknife district and are present in amounts sufficient to produce any of the concentrations in the epigenetic deposits. It is, therefore, unnecessary to call upon magmatic hydrothermal solutions as a source. Gold and silver have a decided affinity for sulphur, arsenic, and antimony, and together with these elements have been concentrated in quartz veins and lenses by secretion processes. The various generations of gold in a single deposit are thought to have resulted by redistribution of the element within the deposit and not to separate introductions.

Native silver does not occur in any of the deposits. Elemental silver occurs alloyed with gold or in sulphides where it substitutes in their lattices. References to silver in the following, are to the element and not the mineral.

Gold and Silver in the Country Rocks

Table 44 lists the contents of gold in the country rocks, shear zones, and deposits. The determination of small amounts of gold and silver in rocks is beset with many difficulties, and it is impossible in many cases to obtain consistent results. The analyses for gold were done by assay methods of large amounts of material, and blanks were subtracted in each case. The low gold contents were checked in some cases by spectrographic methods after chemical enrichment of gold from separated sulphides contained in the rock. The consistency of the results by the two methods was never good, but the values obtained are of the same order of magnitude as those of similar rocks examined by neutron-activation methods by Smales (1955). The silver values were determined by assay and confirmed by spectrographic methods with consistent results.

Goldschmidt (1954) assumes that the ratio of silver to gold in magmatic rocks cannot be less than 20:1. Since the silver analyses given in the table appear to be fairly reliable these could be used as a standard for calculating the gold content. Such a calculation, however, gives values much higher than those given by assay. This may mean that the gold values recorded by assay are too low.

Analyses and assays of separated minerals of the country rocks suggest that most of the gold and silver are bound in the various sulphides. Only small amounts occur in the iron oxides, silicates, and other minerals.

In the greenstone belt, about equal amounts of both elements occur in the metamorphic facies and western granodiorite. The quartz-feldspar porphyries and graphitic tuffs, rocks which are high in sulphides, are enriched in gold and silver. The high sulphide content of the porphyries is thought to be due to granitization processes and the gold and silver probably had a similar origin. As noted in a previous chapter, the high sulphide content of the tuffs is probably due to the action of sulphur bacteria which produced H_2S from the sulphates of the sea water. This H_2S has fixed the available chalcophile elements, including gold and silver, in the sulphides of the tuffs.

There is little difference in the contents of gold and silver in the rocks of the sedimentary area. The argillites and slates are probably a little higher than other sedimentary rocks. Their sulphide content is generally higher and is probably derived by processes similar to those described above for the tuffs. The pegmatites are relatively low in both gold and silver and in sulphur, and stand in marked contrast with the sulphur-rich gold-quartz lenses.

It is probable that the gold and silver contents of the rocks and deposits vary directly with their sulphur and arsenic contents. This is shown in a general way in Table 44. While this relationship can be seen where large amounts of silver, gold, sulphur, and arsenic are present, it is not as obvious when dealing with small amounts.

Table 44

Gold and Silver Content of Country Rocks, Shear Zones, and Deposits

Description of Rock or Deposit	Au[1] (ppm)	Ag[2] (ppm)	S[3] (ppm)	As[4] (ppm)
Greenstone Belt				
Amphibolite facies	0.01	0.6 – 1.4	1,100	2–10
Epidote amphibolite facies	0.008	0.3 – 1.2	2,200	2–10
Meta-diorite and gabbro dykes	<0.01	0.3 – 1.4	1,200	2–10
Graphitic tuffs	0.01–0.07	0.2 – 2.0	14,500	5–100
Western granodiorite	<0.01	0.4 – 1.4	200	<5
Quartz-feldspar porphyry	0.10	0.6 – 2.0	8,000	10–150
Average of chlorite-schist phase of shear zones (Giant-Campbell system)	0.017	0.256	1,200	60
Average of carbonate-sericite schist phase of shear zones (Giant-Campbell system)	0.632	1.13	32,600	15,000
Average of gold-quartz lenses (Giant-Campbell system) (0.654 oz. Au/ton, 0.139 oz. Ag/ton)	22.30	4.77	31,400	17,900
Sedimentary Area				
Knotted quartz-mica schists	0.01	0.9 – 1.2	1,300	5–20
Argillites and slates	0.01	0.3 – 2.0	3,000	5–20
Greywacke	<0.01	0.3 – 1.2	1,400	5–20
Prosperous Lake granite	0.01	0.3 – 1.4	trace	<5
Average of pegmatites	<0.01	0.20	trace	<5
Average of gold-quartz lenses, Tin claims	18.25	8.93	19,300	trace
Late-diabase Dykes	<0.01	1.4	700	4
Late Faults—all rocks	trace to 0.02	trace	trace	trace

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[1] Assays by Mines Branch, Ottawa.

[2] Assays by Mines Branch, Ottawa; confirmed by spectrographic analyses Geological Survey of Canada.

[3] Average values from chemical analyses.

[4] Ranges and average values from chemical and spectrographic analyses.

Geochemistry and Origin of Gold and Silver in the Epigenetic Deposits

Table 45 gives spectrographic analyses of native gold from the characteristic occurrences. Silver is present in all gold but varies in amount in the various occurrences. Small amounts of Fe, Pb, Bi, As, Sb, Cu, and Hg are also present and undoubtedly substitute in the metallic lattice of the mineral. The other elements are probably contaminants and occur in small inclusions of quartz, carbonate, or sericite which are commonly seen in polished sections of the gold.

In the deposits within the greenstone belt the ratio of gold to silver in the ores is approximately 5 to 1, as determined from production figures. In the quartz lenses of the sedimentary area the ratio is approximately 3.5 to 1, as calculated from the available assays.

Table 45

Spectrographic Analyses of Gold from Characteristic Occurrences

Description of Sample	Per cent Concentration of Elements				
	100–10%	10–1%	1–0.1%	0.1–0.01%	0.01–0.001%
In early quartz lenses, Con system	Au, Ag		Si, Hg Pb, Bi	Ca, Fe	As, Sb, Mg Al, V, Cu, Ti
In early quartz veins, Negus-Rycon system	Au, Ag		Si	Hg, Sb Fe, Ca	As, Mg, Pb, Bi Al, V, Cu, Ti
In early quartz lenses, Giant system	Au	Ag		Al, Si Ti, Cu	Fe, B, Mg Sr
In quartz-carbonate stringers cutting early quartz lenses, Campbell system	Au, Ag		Si	As, Hg, Ca Mg, Fe	Sb, Pb, Al, V Cu, Ti
From ice lens, Giant mine	Au		Ag	Fe	Si, Mg, Al Cu
From Ptarmigan veins	Au	Ag		Si, Al, Pb	Mg, Cu, Fe

(*Semi-quantitative spectrographic analyses by Spectrographic Laboratory, Geological Survey of Canada*).

Silver is strongly chalcophile in nature, and in a sulphur-rich environment generally forms sulphides or sulphosalts. The element also occurs in the native state, but in deposits of the Yellowknife-type it is commonly alloyed with gold.

Gold is strongly siderophile and tends to occur in the free state generally alloyed with silver or copper. The element also has a chalcophile tendency and forms two artificial sulphides. Its chalcophile tendency is further shown by its constant occurrence either in or associated with various sulphides, of which pyrite and arsenopyrite are the most common.

Investigations on the nature of gold in pyrite have been carried out by Bürg (1930, 1935), Head (1934, 1935), Haycock (1937), van Aubel (1939), Kuranti (1941), Maslenitsky (1944), and Stilwell and Edwards (1946). Some investigators hold that most of the gold occurs in the native form as microscopic or submicroscopic particles dispersed through the pyrite or in fractures etc.; others maintain that some of the gold is held in the lattice of the pyrite. Both views are probably correct as will be shown presently.

Under the microscope one often observes native gold in pyrite and arsenopyrite as well as in nearly every other sulphide. On the other hand some pyrite and arsenopyrite containing high contents of gold contain no observable particles of gold. In this case, as well as with other gold-bearing sulphides, it is generally necessary to liberate the gold by roasting methods prior to cyanidation. Such an extreme treatment suggests that the gold is part of the sulphide and not held as a mechanical mixture.

Pyrite and arsenopyrite, as well as many other compounds of the transition metals with non-metallic elements or metalloids, possess a moderate degree of metallic bonding. This increases with increase in the metallic or electropositive character of the constituent elements. Because of their partly metallic character, it would be expected that most sulphides, arsenides, antimonides, etc. would accommodate small amounts of nearly all metals in their structures, gold and silver being no exception. In other words these sulphides, arsenides, etc. behave in part as alloys. Furthermore, both gold and silver have a chalcophile character which means that both may be present in sulphides bound to sulphur atoms.

These theoretical possibilities have been investigated experimentally by Maslenitsky (1944) and Kuranti (1941). Both were able to synthesize gold-bearing iron sulphide in which the gold could not be detected microscopically. Kuranti's results are especially significant. He found that up to 2,000 ppm gold could be substituted in the pyrite lattice, and further that the lattice constant of pyrite decreases with increasing gold content, a fact proving solid solution of gold in pyrite.

While these experiments are mainly concerned with gold there is no reason to suspect that silver would behave differently. Furthermore, other sulphides would also simulate pyrite in its tendency to accommodate silver and gold, especially arsenopyrite and certain sulphosalts which are more metallic in character than pyrite.

At Yellowknife there are at least four ages of gold and silver. They are as follows, the oldest first:

1. Early gold and silver contained in pyrite and arsenopyrite in the alteration zones and in quartz lenses. Much of this gold and silver is present in pyrite and arsenopyrite in lattice sites. To free these two elements, roasting followed by cyanidation is necessary.

2. Native gold containing silver; gold and silver in solid solution in sulphosalts in fractures and crushed zones in the quartz lenses and their alteration zones. Four types of native gold are present. One variety possesses a light yellow colour and is generally rich in silver. A more abundant type has a rich golden colour and occurs as blebs and irregular masses in fractures in quartz and in granulated pyrite

and arsenopyrite; also in sulphosalts, stibnite, chalcopyrite etc. It is often accompanied by aurostibite. A third variety, of limited occurrence, is a reddish coloured gold that is often associated with chalcopyrite. The fourth variety occurs on slickensided surfaces of chlorite and sericite schist as thin films, and gives the appearance of being painted on the surfaces.

3. Native gold containing silver; gold and silver in solid solution in freibergite, bournonite and other sulphosalts, and chalcopyrite. The native gold occurs in calcite and ankerite filling vugs and crushed parts in crosscutting quartz-carbonate veinlets. It is generally accompanied by the sulphides and sulphosalts mentioned above.

4. Native gold containing silver in late fractures cutting the orebodies. This gold is generally associated with pyrite and scalenohedral calcite and occurs as splendent leaf gold, spongiform gold, and distorted octahedral crystals. In one case in the Giant system the leaf and sponge gold were observed in an ice lens (Boyle, 1951).

The presence of successive ages of gold and silver is usually explained by separate introductions from magmatic solutions. Just why this should take place has, however, not been satisfactorily answered. It would seem that a more plausible hypothesis, having regard to the geochemical facts at our disposal, is that the succeeding ages of gold and silver are simply due to the redistribution of the two elements originally in the first generation of sulphides. The process would probably be as follows: Gold and silver together with other chalcophile elements, sulphur, arsenic, and antimony, migrated into and through the schist of the shear zones. When they found a site of marked dilatancy, early high-temperature pyrite and arsenopyrite were formed which incorporated the available gold and silver in their lattices. As the deposit cooled and successive structural adjustments took place with crushing and partial recrystallization of the early sulphides, some gold and silver were exsolved together with some sulphur, antimony, and other chalcophile elements. These migrated into nearby fractures where the secondary sulphides were precipitated together with native gold. At this stage aurostibite ($AuSb_2$) was probably formed by reaction of gold and antimony, and much gold and silver were incorporated in the various sulphosalts which formed at this time. The third age of gold and silver in the crosscutting quartz-carbonate veins probably had a similar origin. The fourth age of gold may owe its origin in part to supergene processes and was precipitated from underground waters in late fractures and faults.

The gold and silver in the quartz lenses of the sedimentary area are concentrated mainly in native gold, and the ore is free milling. The source of the gold was probably the sediments, especially the slates and argillites. During metamorphism, gold and silver together with sulphur, zinc, lead, etc., were mobilized and drawn into dilatant zones. Gold and silver were precipitated mainly as native gold; small amounts were incorporated in the sulphides. Locally there has been a minor redistribution of gold and silver which has resulted in a second generation of native gold in narrow late fractures cutting the quartz lenses.

Let us consider now the quantitative aspects of the concentration of gold and silver from the greenstone rocks. As an example we may take the Giant-Campbell system and use the same dimensions as those given in Chapter IX. The average content of gold and silver in the greenstone rock prior to shearing may be taken as 0.01 ppm and 1.0 ppm respectively. The system is estimated to contain 6 million tons of ore averaging 0.654 ounces gold per ton and 0.139 ounces silver per ton. The contents of gold and silver in the unsheared rock and in the deposits are given in the following tabulation.

Content in rock prior to shearing	*Content in deposits*	*Ratio of concentration*
Gold (ounces) 12.2×10^6	3.9×10^6	32%
Silver (ounces) $1{,}219 \times 10^6$	$.834 \times 10^6$	.068%

These estimates show that sufficient gold and silver were present in the sheared rock of the Giant-Campbell system to provide the amounts in the deposits. When we consider that contributions of the two metals may also have come from the rocks flanking the shear zones, there is no need to call upon magmatic solutions as a source. It is logical to conclude, therefore, that there is a sufficient source of the two metals in the host rocks; an efficient process to concentrate them is the fundamental problem in solving the origin of the gold deposits. The author is of the opinion that an efficient process is provided by the agents of regional metamorphism which mobilize the gold and silver in the host rocks and the dilatant features of the shear zones which concentrate the two metals. Both factors must operate in the proper time sequence to produce deposits.

Gold and silver are present in only infinitesimal amounts in the late faults in all rock types. Their absence can be explained by the fact that the processes of regional metamorphism were not operative when the late faults were formed, and hence only very small amounts of sulphur, gold, and silver were mobilized and concentrated from the host rocks.

Chapter XI

GEOCHEMISTRY OF UNDERGROUND WATERS

Occurrence

In many of the underground workings at Yellowknife, natural water issues from late faults and fractures. The occurrences are most common in the workings of the Con and Negus mines, and were observed in only a few places in the Giant mine. Only the natural waters, uncontaminated by mine water, were collected for analyses.

The flow of water from various faults and fractures differs. In the Con system there is a substantial flow from a fracture on the 2,300-, 2,600-, and 2,700-foot levels which has caused difficulties during mining operations. From other fractures the flow is small ranging from a few gallons a minute to a mere trickle.

The pressure as measured with a pressure gauge on diamond-drill holes in the case of the fracture in the Con system mentioned above, is about 1000 psi on the 2,300-foot level, and hence approximates the hydrostatic pressure at that depth. In other fractures the water pressure is about equal to the hydrostatic pressure at the depth at which the fractures are tapped by underground workings.

Chemistry of the Waters

Tables 46 and 47 give chemical and spectrographic analyses of the water, evaporated residue, and natural precipitates from four characteristic occurrences.

The sum of the dissolved constituents in the waters varies from fracture to fracture and also appears to vary from year to year. In the water issuing from the fracture on the 2,300-foot level of the Campbell system (W3) it is 529 ppm; in the water from the Con system (W2), 16,260 ppm. The content of dissolved matter in other waters ranges between these two values.

The temperature of the waters is relatively constant throughout the year and averages about 15°C. This temperature is about equal to the temperature of the rock through which the waters flow. The pH is slightly alkaline and is relatively constant for all waters tested.

The principal cations are sodium and calcium. In some waters calcium exceeds sodium, in others the reverse is true. Other cations include magnesium, strontium, aluminum, manganese, iron, barium, and traces of copper and zinc. Silica and boron are also present in all waters tested. The main anions are Cl^-, HCO_3^-, and SO_4^{2-}. From these chemical results it can be inferred that the principal dissolved salts are sodium chloride, calcium sulphate, and calcium hydrogen carbonate. The first two can generally be detected by tasting the water.

The natural waters contain three gases in solution. Hydrogen sulphide is generally the most abundant, but methane is equally as abundant in some occurrences. Carbon dioxide is generally present, but only in traces. None of the gases are present in quantities great enough to present a hazard to mining operations.

Table 46

Analyses of Waters Flowing from Faults and Fractures in the Yellowknife Greenstone Belt

	W-2 2,300 Level, Con System (Constituents in parts per million)	W-3 2,300 Level, Campbell System (Constituents in parts per million)
Temperature at sampling	14.5°C	15°C
Temperature at analysis	21.1°C	21.1°C
Carbon dioxide (CO_2), calculated		3.2
Colour	0	10
Turbidity	clear	clear
pH	7.0	8.1
Alkalis (as $CaCO_3$):		
Phenolphthalein	0	0
Total	11.8	208
Residue on evaporation:		
Dried at 105°C		549
Ignited at 550°C		522
Conductance, micro-ohms at 25°C	29,831	897.3
Hardness as $CaCO_3$:		
Total	10,203	203
Carbonate	11.8	203
Non-carbonate	10,191	0
Calcium (Ca^{2+})	4,033	61.4
Magnesium (Mg^{2+})	33.9	12.0
Sodium (Na^{+})	2,830	113
Potassium (K^{+})	7.4	1.9
Iron (Fe^{2+}), total	0.03	trace
Aluminium (Al^{3+})	0.33	0.38
Manganese (Mn^{2+})	0.10	0.0
Carbonate (CO_3^{2+})	0	0
Bicarbonate (HCO_3^{-})	14.4	254
Sulphate (SO_4^{2-})	493	99.0
Chloride (Cl^{-})	11,383	105
Fluoride (F^{-})	0	0.3
Nitrate (NO_3^{-})	0	0
Silica (SiO_2)	18	11
Sum of constituents	16,260	529
Saturation index (at 21.1°C)		+0.6
Stability index (at 21.1°C)		6.9
Per cent sodium	37.5	54.5

Water collected in 1957 by G. McVittie, Geologist, Consolidated Mining and Smelting Co. Ltd., Yellowknife, N.W.T.

(Analyses by Industrial Waters Section, Mines Branch, Ottawa.)

Table 47

Spectrographic and Chemical Analyses of Residues and Precipitates from Underground Waters Flowing from Faults and Fractures in the Yellowknife Greenstone Belt

	W-1	W-2	W-3	W-4
Major (100-10%)	Ca	Ca, Na	Ca, Na	Ca
Minor (10-1%)	Si, Na, Mg	Sr	Sr	
Strong trace (1-.1%)	B, Sr, K	Si, K	Mg, Si, K	
Trace (.1-.01%)	Al,	Mg, Al	B, Al	Sr, Mg, K
Faint trace (.01-.001%)	Fe, Ba, Cu Mn, Zn	B, Fe, Cu Mn, Ba, Zn	Fe, Cu, Ba Mn, Zn	B, Fe, Si, Ba Mn, Cu, Zn
Anions in order of abundance	SO_4^{2-}, Cl^-, HCO_3^-	Cl^-, SO_4^{2-}, HCO_3^-	HCO_3^-, Cl^-, SO_4^-	
Dissolved gases in water	H_2S, (CO_2, trace)	CH_4, (CO_2, trace)	CH_4, H_2S, (CO_2, trace)	
pH of water at sampling point	7.5–8.0	7.5–8.0	7.5–8.0	
Temperature of water at sampling point	15°C	14.5°C	15°C	

Key: W–1 Residue of water from Negus fault, 13 level, Negus mine, Campbell system.
W–2 Residue of water from fracture, 2,300-foot level, Con mine, Con system.
W–3 Residue of water from fracture, 2,300-foot level, Con mine, Campbell system.
W–4 Calcite stalagmite—2,300-foot level, Con mine, Campbell system; stalagmite was precipitated from water issuing from fracture.

Spectrographic analyses by W. H. Champ. Determinations of anions, dissolved gases, pH, and temperatures by R. W. Boyle.

Origin of the Waters

The writer has observed waters similar to those at Yellowknife in several other gold mines in the Canadian Shield. Methane gas also occurs in a few gold mines, and in one or two, as at the Central Patricia mine in Northern Ontario, it may present a hazard during mining. In most cases it occurs in pockets and once these pockets are drained there is no further production of the gas.

The natural underground waters at Yellowknife could have three possible origins—meteoric water, connate water (i.e. sea water trapped during the deposition of the lavas), or magmatic water. The last two are improbable. If the waters were of connate origin they would certainly have been dispersed during metamorphism and would have been incorporated in various hydrous minerals. They can hardly be of magmatic origin because they occur in late fractures and faults, structures which were formed long after any magmatic activity in the area. Furthermore, their temperatures approximate the rock temperatures through which they flow, and their pressure is about equal to the hydrostatic pressure at the depth where they are tapped by underground workings.

The chemical and physical facts such as temperature, pressure and elemental content of the waters suggest that they are meteoric waters which have penetrated deep into the rocks along late faults and fractures. In time, these meteoric waters became impounded and reached a chemical equilibrium with the rocks and minerals with which they are in contact. They start to flow only when underground workings intersect the fractures and faults, and in some cases their flow continues only until the reservoirs along the late faults and fractures are drained. In other cases they probably receive continuous additions from the surface and maintain a fairly constant flow. Waters impounded for a long time or in contact with minerals in late faults and shear zones for great distances would contain a large content of dissolved constituents. Those receiving constant additions of meteoric water and only in contact with the rocks for a short time or a short distance, would be relatively low in dissolved constituents. This could account for the differences in the amount of dissolved constituents in the water issuing from different fracture systems.

The waters contain elements which are readily available in the shear zones and late faults. Initially the waters would contain atmospheric oxygen and carbon dioxide. The dissolved oxygen would react with the sulphides to produce sulphates and probably some hydrogen sulphide, and the carbon dioxide would render the carbonates soluble and assist in releasing certain elements such as potassium, sodium, and aluminum from the silicate minerals. The presence of sodium chloride in the water in large concentrations is not unusual. This compound occurs dispersed through all shear zones, faults, and rocks, and as shown in Chapter VIII, it can be readily extracted from the carbonates by leaching with distilled water.

In some waters the methane and some of the hydrogen sulphide probably came from the surface. The writer has detected both gases in considerable amounts in reducing environments, particularly where decaying organic material in muskegs and lake muds overlies the late faults and shear zones. It seems logical, therefore, that these gases are carried down along the late faults and fractures to depth by the meteoric waters.

Chapter XII

SUMMARY AND CONCLUSIONS

Geological and geochemical features described in this memoir are as follows:

1. Four main types of rocks occur within the Yellowknife district—volcanics (Yellowknife group), sediments (Yellowknife group), granodiorites, granites and allied rocks, and late diabase dykes and basic sills.

2. The volcanics consist of flows, interbedded tuffs, and pyroclastics. Their geological features suggest that they were laid down in a sea or ocean. The chemical composition of the basic flows suggests that the majority were originally of basaltic composition. A few dacite flows are also present in the volcanic sequence. Some of the tuffs contain an abundance of carbon and sulphides pointing to the probability that they were formed under reducing conditions where biological activity played a large part in concentrating the sulphur and carbon.

3. The volcanic assemblage contains many conformable sills of gabbroic composition. Both the flows and conformable sills are cut by numerous dykes of gabbroic and dioritic composition. These latter rocks may represent the cafemic components of sediments and volcanics expelled by the granitization processes which formed the western granitic mass (*see* 6 below).

4. Quartz-feldspar porphyry dykes and irregular stocks, some of which carry considerable amounts of pyrite and other sulphides, cut the volcanic rocks and early meta-gabbro and diorite dykes and sills. These rocks are thought to have crystallized in tension fractures from material mobilized during the granitization processes which formed the western granitic mass (*see* 6 below).

5. The sediments of the Yellowknife group consist of greywacke, phyllite, slate, argillite, quartzite, arkose, and conglomerate. A few dacitic and basic lava flows and other rocks such as tuffs and pyroclastics are interbedded with these sediments. The sediments of the Yellowknife group rest with apparent conformity on the volcanic sequence, and their geological features indicate that they are predominantly of marine origin. Some of the sulphur and perhaps all of the carbon in these rocks has been concentrated by biological processes.

6. Three large bodies of granitic rocks occur within the district. These exhibit both intrusive and granitization features. The large granitic body flanking the greenstone belt probably originated by the granitization of a large mass of sediments that once lay stratigraphically below the greenstone belt. Limited granitization of the basic volcanic rocks produced a basic border phase in this granitic mass. The Prosperous Lake granite and the granitic body south of the sedimentary area probably originated by granitization of large parts of the Yellowknife group

sediments. There is no development of a basic front in either the greenstone belt or sedimentary rocks. The early gabbro dykes in the greenstone belt may, however, represent expelled cafemic material (*see* 3 above).

7. The greenstone rocks of the district are folded into a broad northeasterly plunging asymmetric 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 isoclinal folds which in turn have been crossfolded.

8. Diabase dykes 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.

9. The greenstone belt exhibits the characteristic metamorphic facies common to regionally metamorphosed basic rocks. The facies show a distinct relationship to the granodiorite-greenstone contact and grade outward from this contact. The metamorphic zoning includes a marked amphibolite facies adjacent to the granodiorite, a broad, central, epidote amphibolite facies, and an irregular and ill-defined greenschist facies farthest from the granite. Chemical analyses show no marked difference in the major components of the rocks across the metamorphic facies. Water, carbon dioxide, and sulphur increase consistently toward the lower-grade facies, i.e. outward from the granite, suggesting that these compounds, initially present in the rocks, were mobilized and migrated into the cooler zones during regional metamorphism.

10. Two well-defined metamorphic facies are present in the sedimentary area. These are related to the Prosperous Lake granite and southeastern granitic mass and include a knotted quartz-mica schist and hornfels facies adjacent to these granitic masses, and an outer facies of relatively unmetamorphosed greywacke, slate, and argillite. Chemical analyses indicate relatively little difference in the major constituents of the rocks in these two facies. The content of water is lower in the knotted quartz-mica schists and hornfels, and these rocks represent a dehydrated zone adjacent to the granitic masses.

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

12. In the shear-zone systems, the principal ore controls are shear-zone junctions and flexures and drag-folded parts of the large schist zones.

13. In the sedimentary rocks of the Yellowknife group, gold-quartz lenses are developed in faults, drag-folds, saddle reefs, ruptured and sheared axes of isoclinal folds, and other structures. These structures were formed during the complex folding of the sedimentary rocks.

14. Post-diabase faults and fractures cut all rocks in the district. Along the faults, quartz-hematite lenses and 'giant quartz veins' are localized at or near junctions and flexures.

15. In the greenstones the principal minerals in the epigenetic deposits of the shear zones are quartz, carbonates, pyrite, arsenopyrite, stibnite, chalcopyrite, sphalerite, pyrrhotite, various sulphosalts, galena, scheelite, gold, and aurostibite. In the sediments the gold-quartz veins and lenses contain essentially quartz, pyrite, sphalerite, galena, tourmaline, and gold. The characteristic minerals in the late faults are quartz, hematite, carbonates, and chalcopyrite. The minerals in the pegmatites are principally quartz, feldspar, mica, tourmaline, garnet, and locally small amounts of beryl, spodumene, amblygonite, scheelite, and other typically pegmatite minerals.

16. The gold-quartz lenses in the shear zones are enveloped by carbonate-sericite-pyrite-arsenopyrite alteration zones which grade imperceptibly into the chlorite-albite-carbonate schist of the shear zones. Chemical analyses of the alteration zones show that water, carbon dioxide, sulphur, and potassium were added to the highly altered zones, and some silica, calcium, sodium, iron, magnesium, and manganese were removed.

17. The gold-quartz lenses in the sedimentary rocks exhibit little alteration of their wall-rocks. In the alteration zones of some lenses, potassium and sulphur were added and some sodium was removed. In others a narrow tourmalinized zone is developed in the sediments adjacent to quartz lenses.

18. In late faults, chloritization and hematitization are the principal alteration effects. Where quartz lenses are present, silicification of the breccia is widespread.

19. Quartz is the principal epigenetic mineral in all deposits, and several generations are present. Chemical analyses indicate that the gold-quartz lenses in the shear zones were formed from the silica released during the alteration of the shear zones. The processes involved a chemical exchange of silica for carbon dioxide and water. Other quartz lenses and veins in the greenstones, and those in the sediments, are thought to have been derived by metamorphic differentiation and local secretion processes.

20. Several ages of carbonate minerals occur in the epigenetic deposits. In the shear zones the early carbonate is ankerite with a high iron and magnesium content. Younger ages are ankerite and calcite with a low iron and magnesium content. All carbonates probably owe their origin to a redistribution of carbon dioxide originally present in the country rocks.

21. The epigenetic sulphides in the shear zones are thought to have originated partly by a redistribution of sulphophile elements during regional metamorphism of the greenstones and partly as a result of the alteration processes which formed the extensive shear zones. The sulphides in quartz lenses in sedimentary rocks were probably concentrated by metamorphic differentiation processes.

22. Successive generations of sulphides in the shear zones of the greenstones and quartz lenses in the sediments are explained by two processes; (a) exsolution

of certain elements from early sulphides such as pyrite and arsenopyrite, and (b) local secretion processes which concentrated the exsolved elements from the early sulphides. Both processes operated simultaneously and were promoted by shearing and fracturing after the deposition of the early sulphides.

23. Both gold and silver are constituents of all rocks in the Yellowknife district and were originally present in amounts sufficient to produce any of the concentrations in the epigenetic deposits. It is, therefore, unnecessary to call upon magmatic hydrothermal solutions as a source, for these two elements. Gold and silver have a decided affinity for sulphur, arsenic, and antimony and together with these elements have been concentrated in shear zones in greenstones and quartz lenses in the sedimentary rocks by metamorphic processes and the dilatancy of various structures.

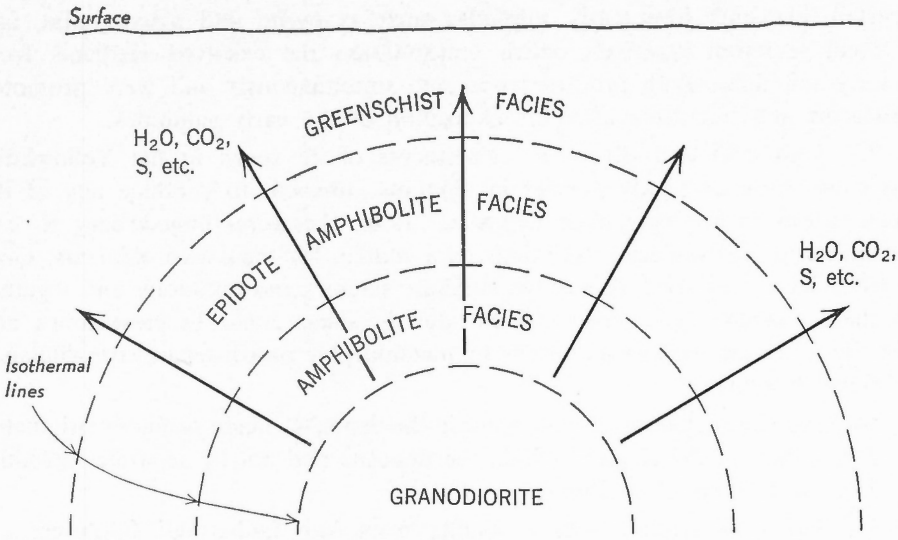
24. Several generations of gold occur in the deposits. These probably originated by redistribution of the element within the deposits and not by separate introductions from hydrothermal solutions.

25. The underground waters, issuing from late faults and fractures, are thought to be meteoric in origin. They carry elements and gases of mainly local derivation.

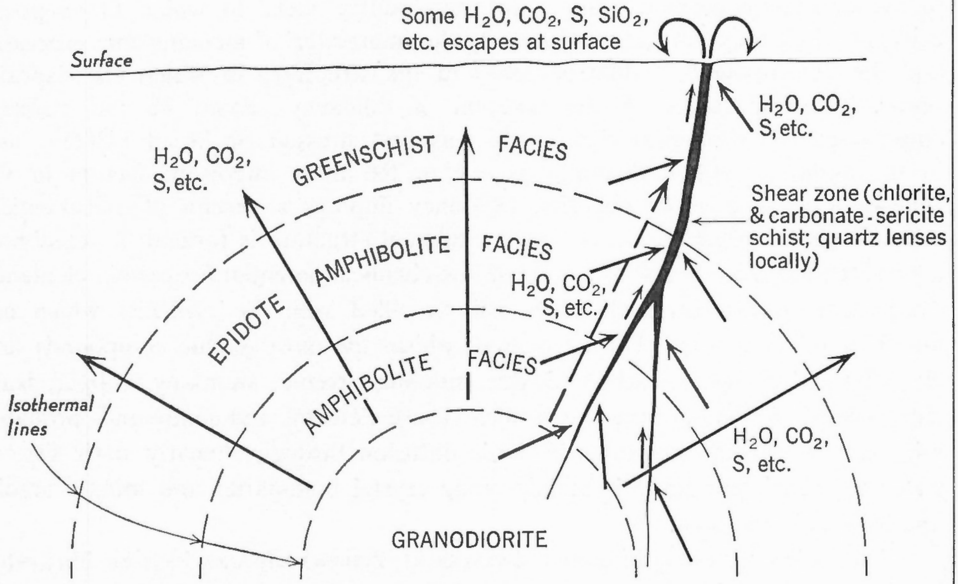
Throughout this memoir the thesis has been stressed that the elements present in the epigenetic deposits came from the country rocks in which the deposits occur and that they were concentrated by the interaction of metamorphic processes and the development of dilatant zones in the structures in which the deposits occur. The importance of the function of dilatancy cannot be too strongly emphasized. Its geological significance was first stressed by Mead (1925), and in the author's opinion dilatancy is one of the most important factors in the genesis of epigenetic ore deposits. Dilatancy imposes a certain physicochemical effect on the surrounding rocks. Once a dilatant structure is formed, it constitutes a low-pressure zone as well as a zone of low-chemical potential for certain elements. To restore equilibrium such zones will be filled with the elements which are mobile within the rocks. During metamorphism the most mobile compounds and elements will be water, carbon dioxide, sulphur, arsenic, antimony, copper, lead, zinc, gold, silver, and in some cases silica. These elements and compounds probably migrate into dilatant structures by ionic diffusion through a nearly static flux of water vapour. Their route is mainly along crystal boundaries and minute cracks and fissures in the rock.

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 29 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 which now form the greenstone belt. This was followed by further deposition of marine sediments (Yellowknife group).



(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.

Figure 29. *Schematic diagrams to illustrate the formation of metamorphic facies and mineralized shear zones.*

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, marked temperature gradients 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, sulphur, and probably some of the chalcophile elements were mobilized 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 29(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 Yellowknife greenstone belt a great system of shear zones was formed near the end of the orogeny and formation of the granitic bodies. As a consequence the migration vectors were radically changed by the dilatancy of the shear zones as shown by Figure 29(b). The shear zones literally sucked the mobile carbon dioxide, water, sulphur, and other elements from the country rocks and funnelled them toward the surface. Because of the great extent and depth of the shear zones the effects of dilatancy were undoubtedly felt over great volumes 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 which 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 sulphur reached a high concentration along them. As a consequence the chemical equilibrium was strongly displaced, and chloritization, carbonatization, pyritization etc., of enormous tonnages of volcanic rock took place. This led to the liberation of silica, potassium, calcium, iron, etc., in addition to 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 country 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 formed. In these sites, secondary reactions, promoted by the low-pressure and lower-chemical potential, resulted in the precipitation of quartz, carbonates, and gold- and silver-bearing pyrite and arsenopyrite, forming quartz-sulphide lenses with adjacent alteration haloes.

During cooling of the deposits and further structural adjustments within the shear zones, much gold, silver, antimony, and other elements were exsolved from the early sulphides and found their way into local dilatant zones such as fractures in quartz lenses and local tension fractures and small faults in the shear zones. Some silica and the components of the late carbonates did likewise. This process gave rise to the successive later generations of native gold, sulphosalts, pyrite, quartz, and carbonates in the shear zones.

In the sedimentary rocks the quartz lenses containing sulphides and gold were concentrated by similar processes. During the 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, sulphur, boron, and various metallic elements migrated into these zones where they were precipitated, forming the gold-quartz-sulphide veins and lenses. The mobilization and migration of the compounds and elements forming the gangue and ore minerals was promoted by the high temperature and stress prevailing 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 favourable sites in the late faults. The agents of regional metamorphism were not active at this time and only the highly mobile compound, water, took a major part in the 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 other elements. The silica and iron migrated into dilatant zones where they were precipitated as quartz and hematite.

In many late faults and fractures, carbonates and other minerals are being precipitated from underground waters at the present time. These waters are probably of meteoric origin, and their dissolved constituents have been derived mainly from the wall-rocks and the fault zones through which they migrate.

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