THE CONCENTRATION AND DISTRIBUTION OF GOLD IN THE URANIFEROUS CONGLOMERATES OF ELLIOT LAKE

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TITLE: The Concentration and Distribution of Gold in the Uraniferous Conglomerates of Elliot Lake

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SCOPE AND CONTENTS: A neutron activation procedure for the determination of Au in sulfides has been utilized to examine the concentration and distribution of Au in pyrite, and, to a lesser extent, in chalcopyrite of the conglomeratic uranium ore of the Denison Mine, Elliot Lake, Ontario. An extensive literature review of the geology of the Elliot Lake area is presented together with brief surveys of the geologies of two analogous areas, the Witwatersrand of South Africa, and the Jacobina of Brazil. A discussion of the two leading theories regarding the origin of such deposits follows. The present state of knowledge concerning the nature and causes of the distribution of Au in both rocks and sulfides is discussed. Analytical results are presented for Au in 58 pyrite, 8 quartz, and 2 chalcopyrite samples, and for Ir in 4 pyrite samples, all from the Denison Mine ore zones. These results are discussed with respect to their implications concerning the origin of the ore and of auriferous and/or uraniferous quartz pebble conglomerates in general.

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ABSTRACT

A neutron activation procedure for the determination of Au in acid-soluble sulfides is described. Sensitivity of the method is of the order of a fraction of a part per billion (ppb). Reproducibility for quadruplicate analyses of a sample in a single irradiation was good as a standard deviation of ±12% was obtained.

The method was used to determine the concentration and distribution of Au in pyrite from the Denison Mine, a uranium-bearing quartz pebble conglomerate horizon at or near the base of the Huronian sequence in the Quirke Lake Syncline, Elliot Lake district, Ontario. Gold content in 58 pyrite samples ranged from 202 to 2084 ppb. with an average of 656 ppb. No trends were observed in the vertical or horizontal distribution of Au in the portion of the mine examined although the horizontal sampling covered some 4500 ft. Local distribution of the gold within pyrite appeared uniform. Comparison of the Au content of two chalcopyrite samples to corresponding pyrite indicated that both sulfides contained similar quantities of Au. Analyses of 8 quartz fractions for Au showed that the pebbles of the conglomerates were not enriched in the metal but contained a concentration comparable to that in normal granitic rocks. In addition to Au, four activation determinations for Ir were carried out. Both Ir and Au were found to be enriched in pyrite to the same extent with respect to their concentrations in G-1.

The two hypotheses used to explain the origin of Au and U in the Huronian quartz pebble conglomerates of Elliot Lake and in other analogous deposits consist of 1) the modified placer theory in which both the Au and U represent original detrital grains, and, 2) the hydrothermal theory in which both minerals are epigenetic deposits from hydrothermal solutions. An attempt was made to interpret the results of this work in terms of these two hypotheses. Thus, the following results may be considered compatible with the placer theory: 1) an estimate of the overall Au concentration in the ore at 66 ppb., 2) gross distribution of the gold, and 3) the concentration of Ir; while a hydrothermal origin is favoured by 1) the distribution of Au within the pyrite, and 2) the concentrations of Au in chalcopyrite and corresponding pyrite. However, although several of the results of the study may be interpreted within the context of a placer origin, no conclusive evidence can be given to the support of that theory.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1. Reasons for this Research

Since gold was discovered in conglomerate horizons of the Witwatersrand System of South Africa, a controversy has existed as to its origin. This problem was renewed when uranium was found in similar conglomerates in the Huronian System at Elliot Lake, Ontario. The present study was undertaken primarily in the hope that knowledge on the concentration and distribution of gold in the uraniferous conglomerates at Elliot Lake would reveal information on the origin and/or source of minerals within such conglomerates. Knowledge of the origin and source would be very important in the prospecting for further similar gold-uranium deposits. It could also lead to the discovery of more extensive deposits from which the presently exploited ones were derived, although it is probable that the source rocks would be of lesser concentrations. Furthermore, there was always the possibility that, during the study, economic concentrations of gold would be proven within the uraniferous conglomerates themselves. Since the ore material at Elliot Lake is necessarily crushed for uranium extraction, then the concentration of gold would not have to be of the minimal economic value (approximately 0.15 to 0.20 oz. per ton) required for a producing gold mine. The gold could be extracted as a by-product with little expense involved.

Since the ores at the Rand include considerable osmiridium, it was originally intended to conduct analyses for iridium, palladium, and gold, in this work. However, as Pd is a fission product of U^{235} and thus, since any natural Pd would be contaminated during irradiation of any sample containing uranium, it was decided that Pd analyses would be impractical. Also, since a large number of results was desirable, and since the procedure for Ir is quite time consuming, it was decided to analyse only gold in the samples processed.

Little work has been done on the occurrence of gold in the Elliot Lake uranium camp. Davidson (1957) has described it as "patchy" and Robertson and Steenland (1960) have stated that gold is not present at Elliot Lake except as in sporadic traces and its manner of occurrence is unknown. It is surprising that so little has been done regarding gold since the analogies of Elliot Lake to the Rand gold camp would tend to suggest the possibilities of finding gold in the former.

2. The Blanket Conglomerate Controversy

As previously stated, the problem concerning the origin and source of auriferous and uraniferous quartz pebble conglomerates has existed since the discovery of the conglomerates themselves. These sediments all have several identical or similar characteristics. They are relatively pure quartz pebble conglomerates of Proterozoic age with arkosic to quartzitic matrices of sericite, quartz, and feldspar, and containing relatively high proportions of pyrite. The matrices also contain varying minor amounts of gold and/or uranium. Two main fields of thought exist regarding the origin of ore minerals in these sediments. The mine and field geologists, who have examined the deposits and their geologies first hand, tend to favour a placer or modified placer origin for the gold and uranium. They believe that these minerals were detrital and syngenetic with the deposition of the conglomerates. Most of the geologists acknowledge that some modification and reworking of the ore has occurred since deposition. The other school is that of the hydrothermalists who base most of their arguments on geochemical evidence. They dispute the theory that the ore minerals were deposited as detrital grains and believe that the gold and uranium are epigenetic minerals, introduced into the conglomerates by hydrothermal solutions following deposition of the gravels. The proponents of these two viewpoints have waged a verbal running battle for years and this has done much to encourage research on the problem. It is hoped that with the recent untimely death of Dr. C. F. Davidson, who was the undisputed authority of the hydrothermal theory, interest in the controversy will not fade.

CHAPTER II

THE GEOLOGY OF ELLIOT LAKE AND OTHER SIMILAR SEDIMENTARY DEPOSITS

1. The Geology of the Elliot Lake Uranium Camp including the Denison Mine

i) General

The Elliot Lake area is located approximately halfway between the cities of Sault Ste. Marie and Sudbury, and is centered some 25 miles north of the North Channel of Lake Huron (see Fig. 2-1). This region is the largest uranium producer in Canada with over 122 million lbs. of U_3O_8 valued at over $1,160,000,000 recovered to the end of 1965.

The generalized geology of the area is outlined in Fig. 2-2. The pre-Huronian basement consists of Keewatin metavolcanics and metasediments invaded by Algoman granites and similar rocks. Deposited on the basement complex is a series of Huronian sediments comprised of subarkoses, greywackes, argillites, limestone, and intercalated conglomerates. Prior to the deposition of the Huronian sequence, there was intense folding, metamorphism, and erosion of the basement so that a major unconformity exists between the two.

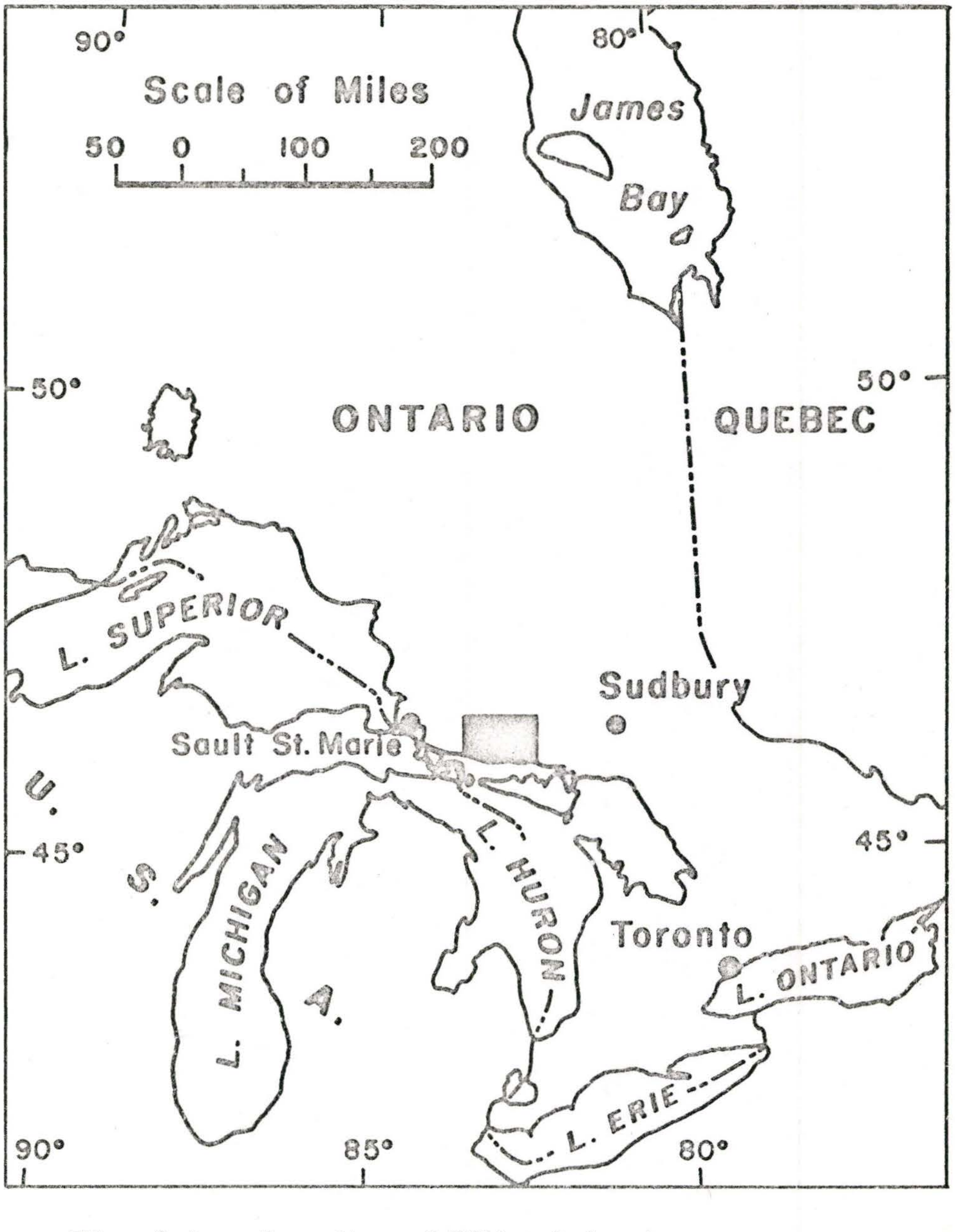


Fig. 2-1. Location of Elliot Lake Area

This is obscured in part by residual deposits, or a saprolith, on the basement which may be up to 50 ft. thick when overlying granite. The Huronian sediments are moderately metamorphosed to the chlorite or greenschist facies and a slight increase in grade is apparent from the north to south. These sediments are folded into a syncline which plunges gently to the west. The limbs dip at an average of 20^{o}. The maximum width of the fold is 9 miles and the sediments attain a maximum thickness of approximately 5,000 ft.

The uranium ore is found in oligomictic quartz pebble conglomerates in the lowermost zones of the Huronian sequence. Trough-like valley depressions occur in the pre-Huronian surface and probably formed, at least partially, by differential erosion of metavolcanic rocks and granite. There are two main "valley" areas in the basement below the syncline. Since the ore conglomerates were among the first Huronian rocks deposited, they were thus, laid down in these valleys.

ii) Pre-Huronian Geology

Metavolcanics are the most common pre-Huronian rock type as found in drill holes. They are mainly andesitic although some are more acidic and approach the composition of rhyolite. The andesite is a dark grey-green fine grained schistose rock containing chlorite, highly altered feldspar, epidote, quartz, sericite, calcite, and black iron oxide. The metavolcanics underlie the east part of the syncline and are exposed to the southeast. They include massive and pillow lavas and are of Keewatin age.

Metasediments present in the basement underlying the Quirke Lake Syncline consist of many types. Those commonly found in drill holes include a dark grey, fine grained sericite schist and a green chlorite schist. Also present are low grade cherty iron formations and a light grey, fine grained orthoquartzite.

The granitic rocks of the basement are Algoman with an age of approximately 2.4 to 2.7 b.y. (van Schmus, 1965). Of the two main types, one is a gneissic, grey to pink, medium to coarse grained granodiorite with many Keewatin inclusions, and the other is a massive, slightly radioactive quartz monzonite with no inclusions. Their trace element content (including Cr, V, Ni, Co, and Cu) is strikingly low for granitic rocks (Pienaar, 1963), but they do have slightly higher uranium and thorium contents than normal acid igneous rocks, containing from 10 to 20 ppm. Th and 5 to 19 ppm. U compared to the average for such granitic rocks of 5 to 15 ppm. Th and 2 to 6 ppm. U (Roscoe and Steacy, 1958).

The pre-Huronian was eroded to a peneplain with valleys in the less resistant metavolcanic belts. Pre-Huronian soil remnants are preserved as a saprolith which is much thicker over granitic terrain than over metavolcanics.

Pegmatite dikes are not abundant or especially radioactive in any of the pre-Huronian terrains of the area.

iii) Intrusions

Sills and dikes of Nipissing diabase have invaded the Quirke Lake Syncline. Van Schmus (1965) has determined their age by Sr-Rb whole rock techniques to be approximately 2.155 b.y. There are two phases of the diabase, an early stage of gabbroic sills and a later phase of approximately vertical dikes. The sills are up to 500 ft. thick, may contain granophyre diklets and segregations, and dip slightly steeper than the bedding. Some Cu mineralization is associated with these sills. The dikes are usually less than 100 ft. thick, strike NW or occasionally E-W, and have steep dips. Almost all diabase intrusions in the syncline have normal radioactivities and no conspicuous change in radioactivity has been observed where dikes cut ore zones. Little wall rock alteration has been produced by the intrusions. In addition to the diabase, there are thin lamprophyre dikes in all rock types.

iv) Structure

The main structure of the area is the Quirke Lake Syncline which plunges west at 1° to 18°. The north limb dips at 15° to 65°S and the south limb at 5° to 25° N. The fold is continued on as an anticline to the south. Secondary folds are locally common in the syncline. Three groups of faults are present and all post-date ore mineralization. No obvious changes in ore tenor have been observed near faults. The 3 groups are a) east-west trending low angle thrust faults, b) northwest trending faults paralleling many of the diabase dikes, and c) northeast trending faults. Bedding plane slips, the thrust faults, the near vertical faults, plus jointing and drag folds suggest that a north-south compression, with several periods of intensity, formed the main fold. There were several periods of post-Huronian deformation. The first was prior to the intrusion of the Nipissing diabase, the second caused foliation in the diabase and altered it to epidiorite and hornblende schist, and the third caused further cleavage to form in the diabase. Incompetent rocks of the syncline indicate small scale crumbling and brecciation whereas competent rocks such as the subarkoses (quartzites) and quartz pebble conglomerates have cataclastic deformation.

v) The Huronian Stratigraphic Column

The nomenclature adopted in this work is that of the Geological Survey of Canada as used by Roscoe (1958), Pienaar (1963), and others. It differs from that used by Robertson (1967) and the Ontario Department of Mines in detail only, and unit boundaries are not changed. (For a comparison of various nomenclatures, see Fig. 2-3.)

The lowermost Huronian consists of the Elliot Group. It contains all formations unconformably overlying the pre-Huronian and underlying a polymictic boulder conglomerate at the base of an argillite-greywacke suite. The entire Elliot Group is from 0 to 950 ft. thick with a general non-uniform thickening to the south. It includes an upper Nordic Formation and a lower Matinenda Formation.

The Matinenda Formation is the lowest Huronian sedimentary unit. It consists of an upper and lower member, both of which are found along the south limb of the syncline, but only the lower member, as correlated by lithology only, is found on the north limb. The lower member is comprised of coarse grained subarkoses, grits, and uraniferous oligomictic conglomerates, while the upper member consists of non-radioactive polymictic conglomerates, subarkoses, and quartzites. The latter ranges from 0 to 470 ft. thick. Graded bedding is common in it but crossbedding is rare. The polymictic conglomerates are very tightly packed with little matrix and are water deposited. The gravel consists of quartz, metavolcanics, chert, and minor granite and quartzite. The lower member was locally eroded before deposition of the upper member which was laid down by swiftly flowing southeasterly running streams. Transgression of the shoreline and reworking of detritus caused the formation of a fine grained equigranular quartzite at the top of the upper member.

Fig. 2-3. COMPARISON OF STRATIGRAPHICAL NOMENCLATURES USED FOR NORTH SHORE OF LAKE HURON.

Logan & Murray 1863	Coleman 1914	Collins 1925		Abraham 1953, 1957		Roscoe 1956 as in Pienaar 1963		Robertson 1965 North of Murray Fault		Robertson 1965 South of Murray Fault		Collins etc. South of Murray Fault		Rock-Types
Greenstone Intrusions	Intrusions	Keweenawan	Olivine Diabase	Keweenawan	Olivine Diabase	Keweenawan	Olivine Diabase		Keweenawan		Keweenawan	Keweenawan	Olivine Diabase	Olivine Diabase
			Granite		Granite		Granite				Cutler Granite		Granite	Granite
			Diabase, incl. Thessalon Greenstone		Diabase		Diabase		Nipissing		Nipissing		Diabase	Diabase Dikes
														Gabbro Sills
Upper Formations	Upper Huronian	Cobalt S	Upper Formations	Cobalt G	Upper Formations	Cobalt G	Upper Formations	Cobalt G	Upper Formations	Cobalt G	Not present in area mapped.	Cobalt S	Upper Formations	Quartzites
Upper Slate Conglomerate			Gowganda		Gowganda		Gowganda		Gowganda				Gowganda	Conglomerate, Quartzite
	Lower Huronian	Bruce Series	Serpent	Bruce Group	Serpent	Quirke G	Serpent	Bruce Group	Serpent	Bruce Group	Serpent	Bruce Series	Serpent	Quartzites
Limestone			Espanola Bruce Limestone		Espanola Bruce Limestone		Espanola Bruce Limestone		Espanola Bruce Limestone		Espanola		Espanola	Dolomite, Siltstone Limestone
Lower Slate Conglomerate			Bruce Conglomerate		Bruce Conglomerate		Bruce Conglomerate		Bruce Conglomerate		Bruce Conglomerate		Bruce Conglomerate	Conglomerate
White Quartzite			Mississagi		Upper Mississagi	Hough Group	Mississagi		Upper Mississagi		Upper Mississagi		Mississagi	Quartzite
					Middle Mississagi		Pecors		Middle Mississagi	Spragge Group	Middle Mississagi			Argillite ± Quartzite→Schists
							Whiskey				Middle Mississagi		Ramsay Lake	Conglomerate→Schists
					Lower Mississagi	Elliot Group	Nordic		Lower Mississagi		Lower Mississagi	Sudbury Series	McKim	Argillite ± Quartzite→Schists
Chloritic Slates							Matinenda (Upper)				Pater Volcanics		Wanapitei	Andesite→Meta-And. Quartzite
Grey Quartzite							Matinenda (Lower)				?			Quartzite - Arkose ±U-Conglomerate
Laurentian Granite	Laurentian Granite		Algoman Granite		Algoman Granite		Algoman Granite		Algoman Granite				Schist Complex (Keewatin)	Granite etc.
	Sudbury Series		Sudbury Series		Keewatin		Greenstone		Keewatin					Sediments
	Granite Keewatin		Schist Complex											Volcanics

The Nordic Formation is only found along the south flank and decreases in thickness to the east. It reaches a maximum thickness of 280 ft. The Nordic consists of interbedded lutites and arenites indicating intermittent deposition in deep water. The sand to shale ratio of the formation decreases to the southeast and thus, still water conditions were more prevalent there. The arenites show crossbedding and graded bedding. The Nordic Formation is characterized by tranquil water deposition with periods of turbulence and intermittent tectonic changes followed by strand line regression. An olive green siltstone with minor greywacke occurs at the base of the Nordic and is a persistent marker bed.

The Hough Group includes all sediments from the Nordic Formation upwards to the base of the Bruce boulder conglomerate. It consists of a lower Whiskey Formation and an upper Mississagi Formation. The Whiskey Formation contains a basal polymictic boulder conglomerate plus interbedded argillites, siltstones, and greywackes. It increases in thickness from north to south. The boulder conglomerate at the base is a good marker horizon and transgresses the lower Huronian rocks, lying on the Nordic, Matinenda, or even the basement. The Mississagi Formation consists mainly of medium to coarse grained arenites and thickens rapidly to the south and southeast, attaining a maximum thickness of 1750 ft. Its contact with the Whiskey is gradational. The feldspathic quartzites of the Mississagi are finer grained, better sorted, and less feldspathic than those of the Matinenda.

The Quirke Group lies between the Hough Group and the Gowganda Formation. The lowest formation of the Quirke Group is the Bruce Conglomerate, an unsorted polymictic conglomerate which makes a good marker horizon. The next is the Espanola Formation, consisting of interbedded limestone, siltstone, and calcareous arenites. Its members are the Bruce Limestone, Espanola Greywacke, and Espanola Limestone. The youngest formation of the Quirke Group is the Serpent which consists of feldspathic quartzite, subgreywacke, and thin beds of polymictic conglomerate and siltstone. It has a characteristic porcellaneous appearance in weathered outcrops and is normally well bedded, finely laminated, and calcareous. The quartzite is finer grained, better sorted, and more calcareous than that of the Mississagi.

The Cobalt Group includes all sedimentary units which unconformably overlie the Quirke Group. In the Quirke Lake Syncline, only the lowermost Gowganda Formation is present. It consists of a heterogeneous assemblage of polymictic conglomerates, greywacke, siltstone, argillite, arkose, and minor quartzite. The conglomerates contain mainly granitic boulders in a greywacke matrix and are probably of glacial or glacio-fluvial origin. The Gowganda has been dated by Sr-Rb methods and is thought to be no younger than 1.800 b.y. (Fairbairn et al., 1967). The same authors have dated the pre-Gowganda Huronian at 2.000±0.100 b.y. These ages conflict with van Schmus data for the intrusion of Nipissing diabase at 2.155+ 0.080 b.y. (van Schmus, 1965).

vi) General Geology of the Lower Matinenda and Ore Zones

The lower member of the Matinenda Formation consists of subarkoses and pyritic, uraniferous, oligomictic conglomerates which are thought to be normal sediments of fluvial origin. The uranium bearing quartz pebble conglomerate-green subarkose sequence is characteristic of the Matinenda (lower Mississagi to some workers) and is used as a marker horizon from Elliot Lake to Lake Timagami. Where overlap brings the Nordic or upper Matinenda near the basement, they contain slightly radioactive pebble bands. This indicates that the radioactivity is associated with whatever is the local basal bed of the Huronian sequence. A basal conglomerate is present in some areas at the bottom of the Matinenda and is overlain by pebbly subarkose with local, thin, oligomictic conglomerate beds. This coarse grained subarkose grades from the north to the east and southeast into a fine grained sugary textured subarkose. The central part of the lower member consists of interbedded, highly pyritic, radioactive, oligomictic conglomerates and greenish yellow coarse grained subarkoses with the conglomerate beds decreasing in thickness toward the top. The upper part of this member is comprised of yellowish green subarkoses and grits.

The ore zones consist of interlacing, multiple, lenticular, sedimentary units with the ore minerals preferentially concentrated in well packed conglomerate zones. There is no apparent relationship between the ore and secondary structures or alterations. Isopachs indicate several thick separate trough-like zones separated by local areas of non-deposition. These thick zones contain the ore mineralization and are related to granite-metavolcanics contact zones and valleys of softer zones in the metavolcanics of the basement. As the trend of these troughs is at an angle to the regional strike, and as the troughs are linear and of limited length, the possibility of strand line currents being present during deposition is discounted. Rather, these factors support an alluvial mode of deposition. The ore conglomerates are usually in the lowest stratigraphic sequence of the troughs but they are found up to 280 ft. above the basement. Most lower zones wedge out against the positive areas or "hills" of the basement and at local highs, the conglomerates may rest directly on the pre-Huronian. Some of the lower conglomerates are not lenticular but are of the blanket type, being continuous over large areas. These form the main ore zones, of which there are only 2. One, on the north limb of the syncline, is 5 miles long by up to 2 miles wide, and the other, on the south limb, is 4 miles long by a maximum of 1 1/2 miles wide. Where more than one ore zone exists in a horizon, the upper ones are much thinner. These ore zones all strike northwest-southeast. Individual ore units are from 8 to 32 ft. thick and consist of interlayered conglomerates and conglomeratic to pebble-free subarkoses. In the ore zones, massive conglomerate units may split into several thin pebble layers with pyrite seams and subarkose lenses. Conglomerate layers and pyrite seams may also follow the foreset beds of crossbedding. These pyrite seams may be up to 2 ins. thick and contain visible black uranium minerals at their bases. Black uranium seams of up to 1 in. also occur and assay to 40% $U_3 0_8$. Scour and fill structures are quite usual at the base of conglomerate zones and are filled with loosely packed conglomerates or conglomeratic subarkoses which are highly pyritic and more radioactive than the main conglomerate beds. Well packed conglomerates commonly have higher uranium values and higher pyrite contents than do loosely packed conglomerates which, in turn, contain more of both than do conglomeratic subarkoses. The pebble-free subarkoses contain little uranium except where they locally have numerous crossbedded pyrite seams. The relationship between the pyrite and uranium is often more apparent than real and instances do occur where the relationship does not hold at all.

Pyrite is usually highest where the conglomerate is best packed and thus, the pyrite-uranium relationship is only an effect of packing. Where one ore conglomerate exists, the highest uranium values are near the base but where more than one unit occurs, the values depend on packing and not on the position of the bed. The uranium content is related only to the lithology of the conglomerates and, as noted, no evidence has been found indicating relationships to structural features or intrusions. Northerly overlap is pronounced in the sediments of the lower Huronian so that ore bodies are progressively younger to the north.

vii) The Gravel of the Ore Conglomerates

The gravel component of the ore conglomerates ranges from small pebbles of 1/4 in. to cobbles of 2 ins. and larger which are well rounded to sub-rounded. Most are dark grey quartz pebbles, approximately 95% of the total gravel being such, so that the conglomerates are oligomictic. Other types of pebbles occasionally found include chert, which comprises up to 3% of the gravel fraction, plus jasper, and very rarely, granite. Some workers have reported finding quartzite pebbles (Joubin, 1954; Holmes, 1958). Pienaar (1963) and Roscoe (1957) found none although Pienaar noted fractured quartz pebbles with a granular mosaic texture similar to quartzite. Pebble size varies along the strike indicating no sorting by strand line currents. There is a general pebble size decrease from northwest to southeast. The conglomerates are texturally mature whereas the subarkoses interbedded with them are immature. Pienaar (1963) believes that the gravels achieved maturity much more rapidly than the accompanying sands during transportation. Quartz pebbles show strain shadows and have cracks filled with regrowth quartz, sericite, and rarely, pyrite. These are the results of regional metamorphism prior to major faulting and introduction of late sulfides.

viii) Matrix of the Ore Conglomerates

The matrix of the oligomictic conglomerates contains sand and silt sized grains of quartz, altered microcline, pyrite, and sericite. Some of the finer parts of the matrix may contain minor chlorite, calcite, and rarely, epidote. Plagioclase and orthoclase have not been recognized. The clastic grains are subangular and poorly sorted. Many minor disseminated minerals have been identified in the heavy mineral and sulfide suites including monazite and zircon. No siliceous cement or authigenic overgrowths of clastic grains have been observed. The existence of sand sized particles in the conglomerate matrix indicates a bimodal size distribution which is diagnostic of fluvial gravels and is uncommon in beach and marine deposits.

The matrix is poorly sorted and fine grained and thus, the conglomerates were not very permeable and were probably less so than some of the better sorted quartzites and grits. There are no significant differences in the potash content of well packed and loosely packed conglomerates. Since the former are more permeable and amenable to the introduction of extraneous material, if any potash had been introduced, it would have been detected. There are also no significant differences in the Co, Ni, Cu, or V content of permeable rudites or impermeable arenites. Well packed conglomerates contain more zirconium, titanium, and total iron than the loosely packed ones. This suggests that the former have a higher heavy mineral concentration although most of the iron is now in the form of pyrite which was either derived from original oxides or was introduced.

ix) Mineralogy of Ore Conglomerates

Pyrite is the most abundant sulfide mineral, constituting over 98% of all sulfides present. From 3 to 12% of each ore zone consists of pyrite and well packed highly pyritic conglomerate beds may contain up to 20%. Most workers recognize that there are 2 types or 2 modes of occurrence of pyrite. The most common pyrite occurs as discrete grains 0.1 to 3 mm. in diameter and appearing euhedral, subeuhedral, or rounded anhedral. These grains are disseminated throughout the matrix of the conglomerates. Pyrite also occurs in a more massive form as small stringers, replacements of clastic material, and clusters. Most workers agree that the individual pyrite grains are detrital, but to varying extents. Joubin (1960) believes that these grains are directly detrital. Robertson and Steenland (1960) note that Arnold found that some of the pyrite had leucoxene centres and thus may have resulted from the sulfidization of pre-existing titaniferous magnetite. Derry (1960) has agreed with this theory. Roscoe and Steacy (1958) found inclusions of anatase and rutile in pyrite and also believe that most of the pyrite has been derived from detrital magnetite, hematite, and ilmenite. Robertson and Steenland (1960) could find no evidence, themselves, of leucoxene in the pyrite but believe the grains to be detrital, although altered. The majority of workers agree that most grains have been recrystallized to some degree. Various theories exist as to the source of the more irregular massive pyrite. The 2 extremes here are a) that this pyrite is essentially hydrothermal and deposited from sulfurous fluids, and b) that it is mainly reworked and remobilized primary pyrite, perhaps with minor amounts of extraneous hydrothermal pyrite.

Of the radioactive minerals present, monazite is the most abundant in the oligomictic conglomerates in general. The high grade uranium minerals, uraninite and a 2 phase uranium-titanium compound (brannerite) are restricted to the ore zones. All these minerals are found only in interstitial material. Monazite grains are rounded and are definitely detrital. Thucolite is found locally where it may line cracks or fractures. According to Robertson (1962), minor uranium and thorium were mobilized during regional metamorphism and are now represented by this thucolite. A further very weakly radioactive hydrocarbon is also present in minor quantities. Robertson (1967) has found no evidence for cross-cutting uranium mineralization as all radioactivity is conformable to the stratigraphy. The grade of the ore over mining widths averages at 2 to 3 lb. U_3O_8 per ton (0.1 to 0.15%), although individual bands may contain up to 20 lb. per ton. Uraninite occurs as angular to subrounded grains of approximately 0.1 mm. diameter. Th-U ratios in the ore, although variable, are comparable to those of the basement. Robertson (1962) has studied the Th-U ratio variations in several ore zones. He found that they varied between overlapping ore sheets in a way that could not be explained by hydrothermal activity. There were gross regional variations and, moreover, the ThO_2-U_3O_8 ratio generally increased from northwest to southeast. The ratio also increased as packing increased. Robertson (1962) suggests that these variations were caused by gravity grading and by different erosional levels in the crustal source rocks. Th rich-U poor monazite is lighter than the U rich-Th poor uraninite and would thus be carried farther downstream.

Many other minerals are present in the ore conglomerates. Most of these belong to the heavy detrital mineral or sulfide suite. Included in the sulfides are sphalerite, galena, molybdenite, pyrrhotite, and chalcopyrite. Chalcopyrite is present only in very minor amounts in ore zones as disseminated blebs or small veinlets. However, it is associated with diabases and granophyric masses within diabases, with basement shears, and also with quartz veins in the Gowganda Formation west of Blind River. This last occurrence is similar to that at Bruce Mines copper deposit in which quartz veins contain chalcopyrite with traces of gold. Also in the conglomerate ore zones of Elliot Lake are small veins and veinlets containing calcite, sphalerite, and thucolite, and others with quartz, calcite, chlorite, and epidote. The only radioactivity in these veins is the thucolite.

x) Alteration of the Ore Conglomerates

The Elliot Lake uranium deposits are not characterized by obvious alteration and replacement along structural features as many other deposits are. Sericite is a very common interstitial mineral but is rarely found in cross-cutting veins and, according to Pienaar (1963), its genesis is a problem. In the vicinity of one diabase dike examined by Pienaar (1963), there was intense chloritization and albitization of the ore conglomerates. The sediments were completely replaced and converted to a slightly schistose chloritic rock in a zone bordering the dike and along post-dike faults and joints up to 30 ft. away. Adjacent sediments were intensely altered. However, there was no clear relationship between the chlorite alteration and uranium content of the conglomerates.

xi) Source Rocks and Origin

It is thought that the sediments of the Matinenda Formation, or lower Matinenda at least, were deposited by fast flowing streams. The linear distribution of the sediments, the lack of continuous strike deposits, and the bimodal size distribution of the conglomerates, are diagnostic features of river or stream sands and not of strong strand line (beach) currents. Also, the fact that the sediments thicken away from their source area and have good stratification does not support an alluvial fan origin. However, some workers, including Derry (1960), have favoured a deltaic origin with deposition near a northward migrating shoreline. Robertson and Steenland (1960) have suggested a cyclic transgressing sea as the depositional environment. They believe that the southeast trend of the ore zones was governed by offshore currents moving detritus to the east.

There is agreement among all concerned that the source rocks for the Huronian, and, in particular, the lower Matinenda, were to the northwest to north of the area. A southeasterly direction of detrital transport has been inferred from crossbedding and gravel fabric by Pienaar (1963) and this corresponds to isopachal trends and the general direction of size decrease.

Source rocks are thought to be similar to the existing basement complex. Pienaar has found a low soda to potash ratio in the feldspar of the lower Matinenda subarkoses and believes that this indicates a low soda source rather than extensive chemical weathering, since other evidence supports poor chemical weathering. Thus, he suggests that the source rocks of the lower Matinenda were potash-rich while the remaining sediments were derived from soda-rich rocks. Also, he believes the source to be mainly plutonics rather than metasediments since very little chert and no other rock fragments are found. Robertson (1967) thinks it is probable that the conglomerates accumulated as placer deposits derived from red phase Algoma granite. Robertson and Steenland (1960) believe the source area to be a metamorphic terrain cut by granites, pegmatites, and quartz veins. Those workers who support a detrital origin for pyrite have suggested its source to be pyritic metasediments of the Archaean basement to the northwest of Quirke Lake.

Hydrothermal and metamorphic activities are thought to have contributed to the uranium deposits to varying degrees by different workers. Robertson (1967) believes the uranium minerals to have been altered and redistributed during diagenesis, periods of tectonic stress, and intrusion of diabase. Pienaar (1963) found no evidence for soda or potash introduction and no evidence for extensive hydrothermal activity, although he noted that some sulfophile elements such as pyrite apparently were enriched by circulating hydrothermal solutions. Robertson and Steenland (1960), on the other hand, believe that there has been late hydrothermal regional soaking with such sulfides as pyrrhotite, chalcopyrite, sphalerite, and minor galena and pyrite, in all the rocks from the basement to the youngest Huronian. However, this soaking has not occurred for galena, at least, since it has been shown recently that all the Pb of the galena is of radiogenic origin.

xii) Geology of the Denison Mine

The Denison Mine is situated on the north limb of the Quirke Lake Syncline. Its 2 mine shafts are located on the west shore of Quirke Lake (see Fig. 2-2) and much of the mine's workings and ore zones lie beneath the lake itself. The main ore zone at Denison lies very near the base of the Huronian sequence. Where there are local highs in the basement, this zone lies directly on the Archaean. The ore zone consists of an upper and lower "reef" of ore conglomerate, each up to 10 or 12 ft. thick but commonly thinner, divided by a more or less consistent band or bands of slightly radioactive, in part pyritic, greenish yellow subarkose known locally as the "Intermediate Quartzite". This subarkose is usually several feet thick. In practice, the entire width of Upper Reef, Quartzite, and Lower Reef, are mined as a unit. Several other smaller ore zones occur at Denison higher up in the sequence but, according to Pienaar (1963), the main upper zone dies out to the east and south. Robertson (1962) correlates the main ore unit at Denison to what is referred to as the Lower Lower Ore Zone at the Algom-Quirke mine but Pienaar correlates it to the main ore conglomerate at Algom-Quirke. Fig. 2-4 is a generalized section of the Huronian at the No. 2 Shaft of the Denison Mine and illustrates the terminology for the Huronian used by company geologists.

2. The Witwatersrand System of South Africa

i) General

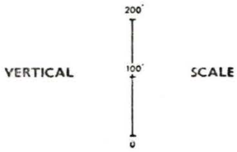
The Witwatersrand System consists of a thick succession of arenaceous and argillaceous sediments which are chiefly quartzites with some interbedded shales, the latter being more common in the lower units. The sequence was deposited in a sedimentary basin which was inset in a stable craton composed of some of the oldest rocks in Africa. The entire system attains a thickness of some 25,000 ft. and covers an area of approximately 2,500 square miles. The series is almost completely lacking in calcareous sediments and contemporaneous igneous rocks are almost insignificant throughout the total thickness. It has not undergone any true orogenic deformation. Two of the more dominant characteristics of the System are the remarkable persistence of thin beds

Fig. 2-4 SECTION THROUGH THE HURONIAN

AT

DENISON MINE - NO. TWO SHAFT

GEOLOGIC UNITS AS USED BY DENISON MINE GEOLOGY DEPARTMENT



LEGEND

- ⋯ DIABASE
- ░ SERPENT FORMATION
- ▧ ESPANOLA FORMATION
- ▦ BRUCE LIMESTONE
- ○ BRUCE CONGLOMERATE
- ┄ UPPER MISSISSAGI
- ═ ARGILLITE
- ▨ LOWER MISSISSAGI
- ᵘ ORE ZONE
- X X BASEMENT COMPLEX
- — MAJOR UNCONFORMITY
- ~ THRUST FAULT

over considerable distances, and the preponderance of shallow water depositional conditions. The Dominion Reef System and the Ventersdorp System are closely related to the Witwatersrand and all 3 constitute a major geological cycle of the early Proterozoic. The basement complex below consists of rocks of the Swaziland System and the "Older Granites". Most of the Witwatersrand sediments are covered by younger rocks of the Ventersdorp System, the late Precambrian Transvaal System, or the Carboniferous-Triassic Karoo System.

The Dominion Reef System consists typically of a basal group of conglomerates, grits, arkoses, and quartzites, up to 300 ft. thick, which is overlain by a zone of amygdaloidal andesitic lavas and a further zone of more acidic igneous rocks, these latter 2 zones being up to 3,000 ft. thick. This system is the oldest of the three.

The Ventersdorp System is the youngest of the 3 groups. In the central Rand it is apparently conformable but in other areas it lies on the Lower Witwatersrand, the Dominion Reef System, or even on the "Older Granites". The Ventersdorp is composed of basaltic to andesitic lavas, quartz porphyries, and felsites, with minor interbedded tuffs, shales, cherts, and breccias. Its thickness and order of succession are extremely variable although, in part, it exceeds 10,000 ft.

There is an extensive development of intrusive dikes and sills, mainly basic, into all 3 systems with dikes predominating over sills. These intrusions usually have very steep to vertical dips, frequently are found along fault planes, and have thicknesses ranging from a few to over 100 ft. At least 4 ages of intrusions have been recognized with the oldest and probably most abundant being related to the Ventersdorp period.

The ages of the various systems and formations have been approximately determined. It is thought that the "Older Granite" of the basement crystallized about 3.2 b.y. ago. The Dominion Reef System is dated at approximately 3 b.y. The Witwatersrand System itself, is estimated to be between 2.2 and 2.9 b.y. old. There was a period of intense chemical alteration, diagenesis, and hydrothermal activity between 2.05 and 2.15 b.y. ago which is believed to correspond to the formation of the Ventersdorp System.

ii) The Witwatersrand System

The System proper is divided into an Upper Division and a Lower Division, based on differing lithologies and Au content. The rocks of the Upper Division are of greater economic values and are, therefore, better known. They outcrop for a total length of 180 miles from a total strike length of 600 miles. As a whole, the System consists of alterations of shales, quartzites, grits, and conglomerates. Banded silicic ironstones, some tillites, and a band of intercalated lavas are also found in the Lower Division. There is 1 band of volcanics in the Upper Division. The Lower Division consists of 45 to 65% argillaceous rocks and contains several marker horizons including the group of tillites. The Upper Division, in mining areas at least, contains only 10 to 20% shales. Most of the important marker beds are conglomerate horizons which are remarkably persistent over extensive areas. These horizons are called "Blankets" when they are auriferous and show amazing lateral continuity and homogeneity. These features distinguish them from modern placers. The quartzites of the Upper Division are hydrothermally altered feldspathic quartzites. The gold and uranium present in the Upper Witwatersrand (and Lower) are almost entirely confined to conglomerate bands or reefs.

Over the entire basin, the Witwatersrand System has been subjected to relatively low grade regional metamorphism. The argillaceous sediments have been converted to compact shales and slates with sericite, chlorite, and chloritoid. Arenaceous sediments show evidence of secondary silicification and pyrophyllitization while the conglomerates contain sericite, chlorite, and chloritoid in their matrix.

iii) The Gold and Uranium Ores

The ore mineralization occurs in 3 forms. The first and most important occurrence is that of the blanket type in which the ore minerals are found in the matrix of tightly packed conglomerate bands. The second mode of occurrence is the carbon-seam type where ore is found on sedimentational parting planes which represent unconformities or disconformities. The Au is usually associated with considerable amounts of hydrocarbon and uranium occurring in thin seams with scattered pebbles. The final type of mineralization is that found in banded pyritic quartzites which are located in scour and fill structures in the footwalls of auriferous conglomerate zones.

The blanket conglomerate is a mildly metamorphosed compact conglomerate consisting of 70% pebbles in a quartzite matrix. The majority of pebbles are vein-type quartz although other varieties of quartz plus chert, jasper, quartzite, and quartz porphyry pebbles have been identified. All these rock types can be found in the Basement Complex. The pebbles have diameters of up to 4 in. They range from closely to loosely packed and from well to poorly sorted. Changes in composition as well as thinning to narrow bands of grit occur down dip. The quartz pebbles are virtually barren with most gold and uranium occurring in the matrix. The pebbles are firmly cemented together with a fine grained matrix of detrital quartz grains which, in turn, are cemented by secondary silica. Sericite, pyrophyllite, chlorite, and chloritoid also occur in the matrix. The heavy mineral suite in the matrix is very extensive and includes minerals ranging from gold to occasional diamond.

Pyrite is the most widespread of the ore minerals in the matrix and constitutes approximately 3% of the blanket as a whole or about 12% of the matrix. It occurs principally as rounded grains (the so-called "buckshot" pyrite) and also as irregular patches and clusters, and as euhedral crystals. The latter 2 occurrences are often overgrowths on "buckshot" pyrite. It is thought that the pyrite is either detrital or a pseudomorphic replacement of detrital quartz, chert, and magnetite. Recently, it has been observed that there are possibly 2 different types of pyrite present, each with its own differing optical and microscopic properties.

Gold is almost entirely restricted to the matrix although there are some small veinlets which cut across pebbles. The Au occurs as minute hackly grains 0.001 to 0.07 mm. in diameter, or as extremely small flakes, and has undergone recrystallization and redistribution. When the Au is very fine it is often enclosed in and intergrown with pyrite and pyrrhotite although there is no evidence of simultaneous deposition and crystallization of gold, sulfides, and uranium minerals.

Detrital grains of osmiridium are found. These are sometimes associated with other platinoids and/or with gold. The ores contain from a trace to 0.4% U_3O_8. The uranium occurs as individual grains of uraninite smaller than 0.01 mm. diameter, or as a hydrocarbon-uraninite mixture. This latter occurrence is found as specks, granules, and thin seams or pods, and is usually associated with pyrite. It has been observed filling cracks in pebbles. The uraninite exists mainly as oval "detrital" grains, many of which have been cracked in situ and slightly displaced. Also, many of these primary grains have been replaced by the hydrocarbon mixture so that approximately 10 to 15% of the total uranium is associated with hydrocarbon. There is also secondary uraninite formed by the reconstitution of primary grains. This uraninite occurs as minute veinlets which are often still connected to parental grains, and as small irregular masses.

In the blanket type of deposit, gold content varies with the size of pebbles and with the degree of sorting. Furthermore, the Au concentration and pebble size vary according to the proximity of the blanket to its point of entry into the basin. This differs from the carbon-seam type of deposit in which gold content indicates a strong dependence on hydrocarbon content.

Exploitable auriferous conglomerates occur in all the main subdivisions of the Witwatersrand System, except in the Hospital Hill Series, although, as previously noted, the majority of economic workings are in the Upper Division. In the other systems, gold is confined to a basal conglomerate and it is sometimes, clearly, reworked gold from older underlying beds.

iv) Origin and Source of Blanket Ores

The goldfields are fanshaped and are thus, thought to have originally formed as deltas. Since there are 4 main goldfields or deltas, 4 sources are presumed. The source is believed to be granitic rocks, with pegmatites to supply the abundant quartz pebbles, and schists. Basement areas with Archaean remnants would satisfy the source requirements. It is thought that the Lower Witwatersrand was eroded to a large extent, to feed the Rand Basin proper. There is not much hope of ever finding the original gold sources, and even if remnants of gold bearing veins or schists were found, they could easily prove uneconomical.

Thus, it has been postulated that a goldfield analogous to that of Southern Rhodesia, but with a larger overall gold content, existed mainly in the area now occupied by the Bushveld Complex, which at that time was a positive area. The released gold from this region found its way directly, or in steps, into the deltas of the Witwatersrand.

3. The Uraniferous and Auriferous Oligomictic Conglomerates of Jacobina, Brazil

Uranium bearing gold deposits exist in Proterozoic reef-type conglomerates of the Serra de Jacobina Range in Brazil. The gold and uranium are associated with pyrite, sericite, and chlorite in the matrix of closely packed quartz pebble conglomerates. The Serra de Jacobina is a sedimentary series which is part of a geosynclinal succession and its completely enclosed by the Archaean basement on which the basal formations unconformably lie. Metamorphism of the sequence is of the amphibolite facies. The formations consist of thin-bedded to massive, white to pale green quartzite and feldspathic quartzite with locally prominent ripple marks and crossbedding, and contain extensive conglomerate horizons and lenses in the lower parts. Sporadic beds of quartz-muscovite schist also occur in the lower portions of the series. The entire sequence is overlain by argillaceous sediments now represented by phyllites. The series dips homoclinally to the east at from 45° to 65° and attains a thickness in the tens of thousands of feet.

In the gold producing area the geology consists of a lower group of thin-bedded crossbedded quartzites containing several conglomerate horizons and an upper group of massive quartzites. The gold bearing reefs are restricted to the lower zone although they are usually well above the basal beds. The sediments are cut by subconcordant altered diabase dikes and by several steep angle reverse faults with horizontal displacements of up to 1200 ft. Two types of reef are present but all significant radioactivity and economic gold values are contained in conglomerate zones referred to as Piritoso-type reefs. In these, the gravel component consists of reddish pink glassy quartz pebbles from 1 to 1-1/2 ins.in diameter. The matrix consists of green chlorite, sericite, and finely divided pyrite which makes up approximately 3 to 5% of the total conglomerate. The ore zones are from 6 to 8 ft. thick and in places they thin to a single pebble layer or split in two. Contacts are irregular and scour and fill structures at the base of the conglomerates are locally prominent. The gold is distributed throughout the matrix from hanging wall to footwall but most of the pyrite and uranium is concentrated in the centre of the reefs and gold values are higher there as well. Gold and uranium mineralization occurs mostly in the thicker parts of the reefs. There is, apparently, a quantitative relationship between gold, uranium, and pyrite. The quartzite which encloses the conglomerate zones is light greenish and is also found as barren zones within the reefs themselves. The average grade of ore in the mined reefs is 0.45 oz. Au per ton and 0.015% U_30_8. No hydrocarbons have been identified in the conglomerates and thorium exists only in traces.

In one area, the gold is found in pyrite grains of the conglomerate matrix and also, in minor amounts, as thin sheets in fracture zones cutting the conglomerate bands. However, in another mining area, the gold uranium-pyrite mineralization apparently follows a fracture and does not favour any lithological unit. White (1961) describes this mineralization and concludes that, since some of the zones cut both quartzite and conglomerate, and since there is no correlation between high gold-uranium values and any particular rock type, the mineralization cannot be of placer origin but must be hydrothermal. Cox (1967) concludes from his studies that a placer origin for the gold, uraninite, and pyrite, is suggested but that most of the evidence for this has been obliterated by redistribution of the minerals during metamorphism. Bateman (1958), in one of the earlier reports on this area, concludes that the geochemical evidence tends to reject a simple syngenetic hypothesis of origin but that an exclusively hydrothermal origin is equally unacceptable. He states that the real problem is to determine the amount of "rearrangement" that has taken place.

Table 2-1: Comparison of Elliot Lake, the Rand, and Jacobina

	Elliot Lake	Witwatersrand	Jacobina
Age	Proterozoic	Proterozoic	Proterzoic
Age of Basement	Archaean	Archaean	Archaean
Total thickness of sediments	5000 ft.	25,000 ft.	>10,000 ft.
Height of ore zones above basement	0 to 250 ft.	Well above basement through several 1000 ft.	1800 to 3000 ft.
Structure	Plunging syncline	Sedimentary basin	Dipping homocline
Metamorphism	Greenschist (chlorite)	Mild (greenschist?)	Amphibolite
Mode of Deposition	Fluvial	Deltaic	Fluvial
Sediments containing ore minerals	Matrix of oligomictic conglomerates	Matrix of oligomictic conglomerates	Matrix of oligomictic conglomerates
Gold (oz./ton)	tr. (to erratic highs)	0.2 - 0.8	0.25 - 0.45
Uranium (%U_3O_8)	0.1 - 0.15	0.01 - 0.06	0.02 - 0.04
Thorium (%ThO_2)	0.05	tr.	tr.
Pyrite(%)	3-12	2-10	2-5
Pebble type	Glassy quartz (grey)	Glassy quartz	Glassy quartz (pink)
Pebble diameter	1-1/4 - 2 in.	1 (up to 4) in.	1 - 1-1/2 in.
Pebble-matrix ratio	63:35 - 40:60	70:30	60:40
Sericite and/or chlorite	significant	present	significant
Carbon (hydrocarbon)	minor	significant	negligible

CHAPTER III

THE CONTROVERSY REGARDING THE ORIGIN OF URANIUM AND GOLD IN BLANKET CONGLOMERATES

1. General

As was demonstrated in Chapter I, there is no complete agreement among geologists and geochemists concerning the source and origin of ore minerals in oligomictic conglomerate deposits of the Elliot Lake or Witwatersrand type. It is obvious from the similarities of these various deposits, as discussed in Chapter II, that they are most probably of similar origins. Bateman (1958), for example, has concluded that the Jacobina, Rand, and Elliot Lake deposits are the product of a similar metallogenic cycle of erosion, sedimentation, and mineral deposition that was restricted to the late Precambrian. Davidson, and others, automatically apply the principle of uniformitarianism to any pertinent arguments or discussion on the origin of these deposits. However, many South African geologists contend that the evolutionary character of terrestrial processes requires modification of this concept, particularly with regard to application to the Precambrian. Thus, it is possible that conditions favourable to the formation of uraniferous and auriferous quartz pebble conglomerates do not exist today.

2. Hydrothermal Origin

The theory of hydrothermal emplacement of the gold, uranium, and other minerals into the oligomictic conglomerates is essentially that of Davidson. His most recent revision of the hypothesis (Davidson, 1964) is that the ore metals were initially introduced into the conglomerates from a granitic source by hydrothermal solutions and were redistributed by multiple migration or lateral secretion in ground waters. To support this theory he presents the following points. Firstly, there are no rich sources of the ore metals in the rock formations from which the strata were derived. Secondly, he contends that the uranium mineralization is contemporary with the remobilization of the underlying granite-gneiss basement which occurred after the sediments were deposited. Thirdly, Davidson argues that high Co-Ni and selenium-sulfur ratios must be regarded as indicative of hydrothermal solutions derived from a granitic source. However, none of these points is sufficient to rule out a syngenetic origin. Proponents of a placer origin contend that a rich source of Au and U is not required. Rather, they believe that these minerals were concentrated after erosion from a typical Archaean basement terrain. Also, few placerists deny that the uranium minerals have been remobilized or recrystallized after deposition. Dating of the uranium would probably correspond to this event which, even if it did correspond to remobilization of the basement, would not indicate that the uranium was not present in the conglomerates prior to the remobilization. Finally, most workers agree that there has been at least minor hydrothermal activity which would give rise to the high Co-Ni and selenium-sulfur ratios of Davidson.

Davidson (1964) agrees that the most recent age dating of the Rand supports a placer origin but he suggests that no dates can be relied upon until the fundamental concepts of South African geology are re-examined thoroughly. He has two leading arguments against a syngenetic origin for the ore minerals. The first is that the auriferous reefs (of the Rand) are devoid of any significant concentrations of all the common refractory heavy minerals such as ilmenite, rutile, zircon, and monazite, which characterize all alluvial gold deposits. Davidson states that all arguments against this fact are subjective and he has produced analyses of the tenor of the heavy minerals in the blankets showing it to be no greater than that of a normal sandstone. The important fact overlooked here is that the pyrite of the ore is considered by many to represent original detrital magnetite, ilmenite, etc. Davidson's second argument against a detrital origin for Au and U is that uraninite does not survive as detrital grains in modern placers. It is suggested by some workers that uraninite does exist in modern placers. However, he contends that even if this is the case, it does not follow that uraninite grains survive since one cannot assume occurrence is synonymous with survival. He further states that all attempts to prove uraninite has travelled far as detrital grains are faulty. Davidson holds strictly to the principles of uniformitarianism, discounting any suggestion that while uraninite possibly does not survive in placers today, this does not imply that it could not have existed in Precambrian times. Finally, he notes that uraninite commonly occurs in patchy clusters which cannot be explained by an alluvial theory but are found in several Soviet epigenetic uranium deposits. However, these clusters could be the result of remobilization of uraninite which most commonly occurs in the conglomerates as discrete individual grains.

3. A Syngenetic Origin

There is much direct evidence favouring a detrital origin for the gold and uranium of oligomictic conglomerates. Most of it has been presented by mine and government geologists who have worked directly on the deposits. All uranium minerals are considered detrital. They exist in a normal detrital assemblage and have the same general distribution as other detritals whereas minerals which commonly accompany hydrothermal uraninite are absent or obviously of later origin. Both the uraninite and gold are concentrated with the other heavy minerals in specific areas. Most uraninite exists as individual oval grains. In vein deposits such grains may be found but only exceptionally. Also, the spheroidal uraninite grains have nowhere assumed the shape of the interstitial voids in which they formed in the conglomerates. The non-survival of uraninite is, according to Liebenberg (1958), and Roscoe and Steacy (1958), unfounded since evidence is slowly accumulating indicating its survival even in modern placers. Robertson and Steenland (1960) state that attrition experiments have been carried out which indicate that, if monazite can survive as a detrital, so can uraninite. According to the same authors, a study of the heavy mineral suite of the Elliot Lake ore found minor diopside and hornblende present and these 2 minerals are non-resistates. Uraninite and pitchblende from veins and other epigenetic deposits contain less than 0.1% $Th0_2$ whereas the crystalline uraninite at Elliot Lake contains over 8% and that of the Witwatersrand up to 2.7%. This variety of uraninite is typical of that found in pegmatites and as an accessory mineral in granitic rocks. Robertson (1962) found variations in the Th-U ratio between partially overlapping ore sheets at Elliot Lake, found further gross regional variations, and also determined that the ratio increased in a southeasterly direction. He concluded that these variations could not be explained or caused by hydrothermal activity. Liebenberg (1958) has found at the Rand that secondary uraninite did not result from extraneous hydrothermal solutions but formed at the expense of primary uraninite and that primary uraninite was a prerequiste for the formation of thucolite and secondary uraninite. Also, the fact that pyrite and uraninite, which are hard and brittle minerals, are fractured and even slightly displaced in cases, indicates that both were present before metamorphism.

Uraninite and gold can be correlated to sedimentary features, namely the oligomictic conglomerates. Hydrothermalists explain this phenomenon by stating that the minerals were introduced into the most permeable rocks which were the conglomerates. However, according to Roscoe and Steacy (1958), large contrasts in uranium content at Elliot Lake cannot be correlated with large differences in permeability as determined by grain sizes and the degree of sorting. Liebenberg (1958) states that the hydrothermal mineralization of thin bands of conglomerate in such a vast body of sediments as the Rand, with such large variations in permeability, appears virtually impossible.

Liebenberg (1958) has found that the gold of the Rand behaves as a member of a heavy mineral suite. Since the gold is malleable, it would undergo plastic flow and recrystallization during metamorphism. As the gold has done so, it is evident that it was present prior to metamorphism. Thus, the shape of the gold is a result of reworking and not a result of solution deposition. Some nuggets still exist in the ore although the majority of gold occurs as hackly particles and veinlets associated with quartz and phyllosilicates and not with sulfides as would be expected if the gold and sulfides had been deposited together from hydrothermal solutions. Also, there is a sympathetic relationship between gold, uraninite, and even osmiridium in some cases, in specific conglomerate bands, and thus, if it is assumed that the uranium and osmiridium are detrital, then the gold is also most probably detrital.

Many workers reject the hydrothermalists' contention that the large amounts of pyrite in the ore are of hydrothermal origin, and that therefore, the same hydrothermal processes could have deposited uranium and gold. Roscoe and Steacy (1958) believe that minor pyrite may be hydrothermal but that most of it is probably derived from detrital magnetite, hematite, and ilmenite. They present several reasons for this conclusion. The geological environment is one where placer concentrations of iron oxides is expected and some hematite and magnetite are present unaltered. Also, many pyrite grains are spheroidal resembling rounded detrital grains. Titanium minerals have been found commonly intimately associated with pyrite and pyritiferous chert pebbles are thought to represent original pebbles of banded iron formation. Furthermore, bedded iron sulfides with no associated radioactivity are abundant in some fine grained Huronian rocks as well as in coarse grained ones. Thus, permeability to hydrothermal solutions was not a main control in their formation. Finally, they point out that iron minerals in sediments and volcanics have commonly been converted to pyrite during low grade regional metamorphism. Robertson and Steenland (1960) found no high temperature hydrothermal effects in the ores of

Elliot Lake and could find no connection between uranium minerals and sulfides, quartz veins, basic dikes, or faults. Liebenberg (1958) also concluded for the Rand that uraninite, gold, and sulfides were not genetically related as they are in polymetallic veins. Although there are sulfides present which contain Co and Ni which usually accompany pitchblende in polymetallic veins, he has found that the relationships of uraninite, gold, and sulfides, are "chance" associations with the various minerals showing different age relations. Liebenberg goes further to say that most of the sulfides in the conglomerates are not of hydrothermal origins. He believes there is little doubt that most of the pyrite, especially the "buckshot" variety, is of placer origin. According to Liebenberg, detrital pyrite grains often occur as the main heavy constituent in modern placers. He feels that even the other sulfides behave strangely for hydrothermally deposited minerals. They mainly occur as small isolated particles not connected to larger parent masses. He states that most of these minerals are secondary and probably represent reconstituted detrital minerals. Liebenberg has found that no dikes or faults acted as feeder channels for hydrothermal solutions and that there are no other feeder channels for their introduction. He rules out the hydrothermal "soaking" of the entire system by stating that some of the younger conglomerate beds were not even deposited before lower ones were metamorphosed. Liebenberg does accept the fact that some pyrite and other sulfides probably originated by a diagenetic process in which black sands were converted to sulfides in the presence of sulfur. He believes this would explain the infrequent occurrence of black sands and would also explain the conversion of radiogenic lead to galena.

4. A Third Hypothesis for the Origin of Uranium

A theory somewhat differing from the two major hypotheses just discussed has been postulated by workers including Derry (1960) and Joubin (1960), and is applicable to the origin of uranium only. Derry favours an alternative hypothesis because of the absence of post-Cambrian uranium deposits formed by detrital processes and because of the lack of obvious hydrothermal features. He suggests that the uranium minerals were deposited contemporaneously or shortly after the deposition of the conglomerates as precipitates from supergene solutions and not as detrital minerals. Uranium and thorium were dissolved in surface waters from surrounding basement areas and precipitated in concentrated quantities under favourable conditions of high porosity, slow drainage, and reducing conditions. The conglomerates received the uranium after light burial under sand or clay by the agency of underground water courses. The minor gummite present in the conglomerates now is the closest mineral to the original precipitates. After burial, the uranium was redissolved and redeposited as uraninite and brannerite. Joubin (1960) favours a similar origin for the uranium minerals. Although he notes that there is a similar distribution of uranium and pyrite, and the same lack of evidence of a detrital origin for both, he favours a direct detrital origin for pyrite but a solution-precipitation origin for uranium. Robertson (1962) points out that the uraninite of Elliot Lake is of the thorium-rich high temperature variety yet exists in an environment where the temperature has never exceeded that of the lowest grade of metamorphism and therefore is not likely a precipitate from ground water. Other arguments based on porosity variations, distribution and shape of uraninite, and analogies of Elliot Lake to the uranium-gold ores of the Rand also discount this theory.

5. Conclusions

Although no definitely conclusive evidence has been put forward, it is apparent from the preceding discussion that the proponents of a modified placer origin for the uranium and gold of Proterozoic oligomictic conglomerates have a better case than do the proponents of an extraneous hydrothermal origin. The majority of data, when examined objectively, is more favourable to a syngenetic than to an epigenetic origin.

CHAPTER IV

THE GEOCHEMISTRY OF GOLD AND ITS DISTRIBUTION IN ROCKS AND SULFIDES

1. General Geochemistry of Gold

Unlike many of the other precious metals, gold is usually concentrated in the late residual liquids by magmatic differentiation and is thus, commonly found in hydrothermal quartz veins associated with granitic magmas. Economic concentrations of gold are therefore related to acidic, rather than basic, magmas. The two main economic occurrences of gold are those associated with hydrothermal deposits, as mentioned, and placer deposits. This latter type results from the fact gold has a high density (19.3 when pure) and is extremely resistant to chemical breakdown or dissolution.

2. The Gold Content of Rocks

With the advent of neutron activation as a method of determining minute quantities of gold in natural substances, much work has been done on the amounts of gold in various rock types. Some of the results pertinent to this work are given in Table 4-1. The determinations by Vincent and Smales (1956) are included since they were among the first to utilize neutron activation for Au determinations in rocks. Although the data of Table 4-1 vary from worker to worker, one general observation is noteworthy. There is a general tendency toward a decrease in gold values from basic and ultrabasic rocks to acidic rocks. Shcherbakov and Perezhogin (1964), in analysing monomineralic fractions of rocks, observed that the gold content decreased from magnetite and ferromagnesian silicates to feldspars. This decrease corresponds to that from mafic to felsic rocks. Their explanation of this behaviour was based on the assumption that gold, although for the most part remaining in residual liquids, would, to some extent, favour covalent bonding over ionic bonding and would thus, most likely be found in the ferromagnesian silicates such as olivine and pyroxene which have minimal ionic bonding. As a magma differentiates and becomes more silicic, the structure of the silicates becomes more ionic and thus, the amounts of chemically bound gold in these minerals will be less than in the mafic minerals. Thus, the concentration of gold in the residual magma will increase even more. It follows that, although basic rocks will contain the larger amounts of chemically bonded gold, economic gold mineralization will occur most commonly in association with acidic rocks, which contain very little gold themselves, but are derived from magmas enriched in it. Although there may be some doubts as to the validity of the basis for Shcherbakov and Perezhogin's arguments, some process, either similar to, or working in an identical way to that outlined, must be responsible for the fractionation of gold in rock-forming silicates.

Table 4-1: <u>Published Data on Gold Content of Rocks</u>

Rock type	Au ppb	No. Samples	Reference
Crustal abundance	2.5	estimate	DeGrazia and Hastin (1964)
Standard Diabase W-1	18	4	Vincent and Smales (1956)
	8.4	2	Vincent and Crocket (1960b)
	5.0±0.6	8	Shcherbakov and Perezhogan (1964)
Standard Granite G-1	10	2	Vincent and Smales (1956)
	4.5	2	Vincent and Crocket (1960b)
	4.6±0.8	5	Shcherbakov and Perezhogin (1964)
Granites	3.2	33	Shcherbakov and Perezhogin
Rhyolites & Trachytes	5.4	14	
Intrusive basalts	10	19	
Gabbroids	8.7	33	
Basalts and Andesites	6.5	29	
Ultramafics	9.4	27	
Shales and Sandstones	3.6	39	
Greywacke, Gowganda Fm.	2.3	1	DeGrazia & Haskin(1964)
Acidic igneous and metamorphics	2.4±1.8		DeGrazia & Haskin
Basic igneous and metamorphics	2.6±0.6		DeGrazia & Haskin
Mid-Atlantic Ridge Basalts	10±3		DeGrazia & Haskin
Shales	4.7±1.6		DeGrazia & Haskin
Sandstones	6.0±3.5		DeGrazia & Haskin
Pelagic clays	12±7		DeGrazia & Haskin

Vincent and Crocket (1960a), in a study of the Skaergaard Intrusive of Greenland, found that the concentrations of gold in rock-forming silicates and oxides throughout the differentiated series remained of the same order as in the liquid. They concluded, on the basis of Eh-pH calculations, that the gold was in the form of uncharged neutral atoms with no attracting or repelling forces involved. These atoms were incorporated or trapped in growing crystals in their vicinity. Mantei and Brownlow (1967) have done a study on the gold content of minerals from the Marysville Quartz Diorite Stock in Montana. They obtained the results in Table 4-2.

Table 4-2: Au in Minerals of Marysville Quartz Diorite Stock

Mineral	Average Au, ppb.	No. Samples
Biotite	76	44
Hornblende	100	37
Magnetite	37	44
Quartz-Feldspar	65	10
Whole Rock	34	5

Mantei and Brownlow concluded that gold could not form bonds in the crystallizing minerals and therefore, it was concentrated in the residual fluids and was finally deposited in quartz veins at the edge of the stock. No bonding could occur since 1) gold would not take part in ionic substitution because of its oxidation potential, and 2) Au^+, having a relatively large electronegativity, would form very weak covalent bonds. They suggested that the gold in the minerals was probably entrapped as uncharged atoms, as did Vincent and Crocket (1960a). According to Mantei and Brownlow (1967), the amount of gold in a mineral was determined by the structure of the mineral and the concentration of gold in the magma at the time the mineral crystallized. They concluded that there was more gold in biotite and hornblende since these were open crystal structures whereas magnetite was a relatively closed structure. Also, they believe magnetite may have formed prior to the silicates and thus, when gold concentrations were low. Keays (1968) found that gold was highly fractionated during the crystallization of the sulfide melt at Sudbury and therefore, he believes it is highly improbable that gold exists as neutral uncharged atoms in silicate melts. He doubts the theory advanced by Shcherbakov and Perezhogin (1964) and states that gold is less electronegative than many of the base metals including iron. However, according to the electronegativity tables of Pauling (Krauskopf, 1967), and others, gold is more electronegative than the base metals including iron. Keays (1967) has postulated his own theory to explain the behaviour of gold during differentiation of a magma. Initially, the gold is as Au^o and is precipitated with early crystal differentiates. With crystallization, the relative amount of volatiles, such as $S_2^=$, Cl^-, and OH^-, increases and gold becomes complexed, thus remaining in solution. Mafic minerals such as amphibole and micas would act as sites of decomposition for these complexes with the resultant precipitation of metallic gold entrapped in the growing crystals. However, in general, complexes would remain stable and persist during the entire process of differentiation.

It can only be apparent from the differences in theories held by various workers that the behaviour of gold during differentiation of a silicate magma is very much in doubt.

3. Gold in Sulfides

It is usually stated that gold occurs in rocks in a dispersed state, and that much of it is bound in sulfides, especially copper sulfides (Shcherbakov and Perezhogin, 1964). The same authors have concluded that most of the metallic gold in sulfides, as well as in silicates, occurs as microscopic and submicroscopic inclusions. This conclusion is supported by Schweigart (1965) in his comments on a paper by Callow and Worley (1965). They discuss sulfide concentrates which still contained up to 2 oz. Au per ton after prolonged cyanidation and thus, they conclude that the gold must have been in solid solution. Schweigart refutes this and states that the very fine particles of gold may be released upon cyanidation if the sulfide is ground sufficiently fine. Thus, he believes that this gold does not occur in solid solution but rather, as minutely dispersed inclusions of free metallic gold. Schweigart also believes this to be the general case for gold in sulfides. Auger (1941) performed spectrographic tests on pyrite from various Canadian gold mines. He found that the gold was unevenly distributed in pyrite crystals in all the mines studied, and that the grade of ore did not affect the gold concentration of the pyrite as determined spectrographically. From these observations, Auger concluded that gold was irregularly distributed in pyrite and did not enter the structure of the crystal in solid solution, but was present in the native or combined form as isolated units or narrow veinlets. He also concluded that the gold was not precipitated at the same time as the pyrite. Hawley (1952) found, in a further study of pyrite from Canadian gold mines, that gold distribution appeared to be more related to structural factors such as the depth of the ore and proximity to contact zones, than to the original temperature of deposition of the pyrite. Schwartz (1944), in a study of the host minerals of native gold, found that, in some mines, chalcopyrite concentrations were a good indicator of gold concentrations, but that no clear relationship existed. Also, in many instances, pyrite was intimately associated with gold although this gold was probably always free native gold since Schwartz found little evidence for solid solution. Thus, it is apparent from all the preceding investigations, that the evidence is strongly against a solid solution relationship of gold to pyrite. Rather, most workers have found that gold most probably exists as free metallic inclusions within pyrite, or sulfides in general.

The only evidence supporting the possibility of gold solid solution in pyrite is that presented by Kurenti (1941). In a synthetic study of gold in pyrite, he prepared a pyrite containing over 2, 000 ppm. Au. The distribution of gold in the sulfide was uniform as shown by spectral analysis. Also, it was found that the lattice constant of the pyrite crystal structure decreased with increasing gold content and reached a constant value at approximately 2, 000 ppm. This evidence indicates that solid solution of gold in pyrite is possible and may occur in natural sulfides.

Gold does occur within pyrite, as in other sulfides, in amounts from negligible traces to economic proportions. However, the majority of pyrite deposits contain relatively insignificant quantities of gold and thus, little is known of them. For example, in a recent study of over 1,200 pyrite samples from deposits in Czechoslovakia (Cambol and Jankovsky, 1967), the detection limit for gold was approximately 10,000 ppb. and thus, the great majority of the samples (89%) were found to contain no detectable gold. Some studies have been done on the trace amounts of gold in sulfides and the results of these are presented in Table 4-3. The significance of the values given in the table is that 4 of the 5 independent studies have found that gold is concentrated in the chalcopyrite fraction of a sulfide crystallate to a much higher degree than in the pyrite fraction. The range of gold concentrations in the various sulfides is very considerable, however.

It is obvious that further detailed studies are required before it can be determined whether sulfide deposits of identical genetic histories contain diagnostic or, at least, consistent quantities of gold, or whether there are no correlations between the amount of gold in a sulfide and its genesis.

Table 4-3: Gold Content of Sulfides

Mineral	Location	Au, ppb.	No. Samples	Reference
Chalcopyrite	-	20,000	15	I. and W. Noddack (1936)
pyrite	-	400	15	
pyrite	-	4,000	15	
Chalcopyrite	Noril'sk Deposits	2,100	27	Ginzburg and Rogover (1960)
pyrrhotite		80	16	
pyrite		3,400	4	
Chalcopyrite	Almalyk Region of Central Asia	22,000	-	Badalov and Terekhovich (1966)
pyrite		3,500	-	
Chalcopyrite	Strathcona Mine Sudbury, Ont.	35.7	11	Keays (1968)
pyrrhotite		9.5	21	
Chalcopyrite	Skaergaard Intrusive, Greenland	6,000	estimate	Vincent and Crocket (1960a)
pyrite		16	2	
pyrrhotite		2.8	2	

CHAPTER V

ANALYTICAL METHODS

1. Neutron Activation as an Analytical Technique

The method of neutron activation for chemical analysis is based on the fact that the amount of radioactivity induced in an element when it is irradiated in a neutron flux is proportional to the concentration of the element present, the neutron flux, and the irradiation time. A comparative technique is used in which a sample is irradiated, together with a standard of known concentration, under identical conditions, and the two induced radioactivities are compared. After irradiation, a small amount of inactive analysis element is added to the irradiated material and this serves as a carrier for the irradiated element during the chemical separation procedure which follows. An analytical method is utilized which separates the analysis element from the remainder of the induced radioactivities to such an extent that the desired element is radiochemically pure. Since the proportion of irradiated element recovered is equal to the proportion of carrier element recovered, the process does not necessitate quantitative recovery. A further advantage of the method is the fact that no post-irradiation contamination from chemical reagents or other sources can influence the result unless the contamination is of such gross proportions as to add significantly to the weight of carrier. The main advantage of a neutron activation analysis is that it is very sensitive for many elements and, for gold, concentrations on the order of a fraction of a part per billion (ppb) may be determined.

2. Preparation of Gold Carrier and Standard Solutions

i) Preparation of Carrier Solution

The approximate concentration used for the carrier solution was 4 mg. Au/ml.

Approximately 400 mg. of Au foil or powder were weighed out on a 5 place balance and placed in a beaker. Five ml. of aqua regia was added and the gold dissolved on a hot plate at very low heat, with a watch glass over the beaker. The solution was then evaporated to near dryness, 1 ml. of conc. HCl was added, and the solution again taken to incipient dryness. This step was repeated twice to convert all Au to the chloride complex and to remove all traces of nitrate. The Au was then taken up in approximately 25 ml. of 1M HCl and was quantitatively transferred to a 100 ml. volumetric flask. The flask was then filled to volume with 1M HCl. This carrier solution was stored in a conical glass flask with a greased glass stopper to prevent any loss by evaporation.

ii) Preparation of the Gold Standard Solution

The standard solution contained approximately 0.02 μgm. Au/ml.

To prepare the standard solution, 10 ml. of the carrier solution containing approximately 4 mg. Au/ml. was pipetted into a 1000 ml. volumetric flask. This solution was diluted to 1000 ml. with 1M HCl to give a concentration of 40 μgm. AU/ml. Ten ml. of this solution was diluted to 1000 ml. with 1M HCl to give a concentration of 0.4 μgm. Au/Ml. Finally, 25 ml. of this solution was diluted to 500 ml. with 1M HCl yielding a gold standard solution of 0.02 μgm. Au/ml.

The standard solution was also stored in a conical flask with a greased glass stopper since any evaporation would change the concentration of the solution.

iii) Density Determination of the Standard Solution

The density of the standard solution was required in order that standard weights could be converted to volumes for calculations of Au content.

Three 1 dram pyrex vials were cleaned and accurately weighed on a 5 place Mettler balance. A 1 ml. aliquot of standard solution was added to each from an accurately calibrated 1 ml. pipette and the vials reweighed. The weights of the aliquots were corrected to exactly 1.0 ml. using the pipette calibration. The values of the 3 aliquots were averaged to give the density of the standard solution.

iv) Loading of the Gold Standards in Ampoules

The standard solution was sealed for irradiation purposes in 2 in. lengths of 4 mm. O.D. x 3 mm. I.D. quartz tubing. Each ampoule was initially cleaned with acetone and weighed on a 5 place balance. It was then loaded with 30 to 40 mg. of Au standard solution using a fresh glass capillary pipette which was discarded after use. Any solution droplets which adhered to the inside wall of the ampoule after loading were carefully wiped away with tissue (such liquid would be lost in the sealing of the ampoule). The quartz ampoule plus solution was reweighed to determine the weight of standard solution. Finally, the ampoule was carefully sealed in an oxygen-hydrogen flame by a glass blower. The overall length of each ampoule after sealing was about 1-3/4 ins. to permit it to fit into the aluminum irradiation can used.

3. Sample Preparation

i) Separation of Pyrite

The basic aim of sample preparation was to obtain a relatively pure aliquot of pyrite free of both quartz and heavy radioactive and magnetic minerals.

Each sample was hand picked and a portion (approximately 1 cu. in.) containing relatively abundant pyrite was selected. This portion was then crushed by hand in a small iron percussion mortar. The crushed sample was screened in sieves and the 100-200 mesh (0.140-0.074 mm.) fraction retained. Fines were discarded.

The second step in the preparation was a separation of heavy from light minerals, the latter essentially consisting of quartz. The heavy liquid Tetrabromoethane of density 2.96 was used. In it only quartz (p = 2.65) floated while the remaining minerals including pyrite (p = 5.01), pyrrhotite (p = 4.6), chalcopyrite (p = 4.2), monazite (p = 4.6-5.4), and uraninite (p = 10.95), sank. Separates were washed clean of tetrabromoethane with acetone. The heavy liquid separation was repeated on samples having a high quartz and low pyrite content.

The third step was a magnetic separation obtained using a Franz Isodynamic Separator. The sample was put through the separator at a side slope of 10° to 15° and a forward slope of 15° to 20° and at a very low initial amperage, to remove the more highly magnetic minerals such as pyrrhotite. It was then run through the separator 4 to 5 additional times, each time with an increase in amperage, until a maximum setting of approximately 1.6 was reached. These runs removed all the slightly magnetic minerals including the radioactives and any chalcopyrite. The pyrite fraction was then checked under a binocular microscope for purity. If the quartz content visually appeared to be greater than approximately 2%, the sample was put through the Franz separator again, with the current off, and by careful adjustment of the slopes, a gravity separation of additional quartz was achieved.

The final result obtained, after all separations had been concluded, was the division of the original whole rock sample into 3 portions; a light mineral fraction composed essentially of quartz, a heavy mineral magnetic fraction containing the majority of radioactive minerals, and a non-magnetic heavy fraction consisting of pyrite.

ii) Separation of Chalcopyrite

In only two cases, the predominate sulfide in the sample was chalcopyrite. This separation was conducted as for pyrite until the pyrite portion had been separated from the magnetic fraction which included the chalcopyrite. This magnetic fraction was then put through the Franz separator several times and, by careful manipulation of the amperage, those minerals less magnetic than chalcopyrite and those more magnetic than chalcopyrite were removed. The final result was a relatively pure (approximately 95%) chalcopyrite sample.

iii) Preparation of Samples for Irradiation

Each sample was finely powdered in a clean agate mortar and loaded in a 1-1/8 in. quartz ampoule 4 mm. O.D. x 3 mm. I.D. Each ampoule was filled with approximately 300 to 400 mg. of pyrite or 200 to 250 mg. of chalcopyrite. It was then sealed with molten polyethylene which was forced into the top of the tube as a plug. Finally, samples were labelled with a narrow piece of masking tape wrapped around each ampoule above the sample level.

iv) Irradiation of Samples and Standards

Samples were irradiated in groups of 8 together with 3 standards since 11 was the maximum number of ampoules, of the size used, that the aluminum irradiation capsules would hold. Fixed positions of the standards with respect to the samples was easily maintained as the 11 ampoules fitted tightly into the capsule. The standards were positioned on different sides of the capsule.

4. Experimental Method

The following procedure was followed in every experiment once the irradiation had been completed and samples and standards removed from the aluminum can.

i) Treatment of Standards

Remove masking tape label from the ampoule, wash in aqua regia for approximately 5 minutes, and wipe clean with tissue to ensure that no radioactive contamination remains. Place the ampoule either in ice water for 10 minutes or on dry ice for 5 minutes to decrease the gas pressure within the ampoule so that no explosion and loss of standard will occur upon opening. Dry the cooled tube with tissue and scratch it in the centre with a file. Break the tube into a 100 ml. beaker containing 5 ml. of gold carrier. Add 5 ml. of 2M HCl and wash the insides of both halves of the broken ampoule using a capillary pipette. Transfer the solution to a clean 100 ml. beaker. Repeat twice, flushing the ampoule halves thoroughly and transferring the washings to the new beaker. This step must be quantitative. Discard the ampoule halves to active waste. Transfer the solution (approximately 20 ml.) to a 125 ml. separatory funnel, add 20 ml. of ethyl acetate, and shake for approximately 2 minutes. Transfer the aqueous phase to a new separatory funnel, add approximately 5 ml. of ethyl acetate, and extract again. Discard the aqueous phase to active waste and combine the gold-acetate phases in a 100 ml. beaker. Add an equal volume of 2M HCl and put the beaker on a hot plate at low heat. Allow the gold to transfer to the aqueous phase and then increase the heat to drive off the last of the ethyl acetate. While the solution is still warm, add approximately 0.5 gm. of hydroquinone to precipitate Au^o. Transfer to a 50 ml. centrifuge tube and centrifuge. Discard the supernatant liquid. Wash the precipitate with 75% H_2O-25% ethyl alcohol, centrifuge, and discard the supernatant liquid. Repeat. Finally, wash the precipitate with 5 to 10 ml. of ethyl alcohol, centrifuge, and discard the supernatant liquid. The gold is now ready to be transferred to a pyrex vial for weighing and counting purposes.

ii) Treatment of Pyrite Samples

Pipette 5 ml. of Au carrier solution into a 100 ml. beaker. Remove the polyethylene plug from sample ampoule and gently tap the powdered sulfide into the beaker. Add 5 ml. of aqua regia to the beaker, cover with a watch glass, and stew on a hot plate under medium heat for approximately 10 minutes. Evaporate to incipient dryness. Add another 5 ml. of aqua regia, stew for 5 minutes, and evaporate to incipient dryness. Repeat a third time. The aqua regia treatments are required to dissolve the pyrite.

Add approximately 2 ml. of conc. HCl and evaporate to incipient dryness. Repeat to remove nitrate and convert the gold to a chloride complex. Add approximately 10 ml. of 6M HCl to beaker and transfer the Au solution to a 125 ml. separatory funnel. Wash the beaker twice with approximately 5 ml. of 6M HCl and transfer the washings to the funnel. The total volume in the separatory funnel is thus approximately 20 ml. Add 20 ml. of ethyl acetate to the separatory funnel and shake for 2 minutes. Transfer the aqueous phase to a new separatory funnel, add 5 ml. of ethyl acetate, and repeat the Au extraction. Discard the aqueous phase to active waste and combine the Au-organic phases in a 100 ml. beaker. Add an equal volume of 2 ml. HCl to the beaker, cover with a watch glass, and place on a hot plate. Heat gently until the gold transfers to the aqueous phase and then increase the heat for 3 to 5 minutes to drive off all ethyl acetate.

Allow to cool and repeat the ethyl acetate extraction. Once the ethyl acetate is driven off after the second extraction, add 0.5 gm. hydroquinone to the still warm solution to precipitate Au^o. Transfer to a 50 ml. centrifuge tube, centrifuge, and discard the supernatant liquid to active waste. Wash twice with 75% H_2O-25% ethyl alcohol. Add 2 to 3 ml. of aqua regia to redissolve the Au. Heat in an electrical bunsen heater to incipient dryness. Repeat with another 2 to 3 ml. of aqua regia. Add 1 to 2 ml. of conc. HCl and heat to incipient dryness. Repeat twice. Take up in approximately 10 ml. of 2M HCl, warm the solution, and add approximately 0.5 gm.

hydroquinone. Repeat the centrifuge and washing steps as before. Wash one final time with 5 to 10 ml. of ethyl aocohol, centrifuge, and discard the supernatant liquid. Transfer the gold to a pyrex vial.

iii) Transfer of Gold to Vials

This procedure applies to both samples and standards.

Transfer the Au^o with a capillary pipette into a 1 dram pyrex vial which has been cleaned, labelled, and weighed. Use approximately 1 to 2 ml. of ethyl alcohol as the transferring medium. Evaporate the alcohol by placing the vial under an infrared heat lamp. Allow the vial to cool to room temperature and weigh to determine the weight of Au^o recovered.

iv) Notes on the Experimental Method

1) All chemicals used were of Analytical Reagent grade.
2) The gold used to prepare carrier and standard solutions was of Johnson Matthey "specpure" grade.
3) All weighing was done on a 5 place "Mettler" balance.
4) Chalcopyrite was the sample sulfide, rather than pyrite, in two experiments. The procedure here was identical to that for pyrite except that, as chalcopyrite is not soluble in aqua regia, the initial dissolution and digestion of the powdered sample was achieved with several treatments of concentrated HNO_3.

5) All aqua regia or nitric acid digestions were followed by digestions in conc. HCl (approximately 12M) since all nitrate had to be driven off in order that it would not interfere with later analytical processes.

6) One experiment was conducted to determine the Au content of the quartz fractions of the original whole rock samples. For the dissolution procedure using a sodium peroxide-sodium hydroxide fusion of these silica samples and the following Au extraction process, refer to Keays (1968).

7) One experiment was performed to determine the level of Ir concentration in the pyrite. The procedure for Ir extraction was also one based on that outlined by Keays (1968).

8) The method used to separate the impurity found in several samples (and discussed in Chapter VI) was one using an ion exchange column technique as developed by Keays (1968).

CHAPTER VI

COUNTING APPARATUS AND TECHNIQUE

1. The Radiochemistry of Gold

Gold has an atomic weight of 197.0 and an atomic number of 79. There is only one naturally occurring stable isotope of gold, that being Au^{197}. When Au^{197} is bombarded by a neutron flux the following reaction occurs:

$$Au^{197}\ (n, \gamma)\ Au^{198}$$

In Fig. 6-1, the decay scheme for Au^{198}, which is the radionuclide produced by the above reaction, is outlined.

2. Counting Procedures

Preliminary counting in this programme was done on a beta radiation counter. However, all Au results used in this work were obtained using a gamma radiation counter and thus, a discussion of beta counting methods is not required. For a thorough summary of the procedures and problems of beta counting, one may refer to Keays (1968).

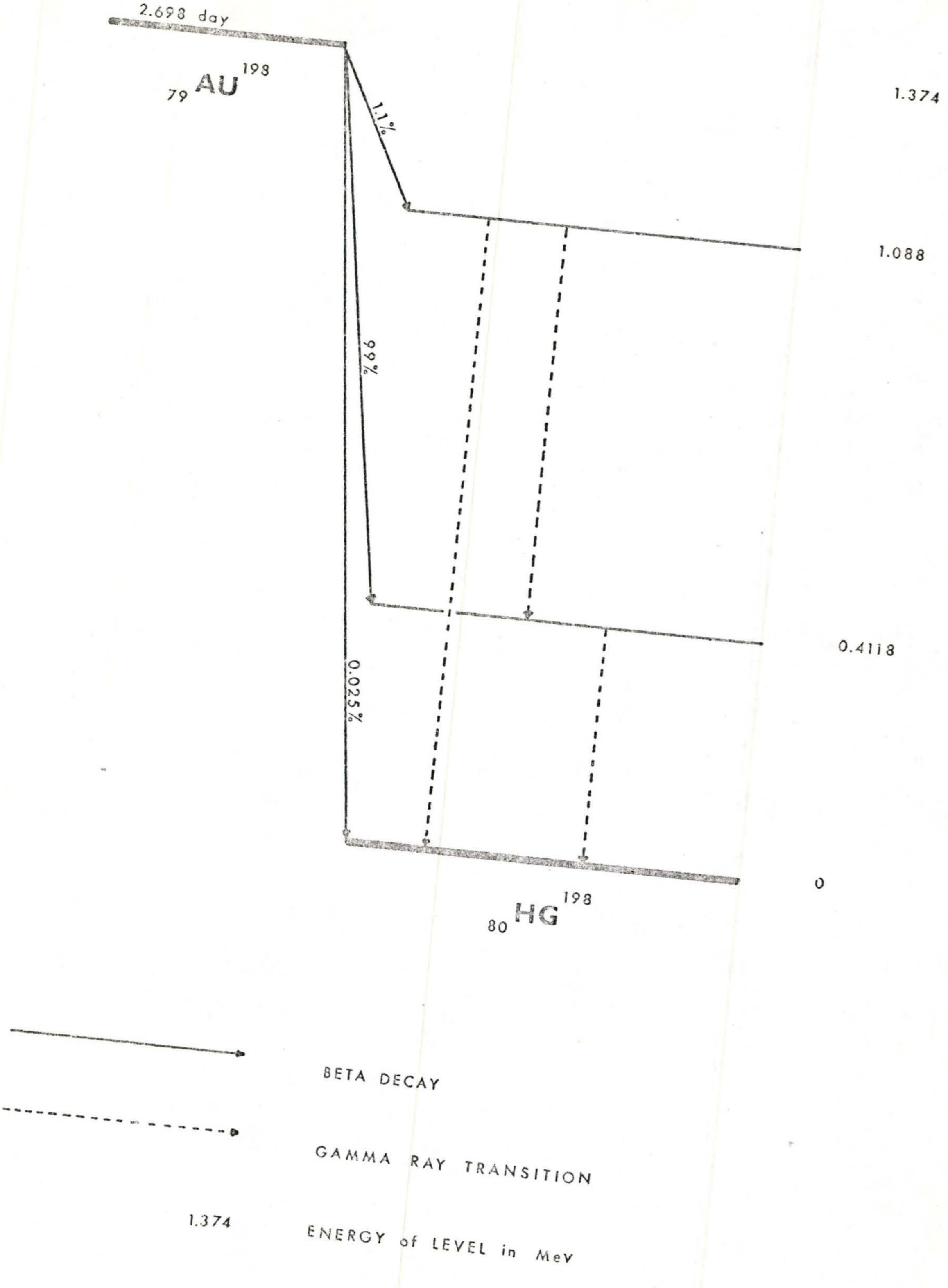
All the analytical results for Au used in this work were obtained by counting the 0.412 Mev gamma photopeak of Au^{198}.

Samples were counted with a Radiation Instrument Development Laboratories (Nuclear Chicago) 1600 channel gamma radiation analyser which included the following components: 1) a 2 in. x 1-3/4 in. NaI(Tl) well-type detector, 2) a 1600 word memory unit, 3) an analog-to-digital converter, and 4) a Telex printout. For the Au studies, 400 channels were utilized.

Samples and standards were prepared in 1 dram pyrex vials and counted over an interval of 10 minutes to a total of ≥ 10,000 counts (usually much more for most samples). With such high counting rates, it was important that the counter automatically compensated for dead time. Background radiation was subtracted from each standard or sample count and averaged approximately 100 counts per 10 minute counting interval over the 0.412 Mev photopeak. Direct comparisons of samples and standards were made possible by integrating the counts over the same number of channels (approximately 30) across the Au^{198} photopeak for both the samples and standards.

Examination of the Au^{198} spectrum and print-out of only .411 the 0.412 Mev gold photopeak, ensured that the data used for calculations originated from pure Au^{198}. Thus, the need for an additional check, as required with beta counting, was not as necessary. However, the purity of the Au^{198} radiation under the 0.412 Mev photopeak

Fig. 6-1: DECAY SCHEME AU^{198}



was checked by half-life determinations, and samples not giving a half-life of approximately 2.7 days were rejected.

3. Identification of Contamination

Photopeaks of an unknown energy were present in the gamma radiation spectra of several samples and were calibrated using a Cs^{137} standard (main photopeak for gamma radiation at 0.66 Mev) and an Au^{198} standard. A determination of the half-life of this contamination was also made. These results were then checked against values for radionuclides listed in Heath (1964), and in Hawkins, Edwards, and McLeod (1961). It was established that the impurity photopeaks most probably were produced by the radionuclide Te^{132} and its short-lived daughter product 2.31 Hr. I^{132}, as shown in Table 6-1.

Table 6-1. Comparison of Impurity to Te^{132}-I^{132}

	Impurity	Te^{132} - I^{132}
Energy of Photopeaks in Order of Decreasing Magnitude (Mev)	.238 .672 .773 .52 .94	.232 .665 .77 .52 .952
Half-life of main Photopeak	3.2 days	78 hr. (3.25 days)

Te^{132} is a fission product of U^{235} and would thus be produced if any traces of uranium were present in the samples irradiated. Since the samples were derived from uranium ore, this is obviously the source of the contamination. However, since none of the photopeaks produced by the contamination overlaps the 0.412 Mev peak of Au^{198}, it is reasonably correct to assume that Te^{132} has not affected the results obtained from the gold photopeak.

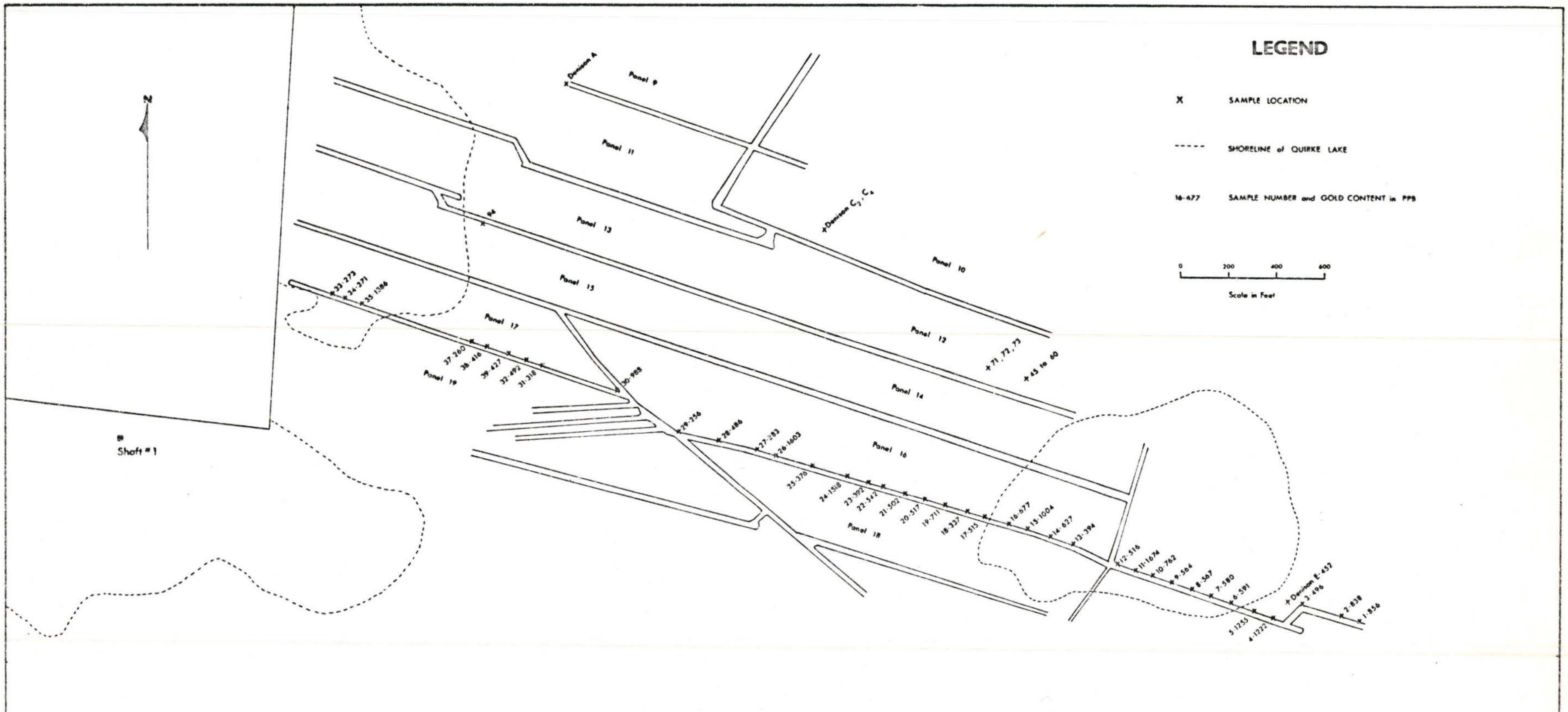
CHAPTER VII

ANALYTICAL RESULTS

The samples collected in this work were all pyritic conglomerates and the results tabulated in this chapter represent the total gold content of pyrite concentrates from these samples unless stated otherwise. All samples are from the Denison Mine (see Location Map, Fig. 7-1).

1. Strike Sampling of Lower Reef

Thirty-seven samples were collected along the strike of the Lower Reef ore zone of the Denison Mine over a distance of approximately 4500 ft. The locations of these samples are shown in Fig. 7-1 together with gold values in ppb. for the pyrite fraction. The results are also listed in Table 7-1. Sample R-35 was taken 10 ft. from a small diabase intrusion. Although it has a higher Au content than adjacent samples, the value is not anomalously high. Throughout the entire sequence along the strike of the Lower Reef, no trend or systematic variation of Au concentration is apparent. The average value for these 37 samples is 658 ppb.



PLAN OF THE UNDERGROUND WORKINGS OF THE NORTHEAST PORTION OF DENISON MINE SHOWING SAMPLE LOCATIONS

Fig. 7-1

Table 7-1: Au Values for Samples in PPB taken from Horizontal Strike Line along Lower Reef

(Samples listed in consecutive order from Southwest to Northeast)

Sample No.	Au ppb.	Sample No.	Au ppb.
R- 1	856	R-21	502
2	838	22	542
3	496	23	392
4	1222	24	1518
6	591	25	376
7	580	26	1603
8	567	27	283
9	564	28	486
10	762	29	256
11	1674	30	988
12	516	31	318
13	394	32	492
14	627	39	427
15	1004	38	416
16	677	37	260
17	515	35	1386
18	337	34	371
19	711	33	273
20	517		

In Table 7-2, the corresponding uranium and reef thickness values are given for the gold values determined along the Lower Reef. A plot of the gold content versus uranium value, given in Fig. 7-2, shows that there is no obvious linear relationship between gold and uranium concentrations. A second comparison of gold values to reef thickness, in Fig. 7-3, again indicates no apparent relationship. The uranium values and corresponding reef thicknesses were obtained from drill core assay data of the nearest hole to sample locations. Thus, the values are approximate and may, in fact, not represent the actual uranium content and reef thickness at each sample location.

2. Gold Content of High Grade Uranium Samples

Two samples which contained abnormally high uranium concentrations were analysed. The results for gold determinations on their pyrite fractions are given in Table 7-3.

Table 7-2: Uranium Assays and Lower Reef Thicknesses for Samples of Table 7-1.

(Uranium values and reef thicknesses from Denison Mine drill hole data)

Sample No.	Au, ppb.	U_3O_8(lb. /ton)	Lower Reef Thickness(ft.)
R- 2	838	4.54	12.7
3	496	7.12	12.9
7	580	4.07	11.6
8	567	4.57	8.9
9	564	5.39	10.4
10	762	4.34	9.5
11	1674	7.66	9.1
12	516	4.33	8.6
13	394	4.53	4.4
14	627	4.29	9.5
15	1004	1.90	2.7
16	677	4.42	8.2
17	5.5	2.16	5.1
18	337	4.62	8.0
19	711	3.34	8.7
20	517	3.62	7.2
21	502	1.92	4.4
22	542	2.40	5.2
23	392	2.63	7.0
24	1518	6.91	5.8
30	988	8.49	6.4
31	318	3.01	16.0
32	492	3.92	6.8
39	427	3.52	9.2
38	416	1.32	8.5
37	260	1.56	6.1
35	1386	0.56	4.0

Fig. 7-2

VARIATION of GOLD in PYRITE with TOTAL URANIUM in ORE

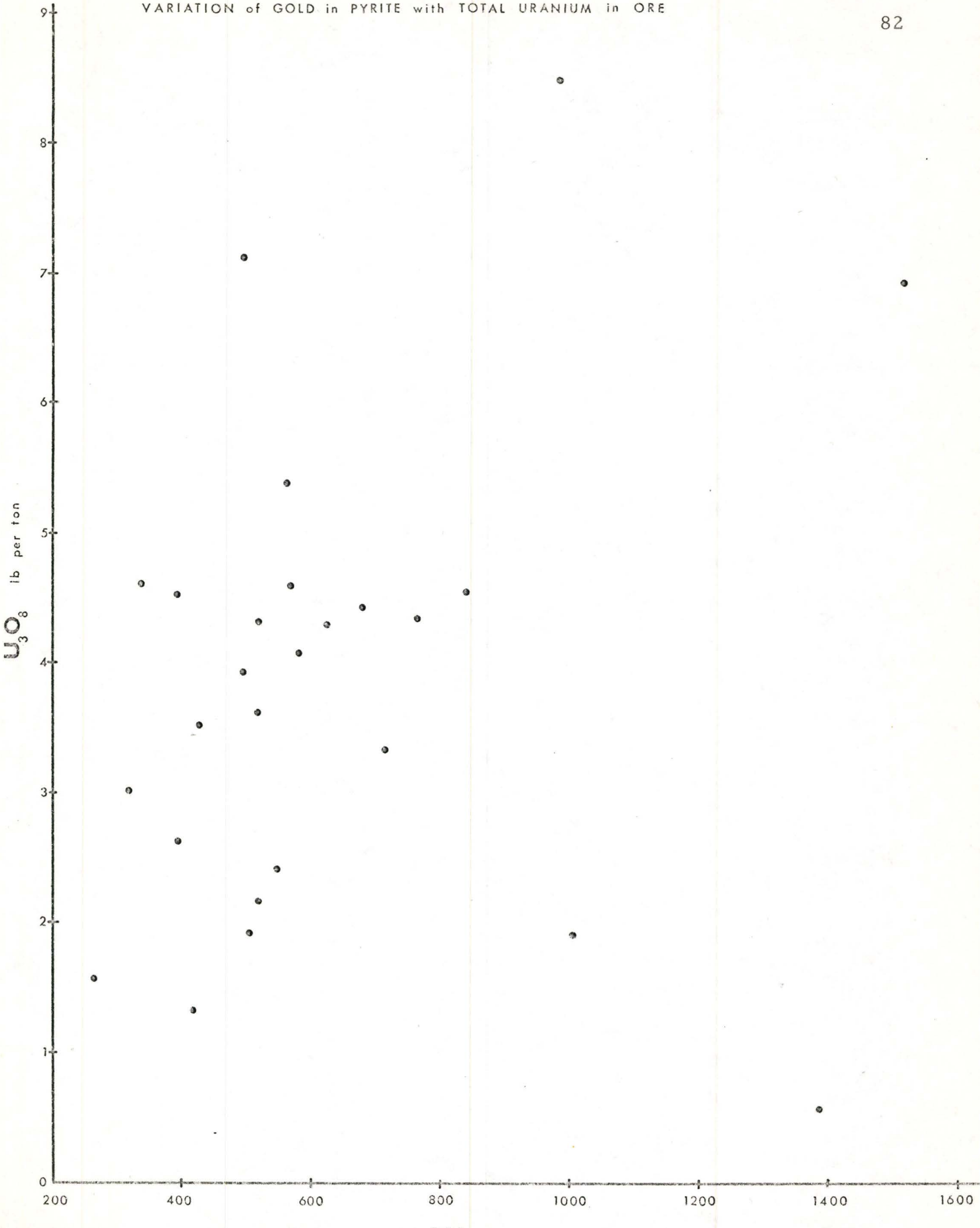


Fig. 7-3: VARIATION OF GOLD WITH REEF THICKNESS

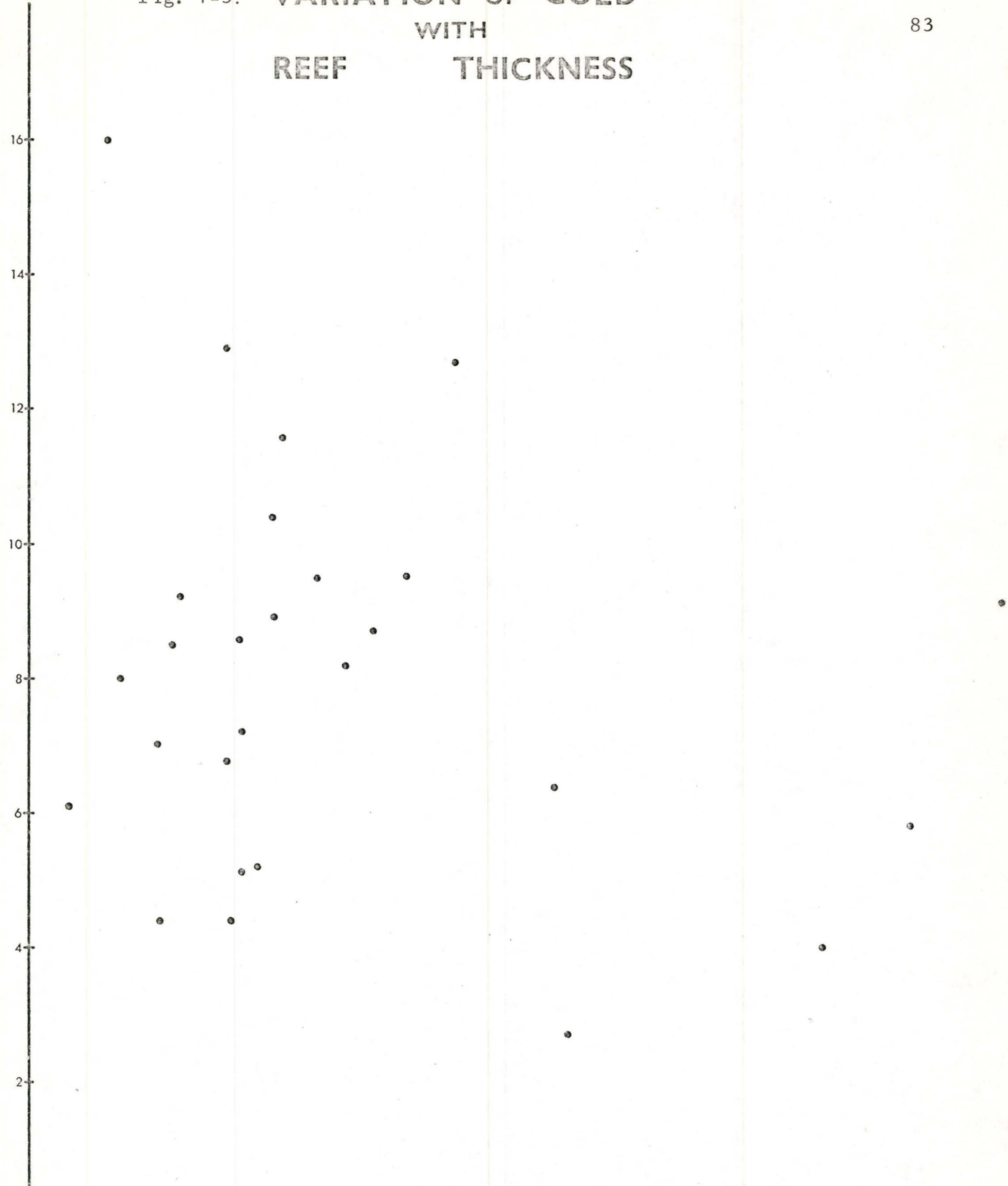


Table 7-3: Gold Values (in ppb.) for High Grade Uranium Ore

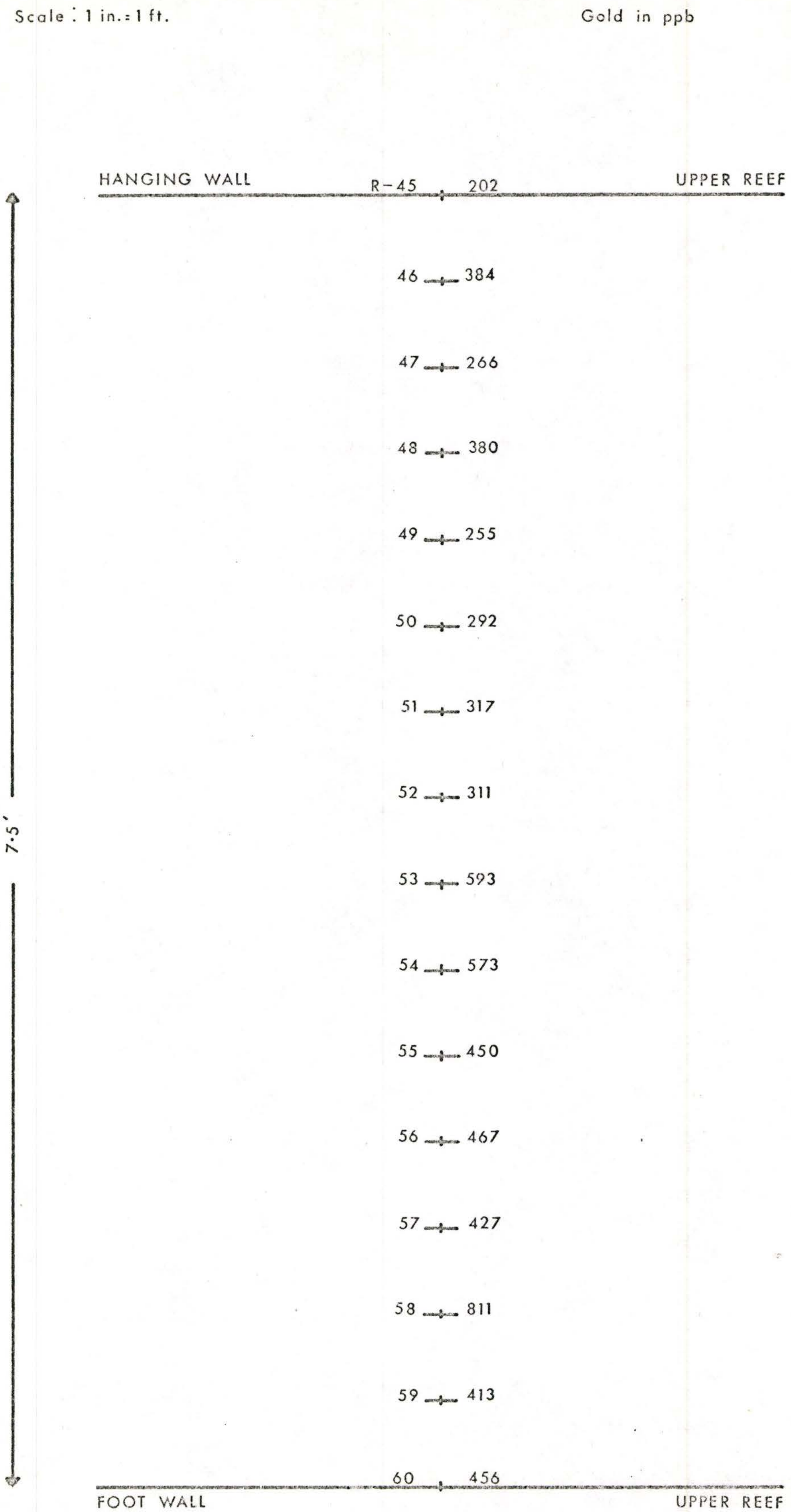
Sample No.	Au, ppb	Number of Analyses	% Standard Deviation
R-41	508	1	
R-94	433±54	4	12.5%
Average for Lower Reef	658	37	

Sample R-41 was a diamond drill core containing "high grade" uranium ore according to Denison Mine geologists. Sample R-94 (location in Fig. 7-1) contained visual black uranium mineralization and was from the Upper Reef. Both samples registered much higher geiger-mueller count rates than all other samples analysed. As shown in Table 7-3, both values obtained are lower than even the average for samples along the Lower Reef, and thus, it is obvious that high gold content does not correlate with high uranium content in these cases. There appears to be no clear relationship at all between gold and uranium concentrations.

3. Vertical Section through Upper Reef

A suite of 16 samples was taken from a vertical section of the Upper Reef across a thickness of approximately 7.5 ft., with a sample collected every 6 ins. Fig. 7-4 shows the sample locations

Fig. 7-4: VERTICAL SECTION - UPPER REEF



and the gold values of their pyrite fractions in ppb. On examination of these results, there is an apparent increase in gold values in the lower half of the section. However, the 16 samples in the section were analysed in 2 lots and the increase corresponds to the second lot so it may be that the differences are due to experimental variations. The average value for the 16 samples is 412 ± 153 ppb. which gives a standard deviation of only 37%. Excepting Sample R-58 which had a gold value in its pyrite fraction of 811 ppb., there is no trend toward higher gold values at the top, middle, or bottom of the Lower Reef.

4. Variations of Au in Pyrite of Low Au Content as Compared to that in Pyrite of High Au Content

To determine whether variations were the same for samples of high and low Au content, 4 aliquots of a sample with known low Au content were analysed and a similar analysis was made of 4 aliquots of a sample with high gold content. The results are shown in Table 7-4.

Table 7-4: Determination of Standard Deviation in a Sample of High Au content as Compared to a Sample of Low Au content

Sample No.	Au, ppb.	No. of Analyses	Std. Deviation as % of $\bar{x}$
R-26	2082±245	4	11.3
R-37	287± 33	4	11.5

These values suggest that variations in Au content in samples of high Au concentrations and in samples of low Au concentrations are of the same order of magnitude. Since the previously determined single value for R-26 was 1603 ppb. and for R-37, 260 ppb., it is also apparent that variations in a sample determination between experiments is of the same or greater order as the variations produced by replicate analyses of one sample in a single experiment.

5. Analysis of Quartz Fractions of the Uranium Ore

Table 7-5 shows the gold content of the light mineral fraction (essentially quartz) of 8 samples from the Lower Reef, 4 of relatively high Au content in their pyrite, and 4 of relatively low Au content in their pyrite.

Table 7-5: Analysis of Quartz Fractions of Samples

Sample No.	Au in Pyrite (ppb.)	Au in Quartz (ppb.)
R- 3	496	2.73
R-13	394	1.87
R-27	283	1.09
R-29	256	0.89
R- 4	1222	3.96
R-11	1674	1.07
R-24	1518	5.12
R-26	1603	7.77
$\bar{x}$ = 3.06 ± 2.43 ppb.		

The data in Table 7-5 indicate a relationship between the Au content in pyrite and that in corresponding quartz. This is probably caused by trace contamination of pyrite in the quartz fractions and thus, it is possible that the quartz fraction of the ore conglomerates contains even less Au than is indicated.

Table 7-6: Gold Value in Quartz of Ore Conglomerates Compared to Igneous and Sedimentary Rock Au Values

Rock Description	Au, ppb.	No. of Analyses	Reference
Quartz fraction of ore conglomerates	3.06±2.43	8	This work.
Granite G-1	4.6 ±0.8	5	Shcherbakov & Perezhogin (1964)
	4.5	2	Vincent & Crocket (1960)
	3.3 ±0.9	10	Keays (1968)
Granites	3.2	33	Shcherbakov & Perezhogin
Quartz	11	9	
Greywacke of Gowganda Fm.	2.3	1	DeGrazia and Haskin (1964)
Sandstones	6.0 ±3.5		DeGrazia and Haskin
Shales and Sandstones	3.6	39	Shcherbakov & Perezhogin

In Table 7-6, the Au results for quartz obtained in this work are compared to values from the literature for acidic igneous and sedimentary rocks. It is evident that the gold found in quartz of the ore conglomerates of Elliot Lake is of the same order as that found in normal acidic igneous rocks or sediments derived from them.

6. Chalcopyrite Studies

Table 7-7 gives the results obtained from 2 chalcopyrite samples (one analyzed in duplicate and one in triplicate) and also indicates the results determined for pyrite from the same or adjacent samples.

Table 7-7: Results of Chalcopyrite Analyses

Sample No.	Au in Chalcopyrite, ppb.	No. of Analyses	Au in Pyrite, ppb.	No. of Analyses
R-73	1398±282	2		
R-72			1803±154	2
R-71			1037±237	2
Denison E	338±59	3	452±165	5

Sample R-73 was taken 1 ft. below the hanging wall of the Upper Reef. It contained a thin "veinlet" of chalcopyrite and minor disseminated chalcopyrite but no pyrite. Sample R-72 was taken 1 ft. below R-73 and sample R-71, another 6 in. below R-72. These latter two samples contained only pyrite and were analysed since they were the adjacent samples to the chalcopyrite of R-73.

The average value of R-71, 72, and 73 is 1413±386 ppb., giving a percent standard deviation of 27.3%.

Denison E was a conglomerate sample taken 4 ft. below the hanging wall of the Upper Reef. It contained both disseminated blebs of chalcopyrite and considerable disseminated pyrite.

It is obvious that Au content of the chalcopyrite, as shown in Table 7-7, is of the same order as pyrite from the same location. In fact, in both cases, the chalcopyrite samples lie within the limits determined for the pyrite samples, and for samples R-71, R-72, and R-73, the standard deviation for the 3 averaged together is less than the deviation for the pyrite samples alone, of Denison E.

7. Overall Gold Results

The average gold value determined from 42 different analyses is 656 ppb. Samples collected from the same location or from vertical sections were considered as a single averaged value in each case. In Fig. 7-5, the results are plotted as a histogram. It is difficult to make generalizations from this graph since 5% of the data represents approximately 2 samples but it would appear that there is a tendency to a bimodal distribution. However, it is apparent that the modal value of the distribution lies between 500 and 600 ppb.

8. Iridium Studies

In 1 experiment only, the iridium concentrations in the pyrite of 4 samples were determined. The results are listed in Table 7-8 and are compared to iridium values established in sulfides and G-1 in Table 7-9.

Little can be concluded from the analysis of only 4 samples but it would appear that the iridium present in the pyrite of the Elliot Lake ore conglomerates is of the same order as that in the sulfides of the Sudbury Nickel Irruptive and is enriched by a factor of 100 above the Ir content of G-1.

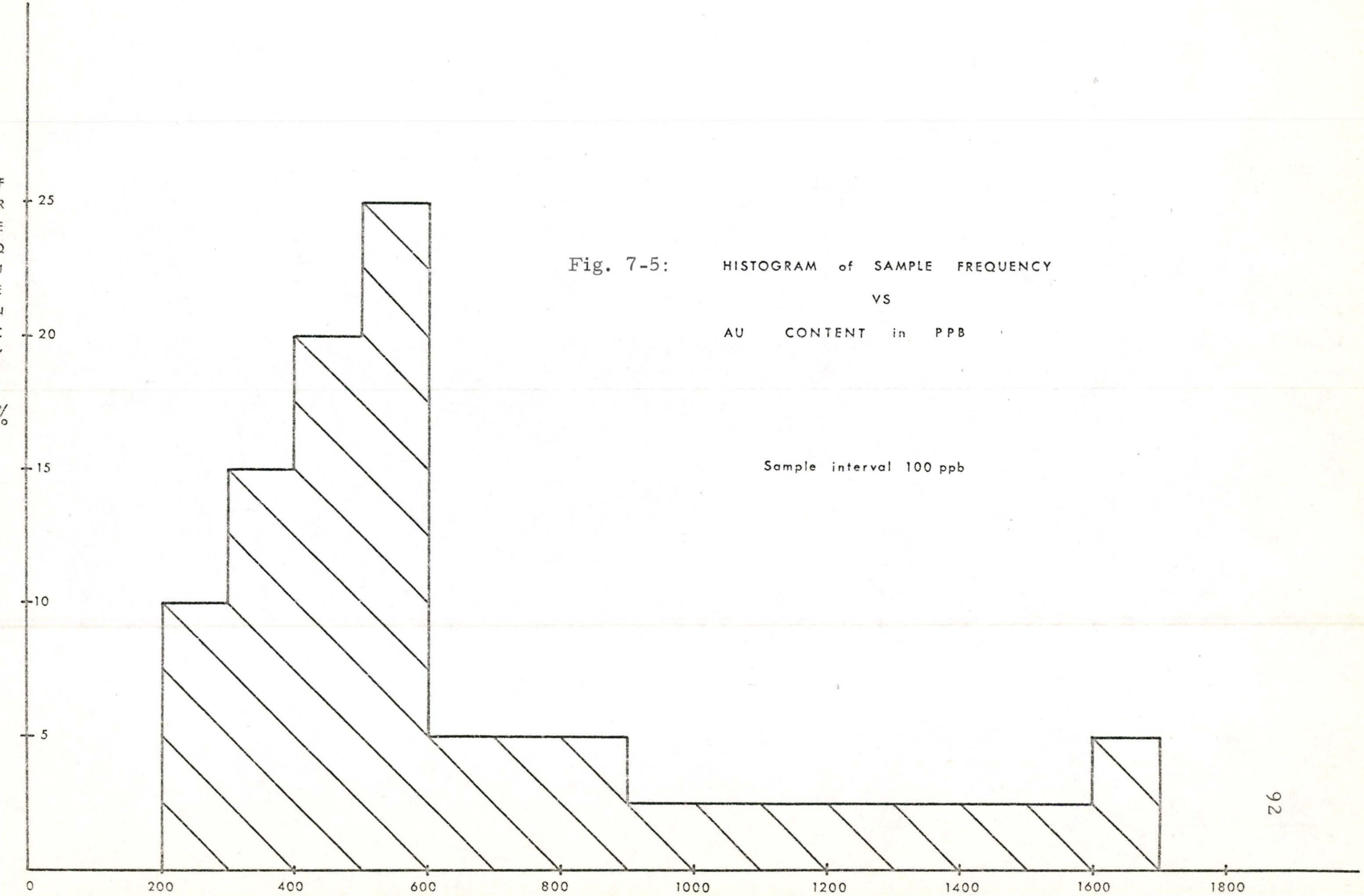


Fig. 7-5: HISTOGRAM of SAMPLE FREQUENCY VS AU CONTENT in PPB

Sample interval 100 ppb

Table 7-8: Iridium Concentrations in 4 Samples Analysed

Sample No.	Ir, ppb.
Denison A	3.22
Denison C_2	3.22
Denison C_4	5.60
Denison E	5.37

$\bar{x}$ = 4.35±1.14 ppb.

Table 7-9: Data from Literature on Ir Content of Rocks and Minerals

Rock or Mineral	Ir, ppb.	Reference
Pyrrhotites of Sudbury Irruptive	1.8 - 53.4	Keays (1968)
Chalcopyrite from Sudbury	1.1	Keays (1968)
G-1	0.044±0.008	Keays (1968)

CHAPTER VIII

DISCUSSION AND INTERPRETATION OF RESULTS

1. Quantitative Comparisons to Placer Deposits

Denison Mine pyrite averages 656 ppb. gold. If a pyrite content of 10% in the ore zones is assumed, then the overall gold content of the conglomerates, neglecting the minor amount in quartz, is approximately 66 ppb. Table 8-1 shows the gold content of modern placers as given in Bateman (1950).

Table 8-1: Gold Placer Values (gold at \$20.67/oz.)

Deposit	Value
Mountain Placers of California	
Cretaceous Conglomerates	\$2-\$3/ton
Miocene Gravels	2.5-3¢/cu. yd.
Quarternary Gravels	12-14¢/cu. yd.
Fairbanks, Alaska	17¢/cu. yd.
Klondike	\$9-\$50/cu. yd.
Columbia	15¢/cu. yd.
North Fork, California	4.2¢/cu. yd.
California (general)	25-34¢/cu. yd.
New South Wales	24¢/cu. yd.

To make a proper comparison, the values in Table 8-1 must be converted to ppb. Assuming a gravel density of 2.7, and a gravel porosity of 30%, a cubic yard would have a mass of 1.6 tons. Using a gold price of $20.67 per oz., the results in Table 8-2 are obtained.

Table 8-2: Conversion of Placer Values to PPB

Deposit	Value in ppb.
Placer with 25¢ Au/cu. yd.	255
Placer with 3¢ Au/cu. yd.	31
Denison Mine ore conglomerate	66

Thus, from Table 8-2, it appears that the gold content of the ore conglomerate at Denison Mine lies within the limits of modern gold placer deposits. A further conversion of the gold content of the Denison ore produces a result of 16¢ per cubic yard (assuming a density of 2.7 and a gold value of $35/oz.). This confirms the fact that the uranium ore does indeed contain gold in concentrations comparable to those of modern placer deposits.

2. The Fineness of Gold in the Pyrite as Compared to the Fineness of Gold in Placer Deposits

The finest particulate gold known to exist as minute flakes has a mass computed to be 1.95×10^{-9} gm. per grain (calculations based on Bateman (1950) who reports that it would require 8,000,000 of these finest particles to equal a value of \$0.01 with gold worth approximately \$20/oz.). The minimal absolute amount of gold found per sample during the present study was 0.03 μgm. or 3×10^{-8} gm. Thus, such samples from the Denison Mine would contain a maximum of approximately 15 particles of gold of minimal size if the gold in the samples were of this very fine nature. It is therefore possible to account for the extremely low values of gold in a single sample using placer gold concentrations if one assumes this gold to be of the finest particulate variety reported to exist.

3. Gold Values at the Denison Mine Compared to other Similar Deposits

The two major gold producing Precambrian conglomerates similar to the uraniferous conglomerates of Elliot Lake are those of the Witwatersrand and the Jacobina. In Table 8-3, their average gold values are compared to that found at the Denison Mine.

Table 8-3: Gold Content of Precambrian Quartz Conglomerates

Deposit	Au oz./ton	Au ppb.
Rand	0.2	6800
Jacobina	0.015	510
Denison	-	66

Thus, the conglomerates of the Denison Mine contain approximately 1% of the gold of the Witwatersrand and slightly over 10% of the gold of the Jacobina.

Gross (1968) has estimated that the Jacobina conglomerates, if unconsolidated, would contain greater than 25¢ per cu. yd. (gold at $35/oz.) and would thus be considered as an enormous reserve of placer gold. The Denison conglomerates would probably contain at least 10¢ gold per cu. yd. even after porosity and compaction allowances,and would thus possibly be considered a marginal economic reserve of "placer" gold also, if unconsolidated.

Although the uraniferous conglomerates of the Denison Mine contain from 10 to 100 times less gold than other analogous deposits, they do contain gold in quantities approaching those of modern unconsolidated placer deposits. Therefore, on the basis of gold concentrations alone, it could be concluded that the gold of the Denison Mine is of placer origin.

4. Horizontal and Vertical Distribution of Gold

It was initially expected that the distribution of gold in the conglomerates would lend positive support to one of the two theories of origin for the ore. However, the results of strike sampling indicate no gold concentration trends or gradient either up or down the strike.

Horizontal distribution shows no obvious trends and generally appears constant with some minor irregularities. Similarly, the distribution of gold in pyrite throughout the vertical section studied shows no tendency for increased concentrations either toward the bottom or the centre of the reef. There is a generally uniform gold content across the entire ore zone. If the gold were of placer origin, one would expect to find it concentrated at specific localities along the strike depending on variations in stream velocity and the other factors controlling placer concentrations. Also, a concentration toward the base of conglomerate zones might be expected as a result of gravity settling of such high density material. However, in Section 8-6, the distribution of the gold within pyrite is discussed and it is concluded that this distribution is uniform with no highly concentrated zones or large particles of gold. Thus, the gold in the Denison conglomerates, if of placer nature, must be extremely fine and this is possible as pointed out previously. Such gold, according to Bateman (1950), will float readily if exposed to air and may travel for hundreds of miles. It is thus widely distributed throughout the entire thickness and width of stream gravels. This gold would not act as a typical heavy mineral and its very fine flaky nature would allow it to behave in a similar way to small clay particles or other fine sediments. Thus, this gold would not be concentrated apart from other minerals during stream transport but would be deposited together with the very fine fraction of normal sediments. In this way, no large concentrations of gold would occur. The distribution of gold resulting from deposition of this type would tend to be even or generally uniform and would exhibit no trends or patterns of concentration. Thus, the distribution of gold in the ore conglomerates matches that produced by very fine particulate gold in stream deposits. However, gold distributed in sulfides throughout an unconsolidated or porous conglomerate by circulating hydrothermal solutions could also be expected to demonstrate the same generally uniform distribution. Thus, the gross distribution of the gold in the conglomerates cannot be interpreted as favouring one theory over the other, although it does not indicate the absence of any support for a placer origin as it could possibly be interpreted to do.

5. Absence of Gold-Uranium Correlations

It would be expected that coexisting minerals of placer origin demonstrate some degree of relationship to each other. However, this study has revealed no definite relationships between gold and uranium concentrations, as shown in Fig. 7-2. Also, a study of two high grade uranium samples established that the gold concentrations of the pyrite associated with the uranium were of average or below average values. Thus, high uranium values do not correlate with high gold concentrations. This lack of interdependence may be explained in two different ways. Firstly, the gold, as previously noted, may be of such fine grain size that, even if of placer origin, it would not be concentrated by common placer mineral concentration methods. On the other hand, if it is assumed that the present uraninite grains represent origin placer deposits, then they are of sufficient size to be effectively transported and concentrated by the usual placer techniques resulting from variations in stream velocities and loads, gravity settling, winnowing etc. Thus, the lack of correlation between gold and uranium concentrations does not necessarily eliminate the possibility of the two minerals being cogenetic and placer in origin. A second explanation for the absence of interdependence is based on the genetic relationship of gold to the pyrite. Many workers have found an "apparent" relationship between pyrite and uranium which holds true in many, but not all, situations. This has been interpreted as a phenomenon based on the degree of packing of the conglomerates and not as a direct correlation between the two minerals. In any case, if a linear relationship does exist between pyrite and uraninite, then such a relationship would not exist between gold and uraninite if the gold were uniformly distributed in the pyrite prior to the deposition of the pyrite in the conglomerates, regardless of whether the pyrite was deposited hydrothermally or detritally. Thus, it may be argued that the absence of any gold-uranium correlation favours the presence of the gold in the pyrite prior to the pyrite's accumulation or deposition in the ore conglomerates, but, as indicated, the placer theory may also be used to satisfactorily explain this lack of interdependence.

6. Distribution of Gold in the Pyrite

The discussion to this point has dealt with the gross distribution of gold within the ore conglomerates of Denison Mine and no mention has been made of the nature of this gold as revealed experimentally. Replicate analyses of a pyrite sample with relatively low gold content determined a value of 287±33 ppb. gold on 4 samples and a standard deviation of only 11.5% (Table 7-4). A similar set of analyses on a relatively high gold sample provided a value of 2082±245 ppb. gold and a standard deviation of 11.3%. Other multiple analyses for gold in pyrite (Tables 7-3, 7-7) give results with the same general standard deviation. Two important implications may be derived from these results, the first being that, since pyrite samples of both high and low gold concentrations have approximately the same sample variations, then it is probable that the gold exists in the same form in both cases. Thus, it is most likely that the gold in pyrite at the 300 ppb. level is of the same origin as the gold in pyrite at the 2000 ppb. level. Secondly, as there are no large local variations in the amount of gold present in any one pyrite sample, it is suggested that the gold is distributed uniformly on a local basis. Such a distribution may be explained more readily by a solid solution phenomenon than by a distribution of flakes of free particulate gold,which would most probably be more unevenly distributed on a local scale although uniformly distributed on a large scale, as discussed previously. It is highly unlikely that the gold from a pyrite sample could be broken down and evenly distributed during crushing and powdering procedures in the laboratory as any large flakes or particles would not subdivide but would just flatten and remain intact. Thus, to have a final uniform distribution of gold, the initial distribution must have been equally uniform. This evidence therefore tends to favour a solid solution or equivalent distribution of gold within the pyrite of the Denison ore. Such gold must have formed within the pyrite at the time the pyrite originally crystallized. This would suggest that the gold is therefore not of direct placer origin and since the uniform distribution involves many individual pyrite grains, it would also suggest that the pyrite is most probably not of detrital origin. There is the possibility, however, that small flakes of particulate gold, if distributed evenly on a very local basis, although with regional variations, could produce the distribution found in the pyrite. Thus, although the local distribution of gold in the pyrite favours a hydrothermal origin for both gold and pyrite, it is possible to explain the distribution in terms of a placer origin of the gold.

7. Implications of Chalcopyrite Analyses

As discussed in Chapter VII, all chalcopyrite results were obtained from the replicate analyses of only two samples. Thus, it would be unwise to generalize from the conclusions arrived at from these studies although the chalcopyrite analysed does represent all chalcopyrite identified in hand specimen during the examination of approximately 100 samples collected at the Denison Mine.

The most significant result obtained from each analysis is derived from a comparison of the gold content in chalcopyrite to that of pyrite in the same or adjacent samples. In the case of sample Denison E, the gold content of the pyrite is low at 452±165ppb. and the gold content of the corresponding chalcopyrite is similarly low at 338±59 ppb. and falls within the limits of gold in the pyrite. In the case of samples R-71, R-72, and R-73, the average gold content for the two pyrite samples (71 and 72) is 1420±196 ppb. The gold value of the chalcopyrite of sample R-73 is 1398±282 ppb. and is thus approximately the same as the average value for gold in the pyrite.

Little is known of the fractionation of gold during formation of sulfides. Schwartz (1944) found that in some Canadian gold mines chalcopyrite was a good indicator of gold concentrations but that no clear relationship existed, whereas in other mines, pyrite was intimately associated with the gold. Vincent and Crocket (1960a) found during studies of the Skaergaard Intrusion of east Greenland that gold was preferentially concentrated in chalcopyrite over pyrite in the sulfide phase of the intrusion. The evidence obtained from the present study in which gold values of both pyrite and chalcopyrite are similar and vary in identical ways supports the view that the gold in each sulfide is cogenetic and thus that the two sulfides, chalcopyrite and pyrite, are themselves cogenetic. This would require that both sulfides be of direct hydrothermal origin since no one seriously believes the chalcopyrite to be detrital, and also that no preferential differentiation of gold occur between pyrite and chalcopyrite during their crystallization. This latter requirement, however, is not supported by either of the above-mentioned published studies but rather is put in doubt by them. Keays (1968) has suggested that fractionation of previous metals during sulfide crystallization from a sulfide melt is a result of the mobility of the previous metal involved and of the order of crystallization of the sulfides. He found that gold was more concentrated in the chalcopyrites of the Sudbury ore than in the pyrrhotites and has postulated that this is because the gold, being highly mobile, remained in the residual liquid while the pyrrhotite, which was the first sulfide to crystallize, separated out. Chalcopyrite, being the last sulfide to crystallize from the residual liquid, thus contained the larger proportions of the gold. According to Keays' theory, then, the only requirement for equivalent proportions of gold in a pyrite and chalcopyrite crystallate would be the simultaneous crystallization of both sulfides. Although this is improbable in a sulfide melt, it may be possible in the case of a hydrothermal solution. Applied to the sulfides of Elliot Lake, this theory would explain the equal concentrations of gold in pyrite and chalcopyrite and would support a hydrothermal origin for both minerals. However, the textural evidence does not support a common origin for both sulfides since most workers agree that the copper sulfide occurs largely as veinlets cutting pyrite and other minerals. Thus, there is a situation in which geological evidence does not correspond to geochemical evidence. There is the possibility that original textures and paragenetic relationships have been obscured by late regional metamorphism. Since the chalcopyrite is a relatively low temperature sulphide compared to pyrite, it may have been remobilized to a much greater extent than any of the adjacent pyrite.

Thus, local redistribution of the chalcopyrite may have produced the observed paragenetic relationships between chalcopyrite and pyrite.

The evidence obtained from the chalcopyrite and associated pyrite does not lend additional support to a placer origin for gold or for pyrite. On the contrary, the evidence favours some form of hydrothermal emplacement of both the chalcopyrite and the pyrite of the Denison ore zones.

8. Interpretation of the Gold Content of Quartz

The amounts of gold found in the quartz fractions of several ore conglomerate samples (Table 7-5), indicate that the gold content of quartz from the conglomerates (essentially the quartz pebbles) is similar to that found in ordinary granitic rocks and sediments. Thus, the enrichment of gold in the conglomerates occurs in the matrix alone where the gold is essentially concentrated in the pyrite. In this way, the Elliot Lake conglomerates are similar to other analogous conglomerates of the Proterozoic. The majority of gold in the Witwatersrand is in the matrix of the conglomerates and only where the gold has been remobilized does it cut into quartz pebbles. At Jacobina, Brazil, the gold is also confined to the matrix of the conglomerates and, according to Bateman (1958), is contained almost entirely in pyrite. Thus, the confinement of gold in the Denison ore to pyrite of the matrix is similar to the occurrence of gold at Jacobina and the Rand where it is present in economic concentrations.

The content of gold in the quartz can also be interpreted as implying that the gold in the pyrite of the uranium ore and the quartz are not from the same primary source. If the pebbles were derived from quartz of hydrothermal veins which contained significant quantities of gold, then it would be expected that some of the gold remain entrapped within the pebbles and thus produce higher gold concentrations than those determined for the quartz. Therefore, if the quartz pebbles of the uraniferous conglomerates are derived from veins, or even from pegmatites, then the gold found in the ore is most probably not derived from either.

9. Implications From Iridium Data

No general conclusions can be drawn from the analysis of 4 pyrite samples for iridium. These samples were processed to determine only the approximate iridium content of the pyrite. From the results, it would appear that the iridium in the pyrite is enriched with respect to Ir in G-1, to the same general extent (approximately 100 times) as the gold is enriched with respect to Au in G-1. Since iridium does not behave in a similar way to gold during fractionation of sulfides (it is concentrated in early crystallates rather than in late crystallates according to Keays (1968)), then the equivalent enrichment of gold and iridium may be better explained by physical means rather than by chemical means. Thus, a placer method of concentration of gold and iridium from a granitic terrain would be expected to concentrate each metal to the same degree and this is, in fact, the situation as observed at the Denison Mine. The implications of the iridium studies would therefore be that both the gold and iridium were of placer origin. However, since a complete study of iridium was not conducted, these results can only be offered as observations and should not be used as conclusive evidence.

10 . General Remarks and Conclusions

Table 8-4 consists of a summary of the results obtained from individual studies in this work as they apply to the two theories of origin for conglomerates of the Elliot Lake type.

The evidence obtained in this work is not of sufficient strength to positively support any one theory of origin for the ore minerals of Proterozoic quartz pebble conglomerates in general and the Denison Mine uraniferous conglomerates specifically. The author has reviewed most of the literature available regarding such deposits and their origins and has concluded that the theory of a modified placer origin is by far the most acceptable and is supported by the majority

Table 8-4: Summary of Results

Study or Analysis	Comments
Distribution of gold along strike of ore conglomerate	Maybe explained within context of placer origin for gold but does not discount hydrothermal origin.
Distribution of gold across vertical section of conglomerate	Maybe explained within context of placer origin for gold but does not discount hydrothermal origin.
Correlation of gold and uranium	Maybe explained within context of placer origin for gold.
Distribution of gold within pyrite	Tends to discount direct placer origin of gold as well as possibility of pyrite being detrital.
Distribution of gold in chalcopyrite compared to that in pyrite	Favours direct hydrothermal origin for chalcopyrite and pyrite.
Comparison of gold concentrations to those in modern placers	Comparable to marginal placer deposits.
Concentration of gold in quartz fraction of the conglomerates	Establishes that majority of gold is in matrix as is gold in other analogous deposits. Also, is most probable that the quartz and gold are not derived from the same primary source.
Iridium concentrations in the pyrite	Suggests that iridium and gold were concentrated by physical (i. e. placer) methods.

of factual data. From this point of view, most of the results obtained in the present study can be interpreted as favouring a direct placer origin for the gold and only a few results put such an origin in doubt. Until more studies are done on the gold content of chalcopyrite in the ore, and on the paragenesis of the chalcopyrite and pyrite, the conclusions based on these studies can bear little weight. More work must also be done on the relationship of gold to pyrite and the nature of its distribution within pyrite. Thus, the two results least favourable to a placer origin for gold are the two most questionable results. On the other hand, the distribution, size, and concentrations of gold in the Denison ore zones, as well as the concentration of iridium, all are those which may be expected for a placer deposit containing extremely fine grained particulate gold.

In conclusion, it is not suggested that this work indeed favours a placer origin for the gold in the Denison Mine uraniferous conglomerates of Elliot Lake. More studies are required before any such definite conclusions can be made. However, the study has pointed out that geochemical evidence can be used to support a placer origin, and thus, such a theory does not have to rely exclusively on geological evidence. On the other hand, exploitable weaknesses in such a theory have been raised and further work concerning them could possibly bring about revisions to the leading existing theories.

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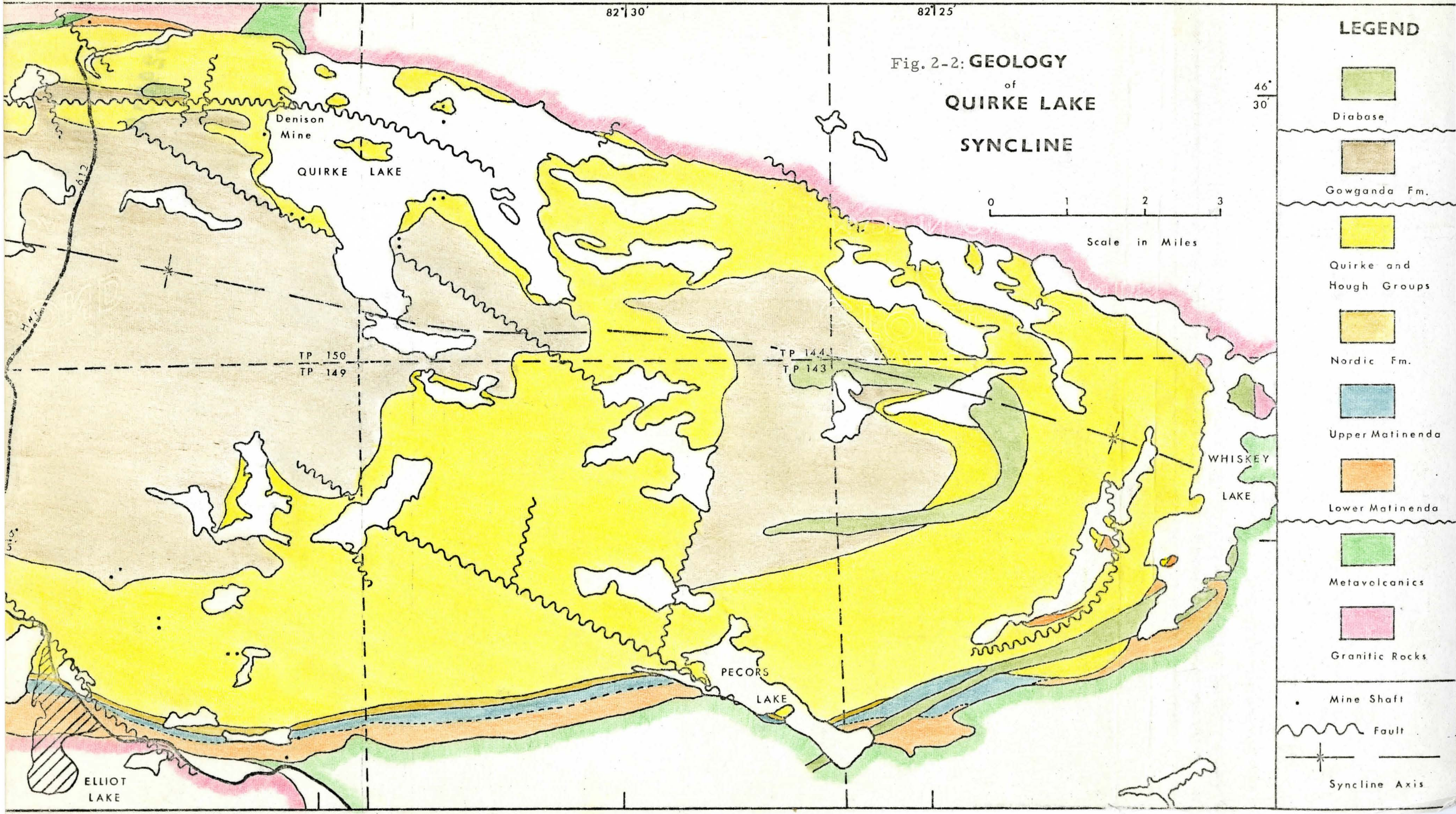

Fig. 2-2: GEOLOGY of QUIRKE LAKE SYNCLINE