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Geology and Geochemistry of the Owl Creek Gold
Deposit, Timmins, Ontario

by

David Michael Kingston

A thesis submitted to the Faculty of
Graduate Studies and Research in partial
fulfilment of the requirements for the degree of
Master of Science

Department of Earth Sciences

Carleton University
Ottawa, Ontario
August, 1987

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August, 1987

Abstract

Gold mined from the Owl Creek deposit is found as inclusions in euhedral and nodular pyrite in tholeiitic basalt and carbonaceous shale. Free gold also occurs in subvertical and subhorizontal quartz veins in basalt. The orebody lies in a heterogeneous deformation zone defined by numerous discrete high strain zones characterized by slaty cleavage. Movement about these zones is predominantly dip-slip.

Field and petrographic studies have defined four episodes of gold precipitation: i) diagenetic in pyrite nodules; ii) epigenetic, auriferous euhedral pyrite in basalt; iii) gold-bearing quartz veins, iv) late quartzose breccia. In polished section gold is most closely associated with pyrite, arsenopyrite and pyrrhotite.

Gold in the main ore zone is enveloped by ankerite-dolomite-sericite-pyrite alteration. Auriferous pyrite from the quartzose breccia is associated with chlorite-sericite-pyrite assemblage.

Sulphur isotope signatures of auriferous pyrite range from +1.8 to +3.5 per mil. This signature is interpreted to be the result of a fluid dominated by H_2S which concentrated ^{34}S .

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CHAPTER I

INTRODUCTION

1.1 General Statement

The Owl Creek gold deposit is an open pit mine operated by Kidd Creek Mines Ltd., 17km northeast of Timmins, Ontario and is situated within the west end of the Archean Abitibi Greestone belt (Figure 1a). Located in Hoyle Township, Owl Creek is only 5km west of Kidd's metallurgical site and 22km southeast of the Kidd Creek mine (Figure 1b).

Hoyle Township was originally mapped by Burrows in 1915 and 1924. The flat nature of the topography often combined with 10 to 50m of glacial overburden results in less than 1% outcrop (Downes, et al., 1982). Based mainly on diamond drill core, Kidd Creek exploration geologists produced a general geology map of the surrounding area in 1982 (Figure 2).

Exploration in the Owl Creek area was initiated by INCO Ltd. in 1966 as a result of an airborne electromagnetic (AEM) anomaly. Upon acquisition by Kidd Creek Mines Ltd. in 1979, the property was drilled and production began in 1982. By the end of 1985 1,064,072 tonnes of 4.0g Au/t ore had been removed leaving approximately 660,000 tonnes of 4.1g/t ore to be mined (Coad et al., 1987).

As pit development of the Owl Creek mine progressed, Kidd geologists mapped successive levels outlining the major rock types and faults in the pit. Gold is found mainly as inclusions in pyrite in massive to pillowed tholeiitic basalt and carbonaceous shale. Free gold is also mined from massive quartz veins (Coad et al., 1987).

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CHAPTER I

INTRODUCTION

1.1 General Statement

The Owl Creek gold deposit is an open pit mine operated by Kidd Creek Mines Ltd., 17km northeast of Timmins, Ontario and is situated within the west end of the Archean Abitibi Greestone belt (Figure 1a). Located in Hoyle Township, Owl Creek is only 5km west of Kidd's metallurgical site and 22km southeast of the Kidd Creek mine (Figure 1b).

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As pit development of the Owl Creek mine progressed, Kidd geologists mapped successive levels outlining the major rock types and faults in the pit. Gold is found mainly as inclusions in pyrite in massive to pillowed tholeiitic basalt and carbonaceous shale. Free gold is also mined from massive quartz veins (Coad et al., 1987).

Figure 1a. General geology of the Archean Abitibi greenstone belt (after Goodwin and Ridler, 1970).

Figure 1b. Location of Owl Creek with respect to Timmins and other major ore deposits in the area. Closed circles are operating gold mines, open circles are prospects and closed square is the Kidd Creek mine.

Figure 2. General geology of the Owl Creek gold deposit and surrounding area (after Coad et al., 1987).

1.2 Previous Work

Since production began many workers have studied selected aspects of the Owl Creek gold deposit.

Elliott (1984) compared the trace element geochemistry of euhedral and nodular pyrite with the trace element and whole rock composition of the shales as well as the $\delta^{34}\text{S}$ ratios of nodular and euhedral pyrite. She concluded that pyrite nodules were formed by bacterial reduction of sulphate (based on S-isotope signatures that ranged from -5.0 to +1.9 per mil) and that the originally framboidal pyrite was subjected to several episodes of pyrite generation and later recrystallization. Preliminary S-isotope data on nodular and euhedral pyrite suggested a correlation between gold tenor and S-isotopic signature of the pyrite.

Although Downes et al. (1984) focused mainly on the nearby Hoyle Pond gold deposit, they recognized an association between elemental carbon content in altered basalt and anomalous gold values in rocks similar to those at Owl Creek. In their preliminary report, Downes et al. (1984) speculated that "snowflake" pyrite (skeletal plates of pyrite along slaty cleavage in carbonaceous shale) along with pyrite in quartz veins are the most likely host for gold both at Owl Creek and Hoyle Pond.

Brisbin (1986) thoroughly documented the geology of benches one and two at Owl Creek in an attempt to determine ore controls. He recognized that the deposit was structurally controlled and suggested that the grey carbonaceous alteration of basalt is not an absolute indicator of ore grade gold concentration.

Springer (1985) investigated the relationship between carbon and

gold in Archean rocks of the Abitibi belt, including those at Owl Creek. She concluded that carbon in sedimentary rocks acted as a good reducing agent and was partially responsible for concentrating gold in sedimentary rocks in amounts up to 1ppm.

Wilson and Rucklidge (1986) looked at the petrographic characteristics of carbonaceous hosts to gold deposits with special emphasis on Owl Creek ore. Based on their studies they concluded the following: 1) carbon was mobilized from carbonaceous sediments into basalts, 2) the incompetent carbonaceous sediments are the foci of shearing and 3) arsenic is closely associated with gold. They also speculated that arsenic minerals occur as 1) thin films on pores and grain boundaries, 1i) submicroscopic ($<2\mu\text{m}$) inclusions in sulphides or 1ii) solid solution of arsenic in pyrite.

1.3 Thesis Objectives

The objective of this study was to combine detailed mapping of benches four and five with detailed geochemistry with the following goals in mind:

- 1) To establish the distribution and types of pyrite;
- 2) To give a detailed petrologic classification of rock types and outline of ore mineralogy at Owl Creek;
- 3) To outline trace element distribution in sedimentary and volcanic rocks from the open pit and the surrounding area; and
- 4) To investigate any possible correlation between the S-isotope signature of pyrite and gold content;

CHAPTER II

REGIONAL GEOLOGY

2.1 General Statement

The Timmins gold camp is located within the west end of the Abitibi Greenstone belt of the Superior Structural Province of the Canadian Shield, northeastern Ontario (Figure 1). The geology of the region is dominated by Archean sedimentary and volcanic rocks (Table I). All Archean rocks have been subjected to lower to middle greenschist facies regional metamorphism. The prefix meta is not used in this text for purposes of brevity but is implied throughout.

Dunbar (1948) divided the volcanic rocks into two groups which he named Deloro and Tisdale. Archean sediments, classified as the Porcupine Group (Lorsong, 1975), are considered to be time equivalent to the upper part of the Deloro Group and the entire Tisdale Group. Porcupine Group sediments were interpreted by Pyke (1982) as a turbidite succession.

2.2 Structural Geology

The major structural feature of the area is the northeast-trending Destor-Porcupine Fault (DPF). Formerly known as the Porcupine Creek Fault (Hurst, 1936), it extends from as far east as Noranda where it emerges from the Cadillac Break, passes through Timmins, then west to the Kapuskasing Structure (Pyke, 1982). Rocks north of the DPF were first folded about a north-trending axis. Later, these rocks were re-folded about east-northeast axes. This resulted in shear folding which is thought to be related to the development of the DPF (Pyke, 1982). This fold axis is delineated by

Table I. Table of Archean lithologic units for the Timmins area (after Pyke, 1982).

ARCHEAN

Mafic Intrusion

Diabase.

Felsic Intrusion

Quartz and feldspar porphyry

Metamorphosed Mafic Intrusive Rocks

Gabbro, quartz gabbro, pegmatoidal gabbro

Metamorphosed Ultramafics

Diorite, peridotite, and
lherzolite; pyroxene hornblendite;
dunite-peridotite.

Porcupine Group

Three Nations Lake Formation

Interbedded lithic arenite and
conglomerate.

Dome Formation

Turbidite sequence; polymictic
conglomerate.

Beatty Formation

Turbidite sequence of lithic and
arkosic wackes and siltstones.

Whitney Formation

Interlayered intermediate mafic tuff
and minor siltstone.

Tisdale Group

Upper Fm.

VI

Felsic calc-alkaline pyroclastics
of andesite-rhyolite composition.
Rare intercalated ultramafic tuff
and cherty sulphide iron formation.

Middle Fm.

V

Iron-rich tholeiitic basalt -
often variolitic.

Lower Fm.

IV

Peridotitic and basaltic komatiite
at base to interlayered komatiites
and Mg- and Fe-tholeiitic basalts
near the top.

Deloro Group

Upper Fm.

III

Calc-alkalic rhyolitic and
dacitic lapilli tuff.
Also abundant iron formation
(Oxide and Sulphide facies).

Middle Fm.

II

Top of formation consists of
pyroclastics; remainder is calc-
alkaline, basaltic and andesitic
flows and ultramafic rocks.

Lower Fm.

I

Volcanic and minor ultramafic
volcanic rocks.

the Porcupine Syncline in Tisdale Township (Ferguson et. al., 1968).

Within the Timmins area, the DPF is a shear zone at least 150m wide and may dip from 80°N to vertically (Pyke, 1982). Stratigraphic relationships in the area indicate both dip- and strike-slip movement with south side down and sinistral strike-slip movement. Other younger and smaller faults traverse the area in a north-northwest direction. The Burrows-Benedict Fault, for example, displaces the DPF approximately 1.5 km in a left-lateral direction (Pyke, 1982).

2.3 Gold Production

The vast majority of the approximately 2 billion dollars worth of gold produced in the area has been from quartz-ankerite veins in metavolcanic and metasedimentary rocks from north of the DPF (Pyke, 1982). Quartz-calcite veins generally found outside the main ore zones contain minimal quantities of gold. Most gold-bearing veins are located along anticline axes and are spatially associated with quartz-feldspar porphyry stocks (Pyke, 1982). These veins have many configurations. They may be continuous and tabular, structurally controlled parallel or branching stringers, or contorted, displaying pinch and swell structures (Pyke, 1982).

To date, most known gold deposits occur in komatiitic and tholeiitic volcanics of the Tisdale Group (formations VI and V) and quartz-feldspar porphyries. By comparison, auriferous pyrite hosted by carbonatized and sericitized basalt (as found at Owl Creek) constitutes only a small fraction of gold ore mined in the Timmins area.

CHAPTER III

GEOLOGY OF THE OWL CREEK OPEN PIT

3.1 General Statement

Ore at Owl Creek occurs in a steeply dipping wedge of Tisdale Group Mg-tholeiitic basalts (Formation IV) and to a lesser extent in Porcupine Group carbonaceous shales (Beatty Fm.) bound by east-trending, subvertical faults (Coad et al., 1987; Figure 2). These rocks have been intensely sheared parallel to stratigraphy. The ore zone trends at 090° and plunges about 20° to the east to a depth of 110m below which the plunge is near vertical and the deposit becomes uneconomic (Coad et al., 1987). Most gold is found as inclusions in pyrite grains; however, visible gold not associated with pyrite may also be observed in massive subhorizontal quartz veins.

When initially opened, the Owl Creek pit was approximately 360m long and 200m wide at the first level. To date, five levels have been mined in 9m high benches to a depth of 45m. Detailed bench mapping in this study concentrated on benches four and five (Figures 3 to 6). As much of the acquired field data as possible has been placed on these maps and sections. A list of the abbreviations used on these figures is provided in Appendix I. The major rock types recognized during mapping are described below.

3.2 Owl Creek Lithologic Units

Arkosic Wacke

Two exposures of arkosic wacke were recognized in the open pit during mapping. In this text they will be referred to as north and south arkosic wacke (Figure 2). A third occurrence, a 5m thick

interflow unit, was identified within the basalt during thin section study. Field observations are based mainly on north wacke exposure due to poor access to the south.

The exposed thickness of the north arkosic wacke is 50m; however, drilling results indicate that the total thickness of this unit is 150m. These rocks are fine to very fine-grained, steeply dipping (75° – 85° N) and massively bedded (Figure 3 & 4). Beds may range from centimetres to tens of metres in thickness and are interbedded with black mudstone laminae up to 5cm in thickness (Plate 1a). These rocks are the least deformed of any observed in the pit. Contacts between individual beds are sharp but rarely faulted.

In some locations the mudstone beds have been ripped up (Plate 1c). This is the best field evidence for stratigraphic tops to the south and it indicates that the beds have been overturned during folding. Coad et al. (1987) described graded beds both in the pit and in drill core indicating that the beds young to the south, but none were recognized in this study. Coad et al. (1987) interpreted these rocks to be turbidites.

In the field, pyrite (< 1%) was observed as euhedral cubes up to 10mm in size, evenly distributed throughout the wacke.

Basalt

Basalt is massive to locally pillowed and intensely sheared (Plate 1b). These rocks strike at 085° and dip between 85° and 90° N and have either a grey or buff colour. Whereas buff basalt is massive or intensely sheared, grey basalt is always intensely sheared. Although a 40m thick section was mapped during this study only 5m could be positively identified as pillowed basalt (Plate 1d). The

PLATE 1: Selected photographs of lithologies exposed in the Owl Creek open pit.

Plate 1a: Interbedded black mudstone (dark grey) in north arkosic wacke (light grey), 4 bench west.

Plate 1b: Contact of intensely sheared basalt (light grey) and north arkosic wacke (dark grey). Note the strong development of S_2 slaty cleavage, 4 bench west.

Plate 1c: Ripped-up mudstone beds in north arkosic wacke. Stratigraphic top is to the south (left). Small white mineral disseminated throughout both mudstone and wacke is euhedral pyrite.

Plate 1d: Pillowed basalt flattened parallel to stratigraphy, 4 Bench west.

Plate 1e: Chloritized pillow selvage, 4 bench west.

Plate 1f: Subvertical quartzose breccia vein between subhorizontal quartz vein to the south (right on photo) and basalt to the north (left on photo, 5 bench north.

Plate 1

entire unit has been altered to assemblages containing carbonate, sericite and pyrite. Pillow selvages have been chloritized (Plate 1e).

Intense deformation of this unit parallel to stratigraphy has resulted in the development of a slaty cleavage. As a result, few primary structures are preserved that permit accurate top determinations. Pyrite may account for up to 5 to 10% of basalt in zones of intense shearing. It occurs as euhedral cubes up to 3mm in size.

Large subhorizontal and subvertical quartz veins are present along the fault-bounded, northern and southern contacts of basalt with arkosic wacke and shale, respectively. Along the north wall of bench five, at the quartz vein-basalt contact, a 20cm wide quartzose breccia occurs (Plate 1e). These veins will be described in detail later.

The contact with the arkosic wacke to the north and the carbonaceous shale to the south is faulted.

Carbonaceous Shale

South of the basalt is a 25m thick carbonaceous shale unit (Figure 3 & 4). These fissile rocks are very fine-grained and black largely due to the presence of carbon. Bedding measurements are difficult to obtain in this unit but are considered to be similar to those of other sediments in the pit. Carbon content appears to be highest in the 20m adjacent to faulted contact between basalt and shale suggesting that carbon was mobilized and concentrated during shearing. Here, the rock takes on a steel grey hue, an almost metallic luster and has a greasy feeling.

This unit contains less than 5% nodular, vermiform and minor

snowflake pyrite as well as a massive lens of pyrite. This lens is 1.5 by 3m where exposed on S bench west and consists of nodular and vermiform pyrite. These pyrite types will be discussed in more detail later in this chapter.

Mudstone

Mudstone is distinguished from carbonaceous shale by its lack of fissility and lower carbon content. This suggests that mudstone is the non-sheared equivalent of shale. It is interbedded with very fine-grained arkosic wacke at 085°/85°N. Wacke beds gradually become more abundant toward the contact with the south arkosic wacke.

Pyrite occurs predominantly as bands up to 5cm thick and as disseminated euhedra less than 1mm in size (Plate 3c). Banded pyrite comprises up to 15% of the rock. Nodular and vermiform pyrite were not observed in mudstone.

3.3 Structural Geology and Vein Types

The structural geology of the rocks found in the Owl Creek open pit is dominated by a heterogeneous deformation zone that runs east-west through the center of the pit and is subparallel to the Deator-Porcupine Fault. This zone is approximately 100m wide and consists of numerous discrete high strain zones characterized by intense cleavage development. Discrete high strain zones may range from 10cm to 10m in thickness. It is these zones with which ore grade auriferous pyrite concentrations are associated. High strain zones are restricted to shale and basalt.

Structural measurements made at Owl Creek are summarized in Figures 7 and 8 and Table II.

OWL CREEK

Poles to Planes

- ▲ S_0
- S_2 Slaty Cleavage
- S_3 Foliation
- Subvertical Veins
- Subhorizontal Veins
- △ Massive Pyrite Bands

Figure 7. Summary of structural measurements made on benches 4 and 5. Note that S_1 is a regional foliation not observed on these benches.

Figure 8. Lineations measured on S_2 slaty cleavage of shale.

Table II. Summary of sources of structural data, Owl Creek pit.

Fabric	Mean Attitude	Rock Type			
		Shale	Mdst	Basalt	Arkosic Wacke
S ₀	090/85N		x		x
*S ₁	070/85N				x
S ₂	095/85N	x	x	x	x
S ₃	140/20N	x	x		
+l ₁	85E	x			
#l ₂	16E	x			

* work done by Brisbin (1986),

+ stretching lineations measured on the S₂ plane defined by quartz pressure shadows,

intersection lineations defined by the intersection of S₂ and S₃.

The S₁ schistosity measured on benches one and two by Brisbin (1986) was not observed in the shale, mudstone or basalt on benches four or five. S₁, as recorded by Brisbin (1986), is similar in attitude to a regional fabric related to the second stage of regional folding as defined by Pyke (1982). In plan view, the intersection of bedding (S₀) and S₁ causes the arkosic wacke to fracture into diamond-shaped wedges (Coad et al., 1987).

Discrete high strain zones (S₂), are subparallel to stratigraphy and are defined primarily by the parallel alignment of sericite in basalt and shale. Faults and high strain zones are parallel to the preferred dimensional orientation direction of these platy minerals (Plate 1b).

Shale is commonly tightly to isoclinally folded (Plate 2a). The axial planes of these folds are subparallel to S₂ and the folds plunge

**PLATE 2: Deformed rock and associated structural fabrics
and vein types at Owl Creek.**

Plate 2a: Tightly folded carbonaceous shale, 5 bench west. Axial surface of fold is subparallel to S_2 slaty cleavage.

Plate 2b: Pinch and swell texture in subvertical quartz vein, 5 bench east. Note book is 18.5 x 11.5cm. Note how slaty cleavage of shale wraps around contours of quartz vein.

Plate 2c: Angular inclusion of auriferous pyrite-bearing basalt in subvertical quartz veins, 5 bench west. Nickel was used for scale.

Plate 2d: Lineation (L_1) defined by quartz pressure shadows about pyrite nodule on slaty cleavage surface of shale, 4 bench east. Note that the pyrite nodule is not present in photo.

Plate 2e: Crenulation cleavage (L_2) on slaty cleavage surface (S_2) of shale, 4 bench east. Photo is taken at an oblique angle to S_2 .

Plate 2f: Fault-bound en echelon, south-dipping quartz veins behind truck, 4 bench west.

Plate 2g: Subhorizontal calcite veins in north arkosic wacke, 4 bench west.

Plate 2

no more than 30 degrees to the east and west. Very rarely, isoclinally folded shale with south trending axial planes plunging 20° to the south can be found. Their rarity precludes determination of their structural significance.

A N-S cross-section of pillowed basalt is exposed at the west end of the pit. The ratio of the vertical to horizontal dimension ranges from five to fifteen to one (Plate 1d). Due to the absence of undeformed pillows it is impossible to determine the degree of strain. However, given the intense shearing of the massive basalt, manifested in the form of slaty cleavage (S_2), it seems reasonable to conclude that flattening parallel to S_2 has occurred.

Slaty cleavage development in both shale and basalt is cut by many northeast and northwest trending faults, the most prominent of which are Blakey and Jack's fault at the east and west ends of the pit respectively (Figure 2). Although displacement along these structures is unknown, Brisbin (1986) reported both strike- and dip-slip movement. These faults are important because they define the east and west boundaries of the orebody.

A lineation, l_1 , is defined by white quartz pressure shadows oriented at opposite ends of spherical pyrite nodules on the S_2 plane in the shale only (Plate 2d). The pressure shadows have rounded ends and show no sign of rotation. The total length of these shadows (4 to 5cm) from tip to tip averages between four and five times the diameter of the pyrite nodule.

A subhorizontal foliation, S_3 , is defined predominantly by amorphous carbon and, to a lesser extent, by sericite in the shale and mudstone. The superposition of S_3 on S_2 has resulted in a well developed large scale crenulation of S_2 and an intersection lineation,

l_2 (Plate 2e). These megascopic crenulations may be up to 20cm apart from crest to crest. The l_2 lineation has the same general trend and plunge as that of the orebody (090, 20E). The significance of this with respect to the orientation of the orebody will be addressed later.

Vein Types

Three types of quartz veins were observed within the highly strained rocks exposed in the Owl Creek pit (Plate 2b, f); 1) subvertical, 2) south dipping, en echelon tensional and 3) subhorizontal veins. All three types may contain up to 10% calcite. Due to mining, only remnants of subhorizontal veins remain; however, their presence was confirmed by examination of Kidd Creek Mines Ltd. cross sections. These cross sections also indicate that the highest gold grades are found in the subvertical and subhorizontal quartz veins. A fourth type, subhorizontal calcite veins, was observed in the less deformed north arkosic wacke (Plate 2g). The salient features of each vein type are summarized in Table III.

Of the four vein types described only type 4 is not associated with high gold values. Although gold was only observed in the subhorizontal veins, assay maps indicate that the rocks enclosing the other two vein types constitute ore. The close association of discrete high strain zones and quartz veins distribution (Figure 7) suggests that vein emplacement, and the associated gold mineralization, is structurally controlled.

Located along the north wall of five bench at the massive subhorizontal quartz vein (type 3)-basalt contact is a 20cm wide quartzose breccia (Plate 1e). Thin section examination revealed a

Table III. Classification of vein types at Owl Creek. Mineral abbreviations are from Kretz (1983). Others are: (Alt'n) alteration minerals; (vfg) very fine-grained; (carb) carbonate; (Au) gold; (Ser) sericite and (*) limited access.

Vein Type	Host Rock	Average Orientation	Size in N-S cross-section. Thickness by length	Mineralogy - Alteration	Textures
1 Subvertical Quartz Veins	Shale and to a lesser extent basalt	090°/85°N	Up to 1cm x 10m	White Qtz. Thin veins (<10 cm) are often gray along wallrock contact. Rarely vfg Py (<1mm) occurs and is restricted to gray Qtz. Alt'n: Ser, Py, C & carb	Pinch and swell texture. Joint sets cut veins at 120°/30° Qtz is strained. May have angular inclusions of basalt or shale.
2 Tensional Quartz Veins	Basalt bounded by subvertical faults	090°/40°S	Up to 1 x 10m	*White Qtz *Alt'n: Ser, Py, Chl, weak C and carb	En echelon array. Veins have tapered ends and a sigmoidal shape.
3 Subhorizontal Quartz veins	Basalt	090°/010°S	Up to 18 x 50m	White Qtz with minor Cal. Free Au in thin (<<1mm) fractures. Quartzose breccia is filled with Chl and auriferous Py Alt'n: Ser, Py, Chl, weak C and carb.	Massive, may have sigmoidal shape. Inclusions of angular basalt or shale (up to 20cm in size, Plate 2g). Inclusions contain auriferous Py. Qtz vein is brecciated at contact with basalt.
Quartzose Breccia	Type 3 Qtz vein	090°/85°N	20cm thick	Angular white Qtz fragments in a Chl, auriferous Py matrix. 10% of Py euhedra are cataclastically deformed. Qtz fragments are riddled with fluid inclusions. Angular white Qtz fragments (3-4 cm) with a cryptocrystalline yellow brown Qtz (Var. chalcedony) and goethite "matrix".	Foliated Chl and rare vfg Ser and carb matrix. Py in both matrix and and carb veinlets. Face controlled carb growth off Py euhedra (Plate 4f). Chalcedony grains are circular (0.1 mm in diam.) and have a radial extinction pattern (Plate 4g). The core has alternating concentric rings of impurities (possibly Fe minerals). Core diameter is 60-80% of individual grain diameter (Plate 4h).
4 Subhorizontal Calcite Vein	North Arkose	140°/15°NW	1cm x 5m	White and pink Cal. No associated Py. Alt'n: weak carb.	End of veins pinch out. Tabular

chloritic, gold-bearing pyrite matrix. Quartz fragments are angular and up to 5cm in size. A texturally identical rock with a brown quartz-goethite matrix is less commonly observed. This matrix is apparently devoid of gold. In both cases the matrix comprises 40% of the rock. This narrow zone, previously unrecognized for its gold content, indicates that there is a gold concentrating stage that post-dates that which produced the gold-bearing massive quartz veins.

Structural Interpretation

The following structural features indicate that S_2 shearing at Owl Creek was predominantly dip-slip.

1) Tight to Isoclinally folded shales. Fold axes are subparallel to S_2 and the folds plunge $< 30^\circ$ to either the east or west. A subequal number of folds plunge to the east as to the west. Most probably the folds were formed by dip-slip shear folding.

2) Stretching lineation (L_1) defined by quartz pressure shadows about spheroidal pyrite nodules. It is thought that pyrite nodules are diagenetic features associated with the activity of anaerobic sulphate-reducing bacteria (Berner, 1970; Berner, 1984). Therefore, because these nodules, or parts of them, are pre-tectonic, pressure shadows can provide valuable information about the deformational history of the host rock (Durney and Ramsay, 1973). At Owl Creek, the shape and orientation of these shadows is compatible with those formed by coaxial deformation as defined by Ramsay and Huber (1983). This means that the pressure shadow deforms in a manner identical to that of the rock matrix surrounding it. This suggests that the quartz pressure shadows formed about pyrite nodules in shale as a result of north-south compression accompanied by dip-slip movement.

3) Fault-bounded en echelon quartz veins. This type of vein development is interpreted as quartz filling of extensional fissures caused by brittle-ductile simple shear (Ramsay, 1980). These en echelon veins observed in cross-section at Owl Creek were formed by normal dip-slip faulting as follows.

Subvertical dip-slip faulting would produce fissures oriented perpendicularly to the first maximum incremental extension at approximately 45° and 135° to the faults in the basalt (Type 2 veins, Figure 9a). The opening of these fissures is accompanied by the precipitation of gold-bearing quartz. Veins were then rotated in response to an increase in the amount of shear strain (Ramsay and Huber, 1983). An increase in shear strain resulted in the development of subhorizontal fissures (Type 3 veins, Figure 9b).

At Owl Creek, this would mean that the massive subhorizontal quartz veins (type 3) began as extension fissures subsequently filled with quartz that were eventually subjected to greater shear strain than type 2 tension veins. The greater shear strain caused the vein to be rotated into a subhorizontal position.

If this is how Owl Creek vein types 2 and 3 developed, it suggests that south-dipping en echelon quartz veins (type 2) are found in basalt subjected to lower shear strain than basalt which hosts subhorizontal quartz veins (type 3).

Structural Evolution of Rocks at Owl Creek

Based on the field evidence presented, a simple four stage model was developed to outline the structural evolution of rocks exposed in the Owl Creek open pit. The four stages are illustrated sequentially in Figure 10 and restricted to the highly deformed shale and basalt.

Figure 9. Cross section of progressive development of extension fissures in basalt subjected to dip-slip movement from early (A) to later (B) stage (after Ramsay and Huber, 1983).

Figure 10. Structural evolution of Owl Creek shale and basalt from a state of zero strain (A) through to the last major phase of brittle deformation (D). Half arrows indicate direction of rock movement in north-south cross section and full arrows indicate possible fluid migration paths.

A schematic cross section of these steeply dipping rocks at Owl Creek at zero strain is illustrated in Figure 10a.

Initial strain, caused by dip-slip movement, resulted in subvertical faults and discrete high strain zones oriented parallel to stratigraphy in shale and basalt (Figure 10b). At this stage, fault-bounded en echelon quartz veins began to form (cf. Figure 9a). Subvertical faulting and fracturing increase the permeability of basalt and provide the most probable conduits for fluid flow which lead to the formation of en echelon and subvertical quartz veins. Subvertical quartz veins frequently contain angular fragments of gold-bearing host rock (Figure 10b) probably produced by hydrothermal brecciation. Rocks subjected to increased shear strain (Figure 10c) as a result of continued dip-slip movement results in rotation of extensional en echelon quartz veins into a horizontal position (cf. Figure 9b). Subhorizontal quartz vein precipitation may have continued during this stage.

Brittle deformation culminated in the brecciation of subhorizontal quartz veins forming subvertical quartzose breccia veins (Figure 10d). Unlike subhorizontal and extensional veins, there is no direct indication as to what type of movement produced the quartzose breccia. Nevertheless, the preponderance of evidence for dip-slip movement during earlier stages of deformation suggest that similar movement produced the quartzose breccia.

This model illustrates how the major vein types observed at Owl Creek are related to each other. Using this model, vein development can be used to evaluate to degree of strain rocks have been subjected to. At Owl Creek, the most highly strained rocks (cf. Figure 10d) are located in the centre and east end of the pit and the least strained

rocks (cf. Figure 10b) are found in the west end of the pit.

Influence of Structural Geology on Ore Distribution

The evidence presented in this chapter indicates that the development of the heterogeneous deformation zone was responsible for increased permeability in carbonaceous shale and basalt which in turn controlled the migration of gold-rich fluids and the subsequent precipitation of auriferous pyrite and gold-bearing quartz veins at Owl Creek. This is supported by the fact that gold is concentrated in intensely sheared basalt and carbonaceous shale rather than in relatively undeformed arkosic wackes. To the west and east the distribution of ore is controlled by the northeast trending Jack's fault and northwest trending Blakey Fault respectively (Figure 2). These faults were interpreted by Brisbin (1986) to be post-ore and therefore could not have controlled the migration of gold-bearing fluids.

This relationship between northeast and northwest trending faults and the heterogeneous deformation zone suggests that discrete high strain zones were the principal conduit for gold-rich fluids and later northeast and northwest faulting served only to define the east-west extent of the orebody as it presently exists.

The similarity in the trend and plunge of the orebody and intersection lineation, l_2 , appears to be a coincidence. In sedimentary rocks, the lineation defined by the intersection of S_2 and S_3 may have influenced the east-west migration of auriferous fluids; however, the absence of this fabric in basalt, which is the main ore zone, indicates that l_2 had no influence on the orientation of the orebody in basalt. This may explain why gold is sometimes

concentrated in weakly deformed mudstone.

3.4 Types of Pyrite and their Distribution

Because most gold is included in pyrite, special emphasis was placed on distinguishing the type and distribution of pyrite during field mapping.

Six types of pyrite were recognized during mapping of the shale-mudstone units (Plate 3a-f):

- i) spheroidal nodules with or without quartz pressure shadows;
- ii) vermiform pyrite (elongate nodule-like pyrite whose long axis is on average 5 times that of any other axis but show no sign of brittle deformation);
- iii) fine-grained disseminated euhedral pyrite in both shale and mudstone;
- iv) continuous to discontinuous bands of massive pyrite parallel to bedding;
- v) a massive pyrite lenticle formed by the accumulation of nodular and vermiform pyrite; and
- vi) "snowflake" pyrite (as defined by Downes et al., 1984) which appears to be late stage skeletal pyrite that formed on slaty cleavage planes of shale.

Table IV summarizes pyrite occurrences with respect to rock type.

Nodular and vermiform pyrite can be brittly deformed; however, mapping indicates that there is no gradational pattern to the distribution of such pyrite in the shale. For example, spheroidal pyrite nodules can be found in one lamina while brittly deformed nodules can be found in adjacent beds. This suggests that the stress

PLATE 3: Pyrite types observed at Owl Creek.

Plate 3a: Spheroidal pyrite nodule hosted by carbonaceous shale, 5 bench west.

Plate 3b: Vermiform pyrite in carbonaceous shale, 5 bench east.

Plate 3c: Alternating continuous and discontinuous banded pyrite in mudstone, 4 bench east. Note how discontinuous pyrite bands appear to be pulled apart.

Plate 3d: Core of massive pyrite lens comprised of both nodular and vermiform pyrite hosted by carbonaceous shale, 5 bench west.

Plate 3e: Deformed rim of massive pyrite lens in carbonaceous shale, 5 bench west.

Plate 3f: Snowflake pyrite (left of Py on photo) developed on slaty cleavage surface of carbonaceous shale, 5 bench east. Lens cap is 55mm in diameter.

Plate 3

applied to the shale caused it to react like a deck of cards, with movement taking place along narrow planes of weakness leaving, for example, pyrite nodules between such planes virtually unaffected. Brittly deformed nodules would define discrete zones of relatively high strain whereas undeformed vermiform and nodular pyrite would delineate discrete zones of relatively low strain in the shale.

Table IV. Occurrence of pyrite types in shale and mudstone.

<u>Pyrite Type</u>	<u>Shale</u>	<u>Mudstone</u>
i) Nodular	Common	Rare
ii) Vermiform	Common	Rare
iii) Disseminated euhedral	Common	Common
iv) Banded	Not Observed	Common
v) Massive Lenticular	Common	Not Observed
vi) Snowflake	Common	Not Observed

A lenticular body of massive sulphide (pyrite) is exposed in the shale (5 Bench west). It consists of a relatively undeformed core made up of both spheroidal pyrite nodules and elongate to vermicular pyrite (Plate 3d) and a highly deformed rim in which pyrite has been mobilized into pressure solution cleavages (Plate 3e). Quartz pressure shadows can be found around many of the nodules. The origin of this lenticle will be addressed later.

Fine-grained euhedral pyrite can be found in massive black mudstone. Its greatest concentration is in a 4m thick sequence of alternating pyrite-rich and pyrite-poor beds oriented parallel to bedding (Plate 3c). In the north this subunit consists of continuous bands of massive pyrite alternating with pyrite-poor black mudstone.

Contacts between pyrite-rich and pyrite-poor beds are sharp. Overall, the pyrite content of these bands decreases to the south where there is a transition from continuous massive pyrite bands into very-fine grained disseminated pyrite. Where disseminated, pyrite is concentrated in the coarser beds. Thin sections show that pyrite is evenly distributed and displays no gradation in grain size. On average, this subunit contains 15 to 20% pyrite.

Bands of massive pyrite locally display a pinch and swell texture similar to that described for subvertical quartz veins. This results in the development of discontinuous pyrite lenses oriented parallel to bedding (Plate 3c). Three-dimensional sections suggest that pyritic bands have been pulled apart by dip-slip movement as described earlier in this chapter.

The association of synsedimentary banded pyrite accumulations and turbidite facies (Ojakangas, 1985) has been interpreted to result from volcanic exhalation. The evidence presented here would support such a mechanism for banded pyrite formation. Although this does not preclude the possibility that interbedded banded pyrite precipitated below sediment-seawater interface from hydrothermal fluid before major deformation took place, field evidence does not support such an interpretation. Geochemical data and discussion presented in Appendix II also support a synsedimentary origin for banded pyrite.

Pyrite habit in both the basalt and arkosic wacke is restricted to euhedral cubes. In both cases there is a bimodal size and concentration distribution; fine-grained pyrite (< 5 mm) is concentrated in discrete high strain zones and coarse pyrite (up to 15 mm) is found in massive, relatively undeformed rock.

can be both stratigraphically and structurally controlled. Nodular, vermiform, and banded pyrite appear to be synsedimentary and their distribution does not appear to be controlled by any structural fabric observed in the pit nor by association with quartz veins.

Conversely, fine-grained euhedral pyrite and snowflake pyrite are associated with discrete high strain zones in basalt and shale, respectively. Snowflake pyrite, for example, is only found plated onto slaty cleavage planes in shale. This suggests that these pyrite types are epigenetic and their distribution in the pit is structurally controlled by the presence of discrete high strain zones (S_2).

CHAPTER IV

PETROLOGY OF OWL CREEK ROCKS

4.1 General Statement

A suite of sixty polished thin sections of drill core and hand samples from the open pit, as well as drill core from holes east of the pit, were described and classified (Tables V and VI). Sedimentary rocks at Owl Creek have been classified according to Pettijohn (1975).

4.2 Primary Mineralogy and Textures

Thin section examination of the sediments revealed little more about the original rock than had already been determined by field studies. This is especially true of the black carbonaceous sediments which are opaque in transmitted light even with as little as 5% amorphous carbon.

The interbedded carbonaceous mudstone and arkosic wacke have sharp contacts. Graded beds described by Coad *et al.* (1987) were not observed. The effect of greenschist facies metamorphism and to a lesser extent alteration obscures primary textures.

The arkosic wacke is the least altered of all the sediments (Plate 4a). The degree of sorting and low grain to matrix ratio are consistent with that of an immature sediment.

Thin section studies reveal the presence of two previously unrecognized units; an interflow sediment (arkosic wacke, OC-86-50) (Figure 3) and a carbonatized tuff. The tuff, which is intercalated with black mudstone, was intersected in drill core east of the pit (OC-80-12, 305.5m), and was originally logged as argillite. With the exception of 15 to 20% euhedral to subhedral plagioclase grains (0.5

TABLE V. Petrographic summary of Owl Creek sedimentary rocks. Mineralogy is listed in order of decreasing abundance. Abbreviations from Kretz (1983). Others are (*), alteration minerals; (carb), carbonate, (ser), sericite.

Sample Number	Petrologic Name (Field Name)	Mineralogy (avg. grain size in μ m)	Degree of Sorting	Grain to Matrix Ratio	Primary Structures & Textures	Secondary Structures & Textures	Comments
86-08, 15a, 20, 80-04(136m), 04(137.7m), H15-10-02	Carbonaceous Shale (Black shale)	Amorph. Carbon Sericite *Carbonate quartz (0.05) pyrite euhedra (0.5 - 3) nodules (5 - 10)	Poor	1:50	- Matrix supported	- Moderate to strong S_2 foliation defined by ser and carb. - Qtz-carb pressure shadows about py nodules. - Nodules may be cataclastically deformed.	- Rocks host massive concentrations of nodular and vermiciform Py. 3 x 1.5m in vertical section - Nodules are the dominant form of Py.
86-01, 02, 03, 18, 25, 28, 31, 34, 41, 58, 59, 80-02 (207.6m), 80-04 (50.5, 120.3, 127.9m), 80-12-2, -4	Weakly Carbonaceous Mudstone (Black mudstone)	Sericite Amorph. Carbon *Carbonate Quartz (0.01-0.005) Pyrite euhedra (0.05 - 0.25) Pyrite nodules (2 x 2-4) Rutile (0.005 - 0.01)	Poor	1:20	- Matrix supported	- Qtz-ser pressure shadows about Py nodules and carb rhombs. - Moderate to strong S_2 foliation defined by ser and carb. - Crenulation cleavage S_3 , defined by carbon at 40° - 50° to S_2 foliation - Post- S_2 and pre- S_3 rhombic carb porphyroblasts. Some have an internal remnant fabric defined by carbon oriented at 45° to S_2 . - Sulphides are associated with Qtz-carb veins. - Irregular stylolite-like carbon.	- This rock is the unshattered equivalent of black carbonaceous shale. - Fewer nodules in this rock, Py euhedra more common.
86-28, 43, 50, 58, 80-12-2, 80-04 (59.6m), 80-12-1	Arkasic Wacke (Greywacke)	Quartz (0.10-0.25) Plagioclase (0.005-0.01) Sericite *Chlorite *Carbonate Amorph. Carbon Pyrite euhedra (2 - 3) Rutile	Moderate	2:3	- Matrix supported - primary grains are visible	- Weak to moderate S_2 foliation. - Very weak crenulation cleavage where present - Some Qtz and plagioclase grains have ser pressure shadows. - Face controlled Qtz fibres associated with Py euhedra. - Qtz-potassium feldspar and carb veins.	- No Py nodules, generally large Py porphyroblasts up to 10 mm in size. Some fine (< 1mm) gold-bearing Py near contact with carbonaceous shale. - Rock fragments may be present.

PLATE 4: Selected textures of Owl Creek rocks in transmitted light.

Plate 4a: Arkosic wacke, crossed nicols. Note twinned plagioclase feldspar in upper right quadrant of photo. Scale bar = 1.25mm.

Plate 4b: Carbonatized tuff, crossed nicols. Note partially carbonatized plagioclase feldspar. Scale bar = 1.25mm.

Plate 4c: Pervasively carbonatized basalt with irregularly shaped black carbon stringers, crossed nicols. Opaque mineral in lower left corner of photo is pyrite. Scale bar = 1.25mm.

Plate 4d: Porphyroblasts with sericite-amorphous carbon and carbonate rim in mudstone, crossed nicols. Note how carbonate tails are twisted parallel to crenulation cleavage defined by black amorphous carbon. Scale bar = 1.25mm.

Plate 4e: Lensoidal carbonate porphyroblast, crossed nicols. Note how internal fabric of porphyroblast is at 90° to foliation. Scale bar = 0.7mm

Plate 4f: Face-controlled quartz fiber growth off pyrite euhedra, crossed nicols. Scale bar = 1.25mm.

Plate 4g: Chalcedony grains in quartzose breccia with goethite, crossed nicols. Note the radial extinction pattern. Scale bar = 0.7mm.

Plate 4h: Chalcedony grains in transmitted light. Note dark cores possibly caused by very fine-grained iron minerals. Scale bar = 1.25mm.

Plate 4

to 0.1mm in length) the rock is completely altered to carbonate (Plate 4b). The rims of many plagioclase grains have been partially replaced by carbonate as well. Thin tuffaceous units are commonly associated with black mudstones in the Timmins area (Pyke, 1982).

Primary mineralogy and textures of basaltic rocks from the Owl Creek pit have been totally obliterated. Only megascopic features, such as rare pillows, are preserved. As eluded to earlier, the identification of interflow sediment at the west end of the pit indicates that two separate basaltic flows exist: a massive basalt to the north and a massive to pillowed basalt to the south. Because both units have been mined out it is now impossible to determine its strike length.

4.3 Secondary Mineralogy and Textures

Sedimentary and volcanic rocks from the pit and surrounding area have been metamorphosed to greenschist facies. In addition, volcanic and to a lesser extent sedimentary rocks have been hydrothermally altered. The minerals of each rock type are summarized in order of decreasing abundance in Tables V and VI.

Basalt

Basaltic rocks yield the bulk of the gold at Owl Creek; therefore, their alteration assemblage will be discussed first. Ankerite, Dolomite, sericite, and pyrite are the alteration minerals, in order of decreasing abundance. Pervasive carbonate alteration is generally expressed by a very fine-grained to felted texture (Plate 4c). Very fine-grained sericite may define a foliation in basalt although relatively undeformed samples commonly shows no preferred orientation of sericite. High sericite

Table VI. Summary of alteration mineralogy and textures for altered basalt. Alteration mineralogy is listed in order of decreasing abundance. Abbreviations after Kretz (1983).

Sample Number	Field Name	Primary Mineralogy	Primary Textures	Alteration Mineralogy	Alteration Textures	Comments
86-10, 12, 40, 48, 52, 53	Basalt	Not preserved	None preserved	Ankerite Dolomite Sericite Amorphous Carbon Pyrite euhedra (0.2-7mm) Chlorite	- Massive vfg Carb-Ser alteration - Moderate foliation defined by Ser. - Fine controlled Qtz fibre growth off Py euhedra - Stylolite-like carbon stringers.	- Py may be associated with an increase in Ser alteration. - Qtz and Kfp veinlets.

commonly correlative with high pyrite content. Patches or fracture fillings of chlorite surrounded by carbonate minerals are locally developed. This suggests that chlorite is a product of earlier regional metamorphism and ankerite-dolomite-sericite-pyrite is the alteration assemblage associated with gold.

Amorphous carbon is a common mineral in the southernmost basalt exposures. The presence of carbon results in a unique grey colour in outcrop (defined by Downes et al., 1984 as grey alteration) which is easily distinguished from the buff carbonatized, carbon-free basalt. In thin section, carbon is found in thin irregularly shaped (stylolite-like) stringers which post-date pervasive carbonate alteration (Plate 4c). The significance of this observation depends on whether or not geochemical data indicate that gold concentration is associated with either carbonatization or carbonization as suggested by Downes et al. (1984).

Sedimentary Rocks

In thin section black shales are characterized by amorphous, opaque carbon. The mineralogy of carbonaceous shale, as revealed by X-ray diffraction, consists of sericite, dolomite, ankerite, pyrite and very minor chlorite and actinolite. The presence of amorphous carbon stringers similar to, but more abundant than, those observed in the basalt suggests that carbon has been mobilized within the carbonaceous shales.

Mudstone and arkosic wacke share common metamorphic assemblages; however, secondary minerals are more prominent in mudstone than wacke. Metamorphic assemblages and textures are summarized in Table V.

Examination of a few oriented samples indicates that S_2 -related

slaty cleavage is defined by sericite and S_3 (subhorizontal foliation) by amorphous carbon (Plate 4d). Rhombic calcite porphyroblasts, restricted to mudstone, consist of a carbonate core which has a weak to moderate fabric defined by sericite, and to a lesser extent carbon, oriented at approximately 45° to S_2 (Plate 4d). The rims of the porphyroblasts are 0.025 to 0.05mm thick and consist of inclusion-free calcite between 0.025 and 0.05mm in thickness. The spatial relationship of the porphyroblasts and the other fabrics indicates that they are post- S_2 and pre- S_3 . Some of the rhombs have sericite and carbonate tails giving the porphyroblast an lensoid shape in two dimensions (Plate 4e). Carbonate rhombs are most likely formed by recrystallization of carbonate introduced into the sedimentary rocks as veinlets.

4.4 Pyrite Textures from Samples Outside the Ore Zone

On a microscopic scale, pyrite can be classified into two general groups: nodular and euhedral. The pyrite outside the ore zone is found predominantly in the sedimentary rocks at Owl Creek.

Nodular Pyrite

Pyrite nodule morphology was described by Elliott (1984) with respect to the following textural features:

- i) size of the sediment-amorphous carbon core,
- ii) degree of concentric pyrite banding;
- iii) development of radial prismatic crystals.

Using these three criteria Elliott (1984) classified nodules as primitive (large core, well developed concentric banding, and no radial pyrite rim), intermediate and mature (indistinctive core, no

banding and well developed rim of prismatic pyrite crystals).

Although shale-hosted pyrite nodules have been documented in Timmins (Elliott, 1984) and Cobalt (Smyk, 1987) there are few comprehensive classification schemes and little discussion of their origin in the literature. The classification scheme adopted by Elliott (1984) may be replaced by a more descriptive system.

Based on the degree of recrystallization, pyrite nodules were divided into two morphological groups: concentrically banded nodules and completely recrystallized nodules (Figure 11). The classification and discussion presented here is based on cross sections of nodules on both the macro- and microscopic scale. In the field, these nodules are virtually impossible to differentiate. Gold was not observed in concentrically banded nodules; however, it is present in recrystallized pyrite. The mineralogy of recrystallized nodules will be discussed in the ore petrology section.

Concentrically Banded Nodules

These nodules may or may not have a carbonaceous core. They are characterized by an allotriomorphic mosaic core of fine-grained (<1mm) recrystallized pyrite and a rim of coarse-grained, radial prismatic pyrite. This rim may be up to 10mm thick, in some cases representing up to half the diameter of the nodule.

Banding is defined by concentric zones of recrystallized pyrite separated by amorphous carbon and less commonly quartz (Figure 11a). Within individual bands grain size does not vary; however, pyrite grains in each successive band increase in size from core to rim. Amorphous carbon and quartz separate zones of different mean pyrite grain size. Elliott (1984) concluded that the core of these nodules

A. CONCENTRICALLY BANDED PYRITE NODULE

B. RECRYSTALLIZED PYRITE NODULE

Figure 11. Two morphological types of pyrite nodules observed at Owl Creek; concentrically banded (A) and recrystallized (B).

is diagenetic but that several episodes of pyrite precipitation and recrystallization have occurred to give the concentric morphology. It is this type of nodule which makes the massive sulphide lens described earlier (cf. Chapter III).

Recrystallized Nodules

These nodules have no internal structure. They consist entirely of pyrite euhedra yet they maintain their original spherical form (Figure 11b). There is no gradation in pyrite cube size from core to rim and voids between pyrite euhedra are filled by quartz. Inclusions of gold in pyrite are commonly observed in polished section. The mineralogy of these nodules as well as other gold-bearing rocks will be discussed later.

Disseminated Pyrite Euhedra

Pyrite euhedra are found in all rock types mapped in the open pit. A summary of the petrographic characteristics of euhedral pyrite from outside the ore zone is given below. This includes banded (type iv) and disseminated euhedral (type iii) pyrite. Although disseminated euhedral gold-bearing pyrite is found in basalt, barren pyrite euhedra described here occur primarily in mudstone and shale.

Pyrite euhedra not associated with gold are generally inclusion-free and average 1mm in size. Pyrite euhedra may have attached quartz fibres what appears to be two dimensions, 90° to cube faces (Plate 4f). This texture is described by Ramsay and Huber (1983) as face controlled quartz fibre growth.

4.5 Ore Petrology

Although most gold in the ore mined from Owl Creek occurs as inclusions in pyrite grains the highest grades are found in the quartz veins (types 1-3) as free gold (J. Heslop, Kidd Creek Mines Ltd., pers. comm.). Of the six types of pyrite outlined from field studies, only euhedral pyrite (type iii) associated with zones of high strain and recrystallized pyrite nodules (type i) contain gold visible under reflected light microscopy.

Fifteen of the sixty polished and polished thin sections were found to contain gold. Auriferous pyrite was observed in basalt, chlorite matrix of the quartzose breccia and, to a lesser extent, in the carbonaceous shale and carbonatized tuff. Less commonly free gold resides in quartz veinlets that post-date carbonate alteration in the basalt as well as in the alteration assemblage itself. Free gold in quartz veins may be observed along the contact with carbonaceous shale (Coad *et al.*, 1987), in carbon-rich microfractures in massive quartz or freely in massive quartz veins. Very little gold was observed in thin sections of quartz vein samples, due to the nugget effect.

Ore and Associated Minerals

The mineral assemblage associated with gold inclusions in pyrite (Table VII) can be divided into two general groups: 1) those dominated by arsenopyrite and pyrrhotite and 2) those dominated by chalcopyrite and pyrrhotite. With the exception of silicates, pyrrhotite is the only other mineral inclusion common to both groups. There does not appear to be any strong association of gold-related mineral assemblage and rock type. Wilson and Rucklidge (1986) proposed a number of possibilities to explain elevated levels of As measured in Owl Creek

Table VII. Minerals associated with gold inclusions in pyrite euhedra; inclusions are numbered in order of decreasing abundance. Mineral abbreviations are taken from Kretz (1983). Others are: (Bas), basalt; (QB), quartzose breccia; (Mat), mudstone; (E), euhedral; (S), subhedral; (A), anhedral; (Rrx), brecciated; (Anl), annealed; (Alt), alutite, PbTe; (Inc), inclusion; (Pf), filling fractures; (Atc), attached.

Sample Number	Rock Type	Pyrite Textures		Inclusions in Pyrite											GOLD			Average Grain Size (um)	Gold Assay (ppm)	Associated Minerals outside Py							
		Z	Py	E	S	A	Brx	Anl	Au	Apv	Ccp	Cc	Cv	Sp	Po	Rt	Mag				Alt	Inc	Pf	Free	Atc		
OC-86-40	Bas	2	X	X					4	3	1				2				X			X			15 x 7.5	0.65	-
OC-86-N01	QB	10	X	X	X				5	6	1	7		4	2	8	3		X			X		X	15 x 15	14.2	Asp
OC-86-N01a	QB	5	X	X	X				5	6	1		3	2	2		4		X			X		X	15 x 10	14.2	Asp
OC-86-N01b	QB	20	X	X	X				6	4	2		5	1	3				X			X		X	15 x 10	14.2	Asp
OC-86-N02	QB	3	X						5	2	2		4	3	1				X			X		X	32.5 x 10	14.2	
OC-86-N04	QB	2	X						3						1	2			X			X		X	30 x 35	14.2	
OC-80-12-4	Mat	2	X						5		4			2	3	1			X			X		X	7.5 x 15	4.90	Ccp, Rt
OC-80-12-5	Tuff	3	X						5	1	2			3	4				X			X		X	10 x 12.5	4.84	Ccp, Po, Rt
OWL-06	Mat	3	X						2	1					3				X			X		X	10 x 15	0.12	Asp, Ccp, Po
OWL-08	Bas	5	X	X					6		2			5	1	3	4		X			X		X	12.5 x 12.5	9.28	Rt
OWL-09	Bas	5	X						3					2	1				X			X		X	10 x 5	0.95	Ccp, Rt
OWL-10	Bas	7	X						2	3		1							X			X		X	15 x 20	24.6	Asp, Ccp
OWL-11	Bas	5	X						3					2	1				X			X		X	10 x 20	5.02	Ccp
OWL-13a	Bas	1	X						3	2									X			X		X	10 x 20	0.14	Ccp, Rt
OWL-13c	Bas	2	X						5					2	1	3	4		X			X		X	10 x 15	0.14	
OWL-20a	Nod	99	X						X	6	3	4	7	2	1				X			X		X	10 x 10	-	-
OWL-20d	Nod	99	X						X	6	3	4	2	1					X			X		X	10 x 10	-	-

ores, such as, solid solution of As in pyrite. However, the present petrographic studies have clearly identified arsenopyrite as the major mineralogical site for arsenic.

With the exception of lath-shaped euhedra of arsenopyrite, all inclusions in gold-bearing pyrite are anhedral. Gold grains are usually found as isolated blebs in pyrite but occasionally they may be found adjacent to chalcopyrite inclusions or at grain boundaries between arsenopyrite and pyrite. Gold was not observed as inclusions in arsenopyrite. Altaite (PbTe), which is common in gold-bearing pyrite nodules, was not observed in pyrite associated with basalt.

Quartzose breccia with a chalcedony-goethite matrix was devoid of gold. Goethite occurs as botryoidal masses of globular grains that average between 0.05 and 0.1mm in diameter (Plate 5g). These veins cross cut, and therefore appear to postdate, massive gold-bearing quartz veins.

Pyrite euhedra at Owl Creek are commonly cataclastically deformed. Cataclasis and pressure solution have been shown to be major mechanisms of pyrite deformation in low-grade metamorphic environments (McClay and Ellis, 1984; Cox et al., 1981; Vokes, 1969)). Fractures in pyrite are usually filled with quartz or, in the case of pyrite from the quartzose breccia, black iron-rich chlorite. Fractures in pyrite are less commonly filled with pyrrhotite and gold (Plate 5b). Mineralogically, recrystallized pyrite nodules are unique in that they contain gold in association with altaite (Plate 5f). Altaite grains are small (5 to 20 μm) anhedral blebs found as inclusions in pyrite and pyrrhotite.

Altaite (PbTe) is only found associated with gold in

recrystallized pyrite nodules (Table VII). Altaite was not observed in gold-bearing euhedral pyrite in basalt. In addition, tellurium levels were found to be very low in basalt-hosted pyrite (cf. Chapter V). This suggests that there may be no relationship between gold in basalt and gold in recrystallized pyrite nodules. Given the presence of tellurides in ore from the nearby Kidd Creek massive sulphide deposit (D.C. Harris, pers. comm.), it is possible that gold-altaite associations in nodules are diagenetic and unrelated to the fluids responsible for precipitating gold in quartz veins and basalt at Owl Creek.

Modes of Gold Occurrence

Ore textures and associated minerals observed in thin section are summarized in Table VII. Gold was found as inclusions or closely associated with pyrite, in the following forms, in order of decreasing abundance (Plate 5a, b, c, d, e, f):

- i) Anhedral blebs in euhedral pyrite;
- ii) Fracture fillings, commonly with pyrrhotite, in cataclastically deformed pyrite euhedra;
- iii) Free gold in quartz veinlets and more rarely in the alteration assemblage of metavolcanic and metasedimentary rocks. Free gold is also present in the chlorite matrix of the quartzose breccia;
- iv) Plated on pyrite euhedra;
- v) At the boundaries of annealed pyrite grains;
- vi) In recrystallized pyrite nodules.

Gold-bearing pyrite is dominantly euhedral and only rarely subhedral. Most auriferous pyrite grains are between 0.5 and 1.0mm in size; grains up to 4mm have been recorded. Inclusions in auriferous

PLATE 5: Microphotographs of gold with associated sulphides and oxides in polished section.

Plate 5a: Anhedral bleb of gold and pyrrhotite and euhedral arsenopyrite in euhedral pyrite hosted by basalt. Scale bar = 0.7mm.

Plate 5b: Gold and pyrrhotite filling a fracture in euhedral pyrite cube. Scale bar = 0.7mm.

Plate 5c: Free gold and pyrrhotite in quartz vein as well as inclusion in pyrite. Scale bar = 0.35mm.

Plate 5d: Gold plated onto the surface of a fractured pyrite cube. Gold is also seen here free in quartz. Scale bar = 0.7mm

Plate 5e: Gold at the boundaries of annealed pyrite grains. Note sieve texture of pyrite. Scale bar = 0.7mm.

Plate 5f: Gold, pyrrhotite, chalcopyrite and altaite inclusions in recrystallized pyrite euhedra from recrystallized pyrite nodule. Scale bar = 0.35mm

Plate 5g: Goethite (light grey) from quartzose breccia vein in reflected light. The dark grey mineral is chalcedony. Scale bar = 1.25mm.

Plate 5h: Sieve texture in gold-bearing pyrite euhedra from recrystallized nodule. Scale bar = 0.7mm.

Plate 5

pyrite give it a sieve texture (Plate 5h). This sieve texture is generally restricted to later gold-bearing and gold-associated pyrite. In a preliminary study of the nearby Hoyle Pond gold deposit, Downes et al. (1984) defined snowflake pyrite (type vii) as fine-grained pyrite in the form of 1 to 5mm 'snowflake-like blotches' occurring along finely dilated slaty cleavage traces and speculated that it was the most likely host of gold both at Hoyle Pond and Owl Creek. The results of this study indicate that euhedral pyrite (type iv) and not snowflake pyrite carries the bulk of gold at Owl Creek, the latter being relatively rare.

Gold grains have an average size of 20um and may range up to a maximum of 100um. It should be kept in mind that the quantity of visible gold observed in polished section is not necessarily proportional to ore grade. Pyrite assaying up to 1 oz/ton may be so fine that it cannot be seen microscopically (Hausen, 1981). With the exception of arsenopyrite and gold, auriferous pyrite-hosted inclusions average between 30 and 75um in size. Arsenopyrite grains are much larger and average 0.1 by 0.25mm in size and, unlike other inclusions, found only partially enclosed by pyrite. Gold to silver ratios of twelve selected gold-bearing pyrites range from 3.3 to 9.4. These data are summarized in Appendix III.

CHAPTER V

GEOCHEMISTRY

5.1 General Statement

Sixty-six samples were collected for chemical analysis from the open pit (Figure 3 to 6) as well as 23 samples from diamond drill core with the following objectives in mind:

- 1) To characterize the major and minor element composition of rocks from the pit.
- 2) To outline the trace element geochemistry of the carbonaceous shale. Special emphasis was placed on determining the possible relationship of carbon content of these rocks to gold tenor.
- 3) To determine if different pyrite types have a unique chemical composition that may allow distinction of syngenetic, diagenetic and epigenetic pyrite and relate these to gold assays.

Closely spaced samples were collected from the four mapped bench faces at Owl Creek for major and trace element analyses. In addition, trace element data from selected pyrite separates were also obtained. Data obtained from Owl Creek rocks are presented in Appendix IV. Precision of the data and the analytical techniques used are also summarized in Appendix IV. Correlation coefficients for major and trace elements with respect to gold are presented in Table VIII.

5.2 Whole Rock Geochemistry

Basalt

The majority of basalt samples were classified as high magnesium tholeiite (Figure 12) as defined by Jensen (1976). Most samples plot close to the boundary line of the calc-alkalic basalt field and three samples fall within it. There is no apparent correlation between

Table VIII. Correlation coefficients for all elements with respect to gold.

	All Rock Types	Basalt
	Au	Au
Si	+ 0.01	+ 0.05
Ti	0.00	0.00
Al	+ 0.01	- 0.14
Fe	+ 0.02	0.00
Mn	- 0.01	+ 0.20
Mg	- 0.01	0.00
Ca	- 0.02	0.00
Na	0.00	+ 0.15
K	- 0.04	- 0.01
C (org)	+ 0.01	+ 0.04
CO ₂	+ 0.03	+ 0.02
P	- 0.02	- 0.02
S	+ 0.01	+ 0.05
Ba	0.00	+ 0.05
Ag	+ 0.07	+ 0.15
Be	+ 0.04	+ 0.04
Co	0.00	+ 0.05
Cr	0.00	0.00
Cu	0.00	0.00
La	- 0.06	0.00
Ni	- 0.01	+ 0.22
Pb	- 0.01	+ 0.25
V	+ 0.01	0.00
Yb	+ 0.04	- 0.10
Zn	- 0.01	- 0.03
B	+ 0.01	- 0.03
Mo	- 0.02	- 0.10
W	+ 0.18	+ 0.18
As	+ 0.22	+ 0.94
Sb	0.00	+ 0.14

Figure 12. Jensen cation plot of basalt samples taken at Owl Creek.

basaltic rocks and gold concentration. The high degree of pervasive alteration prevented classification of these rocks by such schemes as those defined by Streckeisen (1979) and Cox et al. (1979).

Carbon Associated with Gold Mineralization

Sedimentary Rocks

C-isotope data obtained from carbonaceous matter in black shale are summarized in Appendix V. These data along with those obtained by Strauss (1986) and Wilson and Rucklidge (1986) are all strongly negative ranging from -27 to -33.4 per mil. These signatures fall within the range expected for carbon produced by the metamorphism of carbonaceous material of organic origin (Faure, 1986; Schoell and Wellmer, 1981).

Preliminary $\delta^{13}\text{C}$ data also suggests that a small amount of carbon present in carbonate minerals associated with quartz veins is derived from carbonaceous shale. Calcite and ankerite samples from quartz veins have an average C-isotope signature of -7.86 per mil; however, pure hydrothermal carbon has a signature of between -2 and -6 per mil. This suggests minor contribution of carbon from shale to quartz-carbonate veins.

High gold assays from the sedimentary rocks are rare. However, samples from both carbon-rich shale (> 1% carbon) and mudstone contain as much as 895 and 848 ppb respectively. The results of this study and that of Downes et al. (1984) suggest that anomalous gold values in carbonaceous shale are restricted to samples containing 'snowflake' pyrite; however, it should be noted that based on extensive mapping this type of pyrite is much more rare at Owl Creek. Mudstone with low carbon content (< 1% carbon) and with disseminated

fine-grained euhedral pyrite only may also have high gold values (848 ppb). Sediments with the highest gold values are within 15m of the shale-basalt contact.

) These observations indicate that high carbon contents in sediments are not necessarily indicative of high Au contents. A plot of gold versus carbon illustrates that there is no significant linear correlation between the two elements (Figure 13).

Gold values on the order of 100 ppb in Owl Creek shales are anomalous when compared to the background value for shale of 14.7 ppb (Korobeynikov, 1986). Gold values in shale at Owl Creek are of the same order of magnitude as other Archean interflow sedimentary rocks associated with gold reported by Bavinton and Keays (1978) in Kambalda, Australia and Springer (1985) in the Abitibi greenstone belt. In the Archean gold deposits discussed by these authors, interflow sedimentary rocks rarely carry ore grades and tonnages. This leads to the conclusion that the degree of gold enrichment in the carbonaceous interflow shales must be limited by some geochemical factor.

In a structurally controlled gold deposit such as the Owl Creek deposit any one of the following factors may influence gold distribution: i) source of the gold-bearing fluid, ii) migration path of the fluid, and iii) fluid chemistry as it encounters carbon-rich shale or some other suitable reductant. Although all of these factors probably play a role in limiting gold concentration in sediments, fluid-wall rock interactions are the most likely control. A possible explanation for this limiting gold concentration in shales is presented below.

Figure 13. Plot of carbon versus gold. Solid squares are basalt, open square is tuff, solid circles are carbonaceous shale, open circles are mudstone, solid triangles are massive sulphide, open triangles are arkosic wacke, solid diamond is quartzose breccia, and crosses are quartz vein material.

It has been shown by Volkov and Fomina (1974) that the adsorption capacity and reducing environment associated with carbon in sedimentary rocks can play a major role in metal accumulation. At Owl Creek, gold-bearing fluids probably circulated along the dilated slaty cleavage (S_2) of carbonaceous shale. As fluid encounters a reductant such as carbonaceous matter or pyrite, gold and other reducible elements may be precipitated onto these surfaces and, in the case of Owl Creek and nearby Hoyle Pond, generate snowflake pyrite. Given that there is a limited reactive surface area available on these S_2 planes onto which minerals may be precipitated once potential precipitation sites are taken up, auriferous pyrite will no longer be deposited in the shale. Therefore, the amount of reducing agents such as carbon and pyrite present may limit gold concentration. The low permeability of shale perpendicular to compositional layering would probably discourage metal deposition beyond the fluid-rock contact. Due to low permeability of shale and a limited number of carbon-rich surfaces for nucleation of auriferous pyrite, gold concentration in these rocks rarely exceeds 1 ppm.

In summary, carbonaceous sedimentary rocks being mechanically weak, are highly susceptible to fracturing; (cf. Springer (1985) and Brisson (1986)). The resulting increase in permeability due to faulting and reducing conditions provided by carbon, resulted in both a favourable conduit for fluid circulation as well as good reducing environment for precipitation of metals, respectively. However, from a mining standpoint the implications of this interpretation are somewhat academic given the paucity of snowflake pyrite at Owl Creek.

Basalt

Carbonization imparts a grey colour to basalt as described in Chapter IV. The results of this study (Table VIII) and that of Elliott (1984) indicate that the carbon content of basalt rarely exceeds 1.0%. These values are up to one order of magnitude smaller than those found in Owl Creek shale, although gold values are much higher. For example, OWL-10 contains only 1.25% C but carries 15 ppm Au. In addition, the sample with the highest gold assay (OC-86-54W; 21 ppm) contains no detectable carbon. Data from basalt (Figure 13) reveals a correlation between gold and carbon of 0.04.

For this reason it seems unlikely that the fluid which transported carbon is that which carried gold. The lack of relationship between carbon and carbonate discussed in the last chapter strongly suggests that i) carbon was transported by a different fluid from that which transported gold or ii) if carbon was transported by the same fluid it precipitated during a different stage in fluid evolution than when gold was precipitated.

Although carbonaceous matter is present in auriferous pyrite in basalt, it is not necessarily an indication of anomalous gold values. Grey carbonized basalt appears to be more indicative of zones of intense fracturing than ore grade gold concentrations. This conclusion is in agreement with the findings of Brisbin (1986) who suggested that grey zones should not be used solely as a guide for gold exploration in the area.

These data indicate that carbonaceous matter plays no geochemical role in concentrating gold in basalt at Owl Creek, and contrasts with the findings of Downes et al. (1984) in their preliminary study of the

nearby Hoyle Pond gold mine. Downes et al. (1984) speculated that the source of carbon in basalt is the nearby interflow carbonaceous shale. Although this appears to be a plausible interpretation, $\delta^{13}\text{C}$ data would be necessary to evaluate such a hypothesis.

Carbonate Alteration

Basalt is the most intensely carbonatized rock at Owl Creek (10 to 17% CO_2) resulting in the pervasive alteration observed in thin section (cf. Chapter IV). High CO_2 values are not necessarily an indication of high gold concentration; however, all basalt with greater than 1 ppm gold have at least 10% CO_2 . These relationships are illustrated in Figure 14, which indicates a very weak positive correlation (0.02) between Au and CO_2 concentrations. Strongly carbonatized basalt is massive or strongly sheared; however, samples with high gold values (> 1 ppm) are either sheared or within 2m of a discrete high strain zone (cf. Chapter III).

Although shale and mudstone display wide ranges of CO_2 values to a maximum of 12% CO_2 , only rarely do they contain greater than 100 ppb gold. Petrographic study revealed that carbonate minerals in these rocks occur mainly as veinlets and are not primary.

Overall, the plot of CO_2 versus Au (Figure 14) reveals that weak to zero correlations exist between CO_2 and gold in the various rock types. Correlation coefficients are presented in Table VIII for gold and other elements.

In summary, data suggest that although ore grade rocks in the main ore zone (basalt) are strongly carbonatized, rocks with high carbonate content are not necessarily of ore grade. In basalt, only samples collected near a discrete high strain zone have greater than 1

Figure 14. Plot of carbon dioxide versus gold. Solid squares are basalt, open square is tuff, solid circles are carbonaceous shale, open circles are mudstone, solid triangles are massive sulphide, open triangles are arkosic wacke, solid diamond is quartzose breccia, and crosses are quartz vein material.

ppm Au, the highest values coming from samples closest to the basalt-shale contact (OC-86-54W).

Carbonaceous shales containing greater than 2% CO₂ are rare. There are three possible explanations for this.

- 1) Shearing of basalt and shale occurred at different times such that shale was deformed after circulation of CO₂-rich fluids.
- 2) The path of fluid circulation was such that shale was exposed to only limited quantities of this fluid.
- 3) The difference in mineralogy between basalt and shale is such that relatively fewer calcium-bearing minerals were available in shale for reaction with a CO₂-rich fluid to produce significant quantities of carbonate minerals.

Although the first two options are possible there is no structural or mineralogical evidence to support either hypothesis. Certainly, the presence of snowflake pyrite and gold-bearing nodules suggests that indeed some fluids did circulate through shale.

Low CO₂ values in carbonaceous sediments are most likely a function of mineralogy. Being dominated by micas, these rocks have relatively little calcium available to react with a CO₂ charged fluid compared to basalt. As a result, CO₂ values in shale are lower than in basalt.

Chlorite

The only strong association of gold and chlorite is in a quartzose breccia with an auriferous pyrite-chlorite matrix. A sample of this rock contains approximately 14 ppm gold; no appreciable amounts of C or CO₂ are present. This suggests that the fluid from which this later stage gold-bearing pyrite precipitated had a

different chemical composition from that which produced the bulk of the ore in altered basalt and quartz veins.

5.3 Trace Element Geochemistry

Of the eighteen trace elements analyzed in this study only As and W show a positive correlation with gold (Figure 15 & 16).

Arsenic

Arsenic concentrations in these rocks are less than 100 ppm. Background arsenic for basalt in the Timmins area is estimated by Fyon and Crocket (1982) to be 70 ppm. The correlation coefficient of gold and arsenic as a whole is weak to moderately positive (0.22); however, if the ore zone rocks are isolated (mainly the basalts) a much higher, positive correlation is seen ($r=0.94$). This is explained by an abundance of arsenopyrite in these rocks (cf. Table VII).

It was previously stated that auriferous pyrite fell into 2 groups: those associated with arsenopyrite and those associated predominantly with copper minerals. However, only the former association is statistically significant. The data show that where gold concentration is greater than 100 ppb, arsenopyrite is a quantitatively more significant associate of gold than copper-bearing minerals, such as chalcopyrite.

Tungsten

There is a positive correlation between gold and tungsten in all basalt from Owl Creek (Table VIII). The most likely site for W is scheelite. However, none was observed in hand sample with the aid of a ultraviolet lamp or in thin section. Possibly, tungsten is held in carbonate minerals.

Figure 15. Plot of arsenic versus gold. Solid squares are basalt, open square is tuff, solid circles are carbonaceous shale, open circles are mudstone, solid triangles are massive sulphide, open triangles are arkosic wacke, solid diamond is quartzose breccia and crosses are quartz vein material.

Figure 16. Plot of tungsten versus gold. Solid squares are basalt, open square is tuff, solid circles are carbonaceous shale, open circles are mudstone, solid triangles are massive sulphide, open triangles are arkosic wacke, solid diamond is quartzose breccia and crosses are quartz vein material.

Lead, Nickel and Manganese

Table VIII indicates a moderate correlation between gold and Pb, Ni, and Mn in basalt. These associations could indicate that the komatiite to the north of the deposit or the basalt itself is the source of some of the gold. However, the values measured at Owl Creek are of the same order of magnitude as background values for mafic volcanics in the Dome mine in Timmins (Fyfe and Kerrich, 1984). This suggests that if gold was mobilized from komatiite or concentrated within what is now the main ore zone (basalt), large scale concentration of Pb, Ni, and Mn did not accompany gold concentration.

5.4 Gold Concentration in Pyrite Nodules

Three concentrically banded pyrite nodules were sampled from rim to core, assayed for gold and the sulphur isotope signature of each sample was determined. Data are summarized in Table IX and Figure 20 of chapter VI. The implications of S-isotope data will be discussed in chapter VI.

The limited data indicate that the cores of concentrically banded pyrite nodules are enriched in gold relative to the rims. In addition, the massive sulphide (pyrite) lens, which is made-up of concentrically banded pyrite nodules, was found to concentrate gold on the order of 2 to 2.5 ppm (Elliott, 1984). These results are somewhat surprising as these nodules were found to be devoid of gold or other inclusions often associated with gold when examined in polished section (Table VII). There are three possible explanations for this variation in gold concentration.

- 1) Gold was precipitated evenly throughout the nodule as a result of interaction with a gold-bearing fluid. The rims were later stripped of gold by a different fluid. The degree of gold removal (from rim to core) would be a function of fluid chemistry and length of time nodules were exposed to the fluid.
- 2) The original diagenetic nodule was exposed to a gold-rich fluid which impregnated the nodules in gold. The rim was a later, post-ore fluid, overgrowth of pyrite.
- 3) Gold is diagenetic (cf. Chapter IV) and precipitated at the same time as the core of the nodule and is unrelated to the hydrothermal event which is responsible for producing gold-bearing quartz veins and auriferous pyrite in basalt. Massive and nodular pyrite was produced

by a gold-rich submarine exhalative fluid similar to those thought to be responsible for producing massive sulphide deposits.

There is no mineralogical evidence to suggest that the rims of these nodules have been altered with respect to the core and stripped of gold. This makes the first explanation unlikely.

Although the second option is possible it would not explain why gold is associated with tellurium (altaite) in nodules and it is virtually absent from euhedra in basalt.

Therefore, it seems most likely that gold was precipitated at the same time as the pyrite nodules from a submarine exhalative fluid. If gold in pyrite nodules was produced by a syngenetic fluid, different from that responsible for generating gold-bearing quartz veins and auriferous pyrite in basalt, it would explain why gold is associated with altaite in nodules and not in euhedral pyrite in basalt. This model would account for the concentration of gold in the core of nodules should the rim be produced by a later gold-poor fluid or metamorphic overgrowth of pyrite.

This hypothesis is supported by the recent studies of Hannington et al. (1986) who found similar gold concentrations (1.5 to 6.7 ppm) in twenty-two samples of Axial Seamount and southern Explorer Ridge polymetallic sulphides. Hannington et al. (1986) also found that these gold-rich sulphides are associated with up to 0.66 wt. % Pb and >1000 ppm As, both of which are concentrated in Owl Creek pyrite nodules. As is the case with concentrically banded nodules at Owl Creek, gold was not observed in polished section under reflected light despite these high gold concentrations.

The fact that gold was only observed in polished thin sections of recrystallized nodules suggests that recrystallization of

concentrically banded pyrite nodules concentrated gold and altaite. If this interpretation is correct it would explain why both types of nodules have high gold concentrations yet gold is only observed under reflected light in recrystallized pyrite nodules.

CHAPTER VI

SULPHUR ISOTOPE GEOCHEMISTRY

6.1 General Statement

There have been few extensive sulphur isotope studies of Archean gold deposits. This is somewhat surprising given the potential $\delta^{34}\text{S}$ data have to provide valuable information about the nature of mineralizing fluids and the environment in which they precipitate. This is especially true of gold deposits such as Owl Creek, where the majority of the gold mined is found as inclusions in pyrite or associated with wide spread pyritization.

Sulphur isotope studies of pyrite associated with gold in Canadian deposits included those by Pattison et al. (1986), in the Casa-Berardi area; Strauss (1986), in selected deposits in the Abitibi and Wabigoon belts; Cameron and Hattori (1985), at Hemlo; Crocket and Lavigne (1984), at the Dickenson mine; Elliott (1984), at Owl Creek; and Wanless et al. (1960), Yellowknife district. With the exception of the Hemlo study, the above researchers found that pyrite associated with gold has a slightly positive S-isotope signature, ranging from +1.4 to 8 per mil. The only exception to this trend is found at Hemlo where Cameron and Hattori (1985) documented pyrite associated with gold with S-isotope signatures that range from 0 per mil (barite-hosted) to -17 per mil (schist-hosted). In addition, they discovered that gold concentration increased with the ^{34}S concentration of pyrite.

The application of $\delta^{34}\text{S}$ data towards determining the source of sulphur in ore deposits has generally been disappointing (Faure, 1986). One reason for this is that most ore deposits have a complex

geologic history and sulphides are often difficult to classify as syngenetic or epigenetic. Even if such a classification of sulphides was made, the $\delta^{34}\text{S}$ signature of the mineral can only be used to determine that value of the sulphur isotope signature of the source when temperature, oxygen fugacity, and pH of the ore-forming fluid are known (Ohmoto, 1972).

6.2 Objectives

The objective of this aspect of the thesis was to investigate how the $\delta^{34}\text{S}$ signature of pyrite varies with respect to : i) type of pyrite, ii) gold content, iii) host rock and iv) structural setting, in order to obtain a more specific definition of the conditions under which gold was precipitated.

6.3 Analytical Procedures

Pyrite was separated from whole rock powders with the aid of a mechanical panning device ('superpan') at the Geological Survey of Canada. A suite of rocks was selected for sulphur isotope studies so that as many pyrite types and host rocks as possible would be represented.

A total of 28 analyses were made on pyrite concentrates at the OGGS/GSC stable isotope facility at the University of Ottawa. The sulphides were converted to SO_2 by reaction (oxidation) with CuO at 1000°C and measured on a VG-Isogas Micromass 602E spectrometer.

The S-isotopic data for pyrite is presented in Table IX. All data are expressed relative to Canyon Diablo Troilite whose $^{32}\text{S}/^{34}\text{S}$ ratio is 22.22 per mil.

6.4 Results

The data are presented graphically as a function of rock and pyrite type, gold concentration and total sulphur in Figures 17, 18, 19 respectively. Data are summarized in Table IX. Data obtained by Elliott (1984) are presented in Appendix VI and have been incorporated into this aspect of the thesis.

Figure 17. Sulphur isotope signatures of pyrite in each major rock type mapped at Owl Creek. Solid squares are euhedra, open squares are banded, open circles are nodular and vermicular and open star is snowflake.

Figure 18. Plot of sulphur isotope signature versus gold concentration. Solid squares are basalt, solid circles are carbonaceous shale, open circles are mudstone, solid triangles are massive sulphide, open triangles are arkosic wacke, solid diamond is quartzose breccia.

Figure 19. Plot of sulphur isotope signature of pyrite versus weight percent sulphur. Solid squares are basalt, solid circles are carbonaceous shale, open circles are mudstone, solid triangles are massive sulphide, open triangles are arkosic wacke, and solid diamond is quartzose breccia.

Table IX. Sulphur isotope and gold assay data from pyrite concentrates, Owl Creek gold mine. (SF), snowflake pyrite; (E), euhedra; (MS), massive sulphide; (B), banded pyrite; (N), nodule.

Sample	Host Rock	Pyrite Type	$\delta^{34}\text{S}$ (per mil)	Au (ppm)*
OC-86-05	Shale	SF	-0.6	1.3
OC-86-10	Basalt	E	2.7	0.5
OC-86-11	Basalt	E	2.6	3.0
OC-86-14	Shale	MS	4.8	2.0
OC-86-17	Mudstone	E	2.7	9.3
OC-86-18	Mudstone	B	1.0	<0.1
OC-86-25	Mudstone	B	0.0	0.2
OC-86-26	Mudstone	B	-1.5	<0.1
OC-86-27	Carbonate vein	E	-0.9	<0.1
OC-86-32	Shale	E	1.2	<0.1
OC-86-34	Mudstone	E	-1.0	<0.1
OC-86-40	Basalt	E	2.5	4.7
OC-86-41	Mudstone	B	-0.5	0.2
OC-86-45	Mudstone	E	2.5	0.5
OC-86-48	Basalt	E	2.9	0.4
OC-86-50	Arkosic Wacke	E	1.4	<0.1
OC-86-54W	Basalt	E	2.8	370.2
OC-86-55	Mudstone	E	3.0	7.1
OC-86-57	Shale	E	3.2	0.4
OC-86-58	Arkosic Wacke	E	0.1	<0.1
OC-86-61	Shale	E	-0.1	0.2
OC-86-63	Mudstone	E	1.0	0.2
OC-86-66	Mudstone	E	-1.1	<0.1
OC-86-N04	Quartzose breccia	E	3.4	347.5
OC-86-HWY	Basalt	E	5.0	1.8
OC-80-12-4	Mudstone	E	3.0	130.6
OC-80-13	Basalt	E	5.1	4.4
OC-80-17	Peridotitic komatiite	E	2.1	11.1
OWL 20 K1	Shale	N (Core)	-2.0	63.2
OWL 20 K2	Shale	N (Rim)	-3.0	0.8
OWL 20 F1	Shale	N (Core)	1.8	-
OWL 20 F2	Shale	N (Rim)	-2.4	4.5
OWL 20 L1	Shale	N (Core)	-5.0	82.7
OWL 20 L2	Shale	N (Centre)	-2.0	-
OWL 20 L3	Shale	N (Rim)	-4.5	24.6

* Obtained from pyrite concentrates.

6.5 Discussion of $\delta^{34}\text{S}$ Data

The following observations were made based on examination of sulphur isotope data from the Owl Creek gold mine:

- 1) Auriferous pyrite from rocks grading > 1 ppm gold have a distinctively narrow range of $\delta^{34}\text{S}$ values (+1.8 per mil to +3.5 per mil, mean, +2.4 per mil, standard deviation, 0.5; Figure 17 & 18); these rocks are predominantly basalt. Pyrite with low gold values may also have a similar signature. This suggests that there is no correlation between S-isotope signature and gold concentration.
- 2) The widest range of $\delta^{34}\text{S}$ values is displayed by pyrite hosted by shale and mudstone independent of pyrite type (Figure 17).
- 3) Banded pyrite has a slightly negative S-isotope signature (mean, -0.4 per mil).
- 4) Shale-hosted massive sulphide lenticle containing > 2 ppm Au has an average $\delta^{34}\text{S}$ signature of +3.4 per mil.
- 5) There appears to be no strong correlation between S-isotope signature and degree of deformation (i.e., individual zones of high strain as defined in Chapter III; Figures 3 to 6).
- 6) The range and mean $\delta^{34}\text{S}$ values of the limited number of arkosic wacke-hosted pyrite are very similar to those of basalt (Figure 17).

Source of Sulphur

In the immediate area of the mine possible source rocks for sulphur include carbonaceous shale, mudstone, arkosic wacke and komatiite. The probability of each being the source of sulphur in the main ore zone (basalt) based on the S-isotope data is discussed below. The origin of sulphur in the metasediments is also discussed.

Basalt (Main Ore Zone Pyrite)

Both shale and mudstone have wide ranging $\delta^{34}\text{S}$ values. Although the spread is greatest in the nodules, disseminated euhedral pyrite in shale also displays a wide range of values (Figure 17).

Given the relatively wide spread of sulphur isotope signatures of pyrite in both carbonaceous shale and mudstone, it is unlikely that fractionation of S in this pyrite would yield auriferous pyrite with such a narrow and positive range of values such those in basalt (main ore zone). If these rocks were the source of sulphur, fractionation would be expected to produce pyrite with $\delta^{34}\text{S}$ values similar to those of the sediment-hosted pyrite. Possible processes which may explain the sulphur signature of ore zone pyrite will be addressed later.

If any one type of sediment-hosted pyrite is likely to be the source of sulphur based on the $\delta^{34}\text{S}$ data it is the banded pyrite. Its range is the narrowest of all the sedimentary hosted pyrite (-1.1 to +0.1 per mil). However, it seems unlikely that this 60cm wide unit of banded pyrite contains enough sulphur to result in the formation of this ore deposit. The significance of S-isotope signatures of this type of pyrite with respect to their origin will be discussed later in the text.

Arkosic wacke is an unlikely source for sulphur for two reasons; 1) it generally contains < 1% pyrite and 2) it is the least hydrothermally altered rock of those in the pit.

Near Owl Creek, thick accumulations of komatiite are found to the north of the ore zone. Keays (1984) stated that Archean komatiitic magma has a greater capacity to dissolve sulphur and gold than do lower temperature basaltic magmas, thus making them good potential sources for these two elements. Komatiite from east of the pit (OC-80-17) has a $\delta^{34}\text{S}$ signature of +2.1 (Table IX). With this value, these rocks could have been the source of sulphur; however, a much larger suite of samples would be required to back-up such an interpretation. In addition, carbonatization of these rocks would not only mobilize sulphur and possibly gold but also abundant silica to produce quartz veins (Pyke, 1982).

Another possible source for ore zone sulphur is pyrite from the carbonaceous argillaceous rocks as defined by Walker et al. (1970) at the Kidd Creek Mine. Sulphur isotopic values of pyrite from these rocks range from -0.6 to +1.2 per mil; mean, +0.3 per mil, standard deviation, 0.5 (Elliott, 1984). The range in these rocks is much smaller than in sediments from the Owl Creek mine. Although the $\delta^{34}\text{S}$ values would make these rocks a plausible sulphur source their present distance from the mine (20 to 25km) and the uncertain extent of fluid transportation makes them an unlikely source.

Another possible sulphur source is a felsic intrusion. A close spatial association between felsic intrusions and gold has been long recognized in the Timmins area (Cherry, 1983) and such a body could provide enough SiO_2 for the quartz veins associated with pyritization at Owl Creek. However, there is no known major intrusion in the

immediate area of the mine. Recently, a quartz feldspar porphyry was identified in drill core north of the nearby Bell Creek gold mine (K. Hattori, pers. comm.); however, its size and, therefore, likelihood as a source for sulphur and possibly gold is unclear. It is possible that there is another such intrusion near the deposit that is as yet unknown. However, any interpretation based on such an assumption is be highly speculative. The closest major felsic igneous intrusion known in the area is 25 to 30 kilometres north of the ore deposit.

Sedimentary Rocks

Banded Pyrite

It was stated in an earlier chapter that although the origin of banded pyrite was uncertain, Fe/S ratios (cf. Figure 22, Appendix II) along with field evidence suggested that it is synsedimentary. A plot of Fe versus S suggested that the pyrite was syngenetic. Sulphur isotope data appear to support such an interpretation.

Banded pyrite yielded $\delta^{34}\text{S}$ values between -1.4 and +1.0 per mil. (Figure 17). This limited range, along with the banded nature of these rocks and the low carbon content (< 1%) favour a syngenetic, rather than a diagenetic origin for this pyrite. If the pyrite was diagenetic, sulphur isotope fractionation of sea-water sulphate by sulphate reducing bacteria might be expected to have produced a wider range of $\delta^{34}\text{S}$ values than is observed (Cameron, 1982). Possibly, banded pyrite is related to a volcanic centre such as that which produced the Kidd Creek massive sulphide deposit.

The S-isotope signature of this type of pyrite is on average lighter than that of auriferous pyrite found in basalt; however, this does not preclude a hydrothermal origin for banded pyrite. Based on

S-isotope data, banded pyrite could have been produced by a hydrothermal fluid that derived its sulphur from an isotopically lighter source than that from which pyrite in basalt originated.

Graphitic banded iron formation containing pyrite and pyrrhotite reported by Crocket and Lavigne (1984) at the Dickenson Mine, Red Lake, Ontario, is very similar to that observed at Owl Creek. The average sulphur isotopic composition of pyrite (0 per mil), the relatively large range of values (10.5 per mil) and the presence of graphite (interpreted to be of organic origin) have lead Crocket and Lavigne (1984) to conclude that the sulphur was derived primarily by bacterial reduction of seawater sulphate. One possible problem with such an interpretation is that it is not generally agreed upon as to when sulphate-reducing bacteria became prevalent in Archean seawater. For example, Cameron (1982) concluded that sulphate-reducing bacteria only became important around 2.3 billion years ago, whereas Monster et al. (1979) believed that they became a factor between 3.2 and 2.8 billion years ago. Such an interpretation does not appear to be applicable to the banded pyrite accumulations at Owl Creek because of the small isotopic range and the lack of carbon in rocks which host this type of pyrite.

In conclusion, it can be stated that although S-isotope data appears to narrow down the possible genetic origins for banded pyrite found at Owl Creek they cannot be used to distinguish between a syngenetic and epigenetic origin.

Nodules

Of the five types of pyrite whose sulphur isotope composition were determined, the largest spread was found in vermiform and nodular

Figure 20. Sulphur isotope signature of three concentrically banded pyrite nodules (OWL-20F, K, L). Gold content is recorded beside symbol in ppm.

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pyrite. The $\delta^{34}\text{S}$ range is -2.7 to 4.8 per mil, including massive sulphide samples which are composed predominantly of nodular and vermiform pyrite. S-isotope values of the core and rim of three concentrically banded nodules were also obtained (Table IX). Although statistically insignificant, they also have a large spread in $\delta^{34}\text{S}$ values (+1.8 to -5.0 per mil). These data, along with the restricted occurrence of nodules in carbonaceous shale points to a diagenetic origin for this type of pyrite.

It was suggested in chapter V that the core of pyrite is diagenetic and the rim is a late overgrowth. The negative S-isotope signatures of the rims of three concentrically banded nodules (Table IX and Figure 20) suggests that pyrite which forms the rim does not have the same sulphur source as auriferous pyrite in basalt. The negative and relatively wide ranging values suggest that the most likely sulphur source is the shale itself. Possibly, pyrite in the shale was mobilized within the sedimentary rocks during metamorphism to form successive concentric bands around the diagenetic core. Shale and the less permeable mudstone are the only rocks at Owl Creek with negative S-isotope signatures.

Positive $\delta^{34}\text{S}$ Values from Au-bearing Pyrite

In order to make a definitive statement about the composition of the ore fluid and conditions under which gold at Owl Creek was precipitated much more data are required than have been presented here. Oxygen fugacity data and calculated temperatures based on the difference in S-isotope signatures of pyrite and pyrrhotite, for example, might help delineate such conditions. What follows is a discussion of possible mechanisms responsible for the positive S-isotope signature of auriferous pyrite at Owl Creek.

The slightly positive range of $\delta^{34}\text{S}$ values from gold-bearing pyrite at Owl Creek is consistent with $\delta^{34}\text{S}$ signatures of many other Archean gold deposits (Colvine et al., 1984). This positive signature is considered by some authors (Lambert et al., 1984) to be produced by fluids dominated by reduced sulphur species which concentrate ^{34}S as a result of desulphurization of source pyrite to pyrrhotite.

A similar argument was proposed by Goodz et al. (1986) to explain positive S-isotope values of sulphides in the Cobalt area. Goodz et al. (1986) stated that such a fluid could be derived by desulphurization of source pyrite to yield pyrrhotite and a ^{34}S -enriched fluid. This reaction could have generated a fluid that would have had an initial $\delta^{34}\text{S}$ value in excess of +5.0 per mil.

Although such a mechanism would explain the positive $\delta^{34}\text{S}$ value of auriferous pyrite and is obviously a plausible hypothesis for some sulphides, there is no indication that such a process operated at Owl Creek, given that there is no significant concentration of pyrrhotite present in any of the rocks near the deposit. Nevertheless, this does not preclude the possibility that such fractionation took place at

depth with some unknown sulphide occurrence.

Another possible explanation for positive $\delta^{34}\text{S}$ signatures of gold-bearing pyrite centres around the various sulphur species present in an ore fluid and their ability to concentrate the heavy sulphur isotope. Although fractionation of sulphur isotopes can take place at the sulphur source, the site of precipitation and anywhere in between, a probable source rock with a measured $\delta^{34}\text{S}$ signature was not identified by S-isotope analyses. For this reason the following discussion is based on the assumption that fluid responsible for transporting sulphur used to precipitate auriferous pyrite in basalt had a S-isotope signature of 0 per mil.

At temperatures below 500°C H_2S , HS^- , S^{2-} and SO_4^{2-} are important sulphur-bearing species in an ore fluid (Faure, 1986). The relative proportions of the first three species are controlled by the hydrogen ion activity, whereas the abundance of SO_4^{2-} is controlled by oxygen fugacity (Faure, 1986). Given that there is no barite although Ba up to 890 ppm is present (cf. Appendix IV) in these rocks, it can be concluded that SO_4^{2-} was present in unimportant quantities due to the low oxygen fugacity of the ore fluid. It is possible that the positive S-isotope signature of auriferous pyrite at Owl Creek is related to the degree to which HS^- and H_2S concentrate ^{34}S . Experimental studies by Fry *et al.* (1986) indicate that in an open system at $\text{pH} < 5$, H_2S is enriched in ^{34}S by 2.4 per mil relative to HS^- .

In the case of Owl Creek, if gold was transported by an acidic solution in an open system where H_2^{32}S is progressively removed, pyrite formed by the reaction of H_2^{34}S with iron-bearing carbonate minerals in basalt would be enriched in ^{34}S by up to 2.4 per mil. Although an acidic fluid for gold transport is in disagreement with

the studies of Seward (1984, 1973) it would account for the S-isotope signatures of auriferous pyrite at Owl Creek. In addition, studies by Hannington et al. (1986) have documented gold-rich submarine exhalative massive sulphides produced by acidic solutions (pH=5). The limited range of S-isotope signatures on pyrite associated with gold at Owl Creek may be a function of the limited ability of H_2S to concentrate ^{34}S (Faure, 1986).

This interpretation of S-isotope data as it relates to gold transportation has one major problem; if gold is transported by an acidic solution such as those responsible for producing massive sulphide deposits why is it that there is not a larger quantity of Cu, Pb and Zn sulphides at Owl Creek? The reason for this may be related to the migration path of the gold-bearing fluid, composition of the rocks through which the fluid travelled and the sequence of sulphide mineral precipitation with respect to pH.

Although not accepted by all, most models of hydrothermal systems responsible for producing massive sulphide deposits involve a convective cell of acidic fluid operating over long periods of time (Franklin et al., 1981). This model also assumes that base metals are leached from the rocks through which these fluids circulate. If, in the case of Owl Creek, an acidic gold-rich fluid moved directly up the shear zone taking a less circuitous route than fluids thought to be responsible for producing massive sulphide deposits and the rocks through which this fluid passed were poor in Cu, Pb and Zn then large quantities of base metals other than pyrite would not be expected. In addition, experimental studies by Finlow-Bates (1980) indicate that an acidic fluid (pH<5) with low metal concentrations below 350°C will

favour precipitation of iron sulphides such as pyrite over zinc or copper sulphides. This suggests that an acidic, gold-rich fluid would be capable of precipitating auriferous pyrite with a positive $\delta^{34}\text{S}$ signature without generating significant quantities of other base metals.

Nevertheless, it must be kept in mind that the source of the sulphur was not identified; therefore, equal consideration must be given to the presently accepted hypothesis of Seward (1984, 1973) that gold was transported by a fluid of near neutral pH. In this case the positive S-isotope signature may have been generated by the interaction between the ore fluid and an as yet unknown sulphur source which yielded a ^{34}S -enriched fluid as a result of the desulfurization of pyrite to form pyrrhotite as described by Goodz et al. (1986).

CHAPTER VII

SUMMARY AND CONCLUSIONS

7.1 Model for Gold Precipitation

Field and petrographic observations have delineated four phases of gold precipitation at Owl Creek. The following list outlines their relationship with respect to a relative sequence of geological events.

1. Volcanic and sedimentary rocks emplaced. Sedimentation was accompanied by synsedimentary banded pyrite and diagenetic nodular pyrite formation. Gold in the core of pyrite nodules is interpreted to be diagenetic and represents the first phase of gold precipitation.
2. Carbonatization of basalt. This is believed to strengthen the rock and allow brittle-ductile deformation (Colvine et al., 1984).
3. Regional deformation resulted in subvertical east-west trending stratigraphy and emplacement of basalt adjacent to carbonaceous shale.
4. Regional greenschist facies metamorphism. This event also mobilized carbon from shale into basalt and is unrelated to gold precipitation in basalt.
5. Brittle deformation of basalt caused by dip-slip movement resulted in the development of discrete high strain zones parallel to stratigraphy. High strain zones increased the permeability of basalt were conduits for gold-bearing fluids.
6. In the second phase of gold precipitation, acidic gold-bearing

fluids came in contact with intensely carbonatized basalt. This reaction caused an increase in pH of the fluid and resulted in gold precipitation. Iron carbonates react with $\delta^{34}\text{S}$ enriched H_2S to produce auriferous pyrite with a slightly heavy S-isotope signature.*

7. Dip-slip movement continued and en echelon extension fissures formed in basalt. Fissures were immediately filled with gold-bearing quartz and minor calcite. Subvertical quartz veins were formed by fluid flow up subvertical faults often incorporating angular fragments of auriferous pyrite-bearing basalt.

8. Continued dip-slip movement in areas of highest strain rotated en echelon extensional veins into a subhorizontal position. These quartz veins represent the third phase of gold precipitation.

9. Brittle deformation of gold-bearing subhorizontal quartz veins resulted in the development of quartzose breccias. The matrix of these breccias consists of either chlorite and auriferous pyrite or chalcedony and goethite. This represents the last known phase of gold precipitation.

7.2 Conclusions

Based on the results of this study the following conclusions can be drawn about the Owl Creek gold deposit.

- 1) Owl Creek is a structurally controlled gold deposit hosted by tholeiitic basalt and carbonaceous shale.
- 2) Dip-slip movement resulted in the development of numerous discrete high strain zones and extension fissures in basalt which were filled with gold-bearing quartz. High strain zones acted as conduits for fluid flow and subsequent precipitation of auriferous pyrite in basalt.
- 3) Field and petrographic relationships delineate four phases of gold precipitation in order of occurrence: i) diagenetic precipitation of gold and altaite in pyrite nodules; ii) precipitation of auriferous pyrite associated with discrete high strain zones in basalt and to lesser extent shale; iii) formation of gold-bearing quartz veins which incorporate angular fragments ore grade basalt and shale carrying auriferous pyrite; iv) subvertical quartzose breccias which cut subhorizontal gold-bearing quartz veins and whose matrix consists of chlorite and gold-bearing pyrite.
- 4) Gold is found both as inclusions in pyrite and free in subhorizontal and subvertical quartz veins. Gold inclusions in pyrite are closely associated with arsenopyrite.
- 5) The alteration assemblage associated with gold in the main ore zone (basalt) is ankerite-dolomite-sericite-pyrite. In the quartzose breccia the assemblage is chlorite-sericite-pyrite.
- 6) Gold is associated with altaite only in recrystallized pyrite

nuclei in carbonaceous shale and is interpreted to be diagenetic.

7) Carbonization of basalt post-dates carbonatization and its introduction does not appear to be directly related to gold precipitation.

8) Gold-bearing pyrite has a narrow range of S-isotope ratios (+1.8 to +3.5 per mil).

9) There is no linear correlation between gold concentration and $\delta^{34}\text{S}$ signature of pyrite.

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APPENDIX I: Abbreviations and symbols used on bench maps.

Alteration	alt
Average	ave
Calcite	cal
Carbonatized	carb
Crenulation	cren
Decrease	dec
Disseminated	dissem
East	E
Euhedral	euh
Fault
Foliation	fol
Fragment	frag
Graphite	gr
Increase	inc
Massive Sulphide	MS
Moderate	mod
Nodule	nod
North	N
Parallel	
Percentage	%
Plunge	P _#
Quartz	qtz
Sample location	X
Sedimentary	sed
Sericite	ser
Shale	shl
South	S
Strong	str
Trend	T
Very fine-grained	vfg
Visible gold	VG
Volcanic	vol
West	W

Appendix II: Relationships Between C, S, Fe and Au

Studies by some authors suggest that the relationship between S, C and Fe is useful in distinguishing between syngenetic and diagenetic pyrite (Ohmoto et al., 1987; Berner, 1984; Raiswell and Berner, 1985). Field relationships were found to be inconclusive with respect to the origin of some sediment-hosted pyrite types, especially banded pyrite (cf. Chapter III). Plots of C vs. S and S vs. Fe (Figure 21 and 22) were made in an attempt to shed some light on this problem.

In Figure 21, the lack of correlation between C and S suggests that very little if any of the pyrite found in the sediments is diagenetic. Raiswell and Berner (1986) state that formation of diagenetic pyrite is initiated by bacterial reduction of sulphate to produce H_2S which may later react with detrital iron minerals to produce pyrite. Because bacteria are the principal factor limiting pyrite formation in this hypothesis a strong positive correlation between C and S would indicate diagenetic origin. As this is not the case it can be concluded that, with the exception of nodular pyrite, little if any pyrite at Owl Creek can be definitively identified as diagenetic pyrite.

Nodules were omitted from this aspect of the study because representative sulphur and carbon to Fe ratios were difficult to obtain. The fact that nodules are restricted to carbon-rich shale suggests that they are diagenetic.

In a plot of Fe vs. S (Figure 22) there are three clusters of samples; 1) Group A, which has a linear S/Fe relationship, low gold values (<100 ppb) and consists of pyrite types iii, iv, and vi. All samples of shale and the majority of mudstone samples fall into this

Figure 21. Plot of carbon versus sulphur. Solid squares are basalt, open square is tuff, solid circles are carbonaceous shale, open circles are mudstone, solid triangles are massive sulphide, open triangles are arkosic wacke, solid diamond is quartzose breccia and crosses are quartz vein material.

Figure 22. Clustering of rocks based on the Fe to S ratio. Solid squares are basalt, open square is tuff, solid circles are carbonaceous shale, open circles are mudstone, solid triangles are massive sulphide, open triangles are arkosic wacke, solid diamond is quartzose breccia and crosses are quartz vein material.

group; ii) Group B, which is characterized by intermediate S/Fe ratios (generally < 0.5) have anomalously high gold values (> 100 ppb), and consists namely of basalt but also mudstone, quartzose breccia, carbonatized tuff, volcanic and sedimentary rocks; iii) Group C, comprises both sedimentary and volcanic rocks, but with very low sulphur contents. Pyrite in group A is sediment-hosted only, whereas pyrite in groups B and C consists of samples from each major rock type.

GROUP A

Raiswell and Berner (1985) have stated that a good linear correlation between S and Fe in sedimentary rocks is indicative of syngenetic pyrite that formed under anoxic conditions. Provided that abundant H_2S is present, the only limiting factor for pyrite formation is the amount of reactive detrital iron present. Figure 18 indicates that all shale and about half the mudstone population fall into this group.

A diagenetic origin for banded pyrite is unlikely due to the poor correlation between iron and carbon. According to Raiswell and Berner (1985) if pyrite is diagenetic its production is controlled by the presence of carbonaceous matter and a good correlation should exist between carbon and iron, which does not (Figure 21).

Although field relationships were found to be inconclusive with respect to the origin of banded pyrite (cf. Chapter III), the geochemical method outlined by Raiswell and Berner (1985) supports a synsedimentary origin. Nevertheless, until further field or petrographic evidence is found it should be stated that the geochemistry of rocks in Group A is compatible with, but does not

prove that, banded pyrite is syngenetic.

In Group A, relatively high gold content (Figure 23) is independent of rock or pyrite type. The only thing that samples from Group A in Figure 23 have in common is that they are either from the zone of high strain or within 20m of it. This supports the statement made in an earlier chapter that geochemistry appears to play only a minor role in concentrating gold and that the increased permeability imparted on Owl Creek rocks as a result of intense shearing is the principal factor responsible for the presence of gold at Owl Creek.

GROUP B

In group B there is a linear relationship between S and Fe (Figure 22). Contouring for gold concentration (Figure 23) illustrates that, with the exception of veins, most samples grading greater than 100 ppb Au are found in this group. As is the case in Group A, samples with high gold concentrations are associated with zones of high strain independent of rock type.

Figure 22 also shows that iron is proportionally more dominant than sulphur in these rocks. Within the group itself, the ratio of Fe to S is higher in basalt than sedimentary rocks, which cluster in the top half of the population.

With respect to basalt samples, this relationship can be explained by the fact that most of the S is present in pyrite and mineral inclusions in pyrite (ie. pyrrhotite, arsenopyrite, etc.) whereas iron occurs in iron carbonates and chlorite as well as in pyrite. In the case of sedimentary rocks, fewer iron-bearing minerals, such as ankerite and chlorite, are present (cf. Chapter IV). In addition, even though auriferous pyrite is present, undoubtedly

Figure 23. Gold concentration of rocks in groups A and B of Figure 18. Solid circles are greater than 10 ppm gold, solid squares are 1 to 10 ppm gold and solid triangles are 0.1 to 1 ppm gold.

some syn-sedimentary pyrite with Fe to S ratios of close to 1 (as in Group A) is also hosted by these rocks. These factors combine to give these rocks slightly lower Fe to S ratios than basalt and higher Fe to S ratios than those of sediments in Group A.

It was shown in chapter V that anomalous gold values are associated with intense carbonatization (cf. Figure 14). With the exception of two rocks, all samples which lie in Group B are strongly carbonatized (Figure 24).

GROUP C

Rocks in group C, including all arkosic wackes, generally have less than 1% sulphur. Background values for sulphur in shale and basalt in the Timmins area are 1.06% (Cameron and Garrels, 1980) and 0.077 (Naldrett et al., 1978), respectively. These background values suggest that little, if any, sulphur has been added to these rocks. For this reason it is not surprising that gold assays of this group are all less than 100 ppb (Figure 23). The variable iron values are consistent with the presence of iron-bearing minerals such as ankerite and chlorite rather than pyrite.

The sedimentary rocks which fall into this group show the least amount of alteration (cf. Chapter IV) and are more than 20m away from the heterogeneous zone of high strain (cf. Chapter III, 3.3 Structural geology).

Intensely carbonatized rocks in this group (Figure 24) are basalt with both high and low gold concentrations (Figure 23). This is not surprising as it was shown earlier (cf. Chapter V) that although gold concentration is associated with high CO₂ values, the converse is not necessarily true.

Figure 24. Carbon dioxide concentration of rocks from Groups A, B and C. Solid circles are greater than 15% CO_2 , solid squares are 10 to 15% CO_2 , and solid triangles are 5 to 10% CO_2 .

Appendix III: Gold to Silver Ratios

The gold to silver ratios of twelve gold grains from basalt and quartzose breccia were determined by electron microprobe analysis (Table X). Additional ratios were determined by trace element analyses of pyrite separates (Appendix IV). Although the results are not statistically significant, there appears to be a correlation between mode of gold occurrence and Au/Ag ratios. Gold found as inclusions in pyrite has an average ratio of approximately 9:1 whereas the values for gold found as fracture fillings or attached to pyrite grains is approximately 4:1. These ratios fall within the range measured by Boyle (1979) for mafic rock-hosted gold deposits in the Timmins area (7 to 11.6).

A possible explanation for the lower Au/Ag ratios of gold found as fracture fillings is that silver is more mobile than gold at lower temperatures (Boyle, 1979). Therefore, since gold found as fracture fillings and coatings on pyrite must have formed later than gold inclusions, it seems reasonable to conclude that the gold-bearing fluid must have cooled sufficiently to cause a relative increase in silver mobility. This resulted in lower Au/Ag ratios later in the paragenetic sequence. (It should be kept in mind that many factors, such as , temperature, pressure, pH, oxidation potential (Eh) and the activities of various complexing ligands affect the stability of gold in solution (Seward, 1984). Therefore, although temperature effects on the evolution of ore-forming fluids may have played an important role in determining the Au/Ag ratio, it is only one possible aspect.

Table X. Gold to silver ratios of selected gold grains from Owl Creek. (QB), quartzose breccia; (BAS), basalt; (MUD), mudstone; (CS), carbonaceous shale; (MS), massive sulphide; (KOM), peridotitic komatiite; (Atc), attached; (Ff), fracture filling; (Inc), inclusion in pyrite; (*) Au/Ag ratios determined by trace element analyses of pyrite grains only. All other ratios were determined by electron microprobe analysis.

Sample Number	Rock Type	Gold Texture with respect to Pyrite	Au/Ag Ratio
OC-86-N01	QB	Atc	3.8
OC-86-N01	QB	Atc	3.9
OC-86-N01	QB	Ff	4.0
OC-86-N01	QB	Inc	7.2
OC-86-N01	QB	Inc	3.3
OWL 13c	BAS	Inc	8.3
OWL 13c	BAS	Inc	8.8
OWL 13c	BAS	Inc	9.4
OWL 13c	BAS	Inc	8.8
OWL 13c	BAS	Inc	8.3
OWL 13c	BAS	Inc	8.8
OWL 13c	BAS	Free	8.9
OC-86-N04	QB		4.5*
OC-80-13	BAS		1.5*
OC-80-17	KOM		3.7*
OC-86-12-4	Mudstone		7.3*
OC-86-5	CS		0.7*
OC-86-11	BAS		0.6*
OC-86-14	MS		0.2*
OC-86-17	Mudstone		1.6*
OC-86-54W	BAS		4.8*
OC-86-55	Mudstone		2.4*
OC-86-57	CS		0.1*
HWY	BAS		0.6*

**APPENDIX IV: Geochemical Data with Summary of Analytical
Techniques and Precision of Data**

Technique

Major element analyses reported as the oxides SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , MnO , MgO , CaO , Na_2O , K_2O , and P_2O_5 were obtained by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP/AES) performed by the Analytical Chemistry Section of the Geological Survey of Canada, Ottawa. H_2O , CO_2 , C and S analyses were obtained by chemical methods involving decomposition in a Leco furnace and detection by infrared spectroscopy (IR). ICP/AES data were obtained on 0.5g of sample fused with lithium metaborate dissolved in 5% HNO_3 and diluted to 250ml. Trace elements were analyzed on 1.0g of sample. The following tables summarize the analytical techniques used to generate both whole rock and trace element data. Precision of data is also presented.

WHOLE ROCK ANALYSES

Element (Reported as oxides)	Extraction	Method
SiO ₂	Fused with LiBO ₂ and dissolved in HNO ₃	ICP/AES
TiO ₂	Fused with LiBO ₂ and dissolved in HNO ₃	ICP/AES
Al ₂ O ₃	Fused with LiBO ₂ and dissolved in HNO ₃	ICP/AES
Fe ₂ O ₃ (t)	Cold HF leach (modified Wilson method)	Titration
MnO	Fused with LiBO ₂ and dissolved in HNO ₃	ICP/AES
MgO	Fused with LiBO ₂ and dissolved in HNO ₃	ICP/AES
CaO	Fused with LiBO ₂ and dissolved in HNO ₃	ICP/AES
Na ₂ O	Fused with LiBO ₂ and dissolved in HNO ₃	ICP/AES
K ₂ O	Fused with LiBO ₂ and dissolved in HNO ₃	ICP/AES
H ₂ O(t)	Fused with LiBO ₂ and dissolved in HNO ₃	ICP/AES
C	Fused with V ₂ O ₅	IR
CO ₂	Dissolved in HCl as part of CO ₂ analyses	IR
P ₂ O ₅	Dissolved in HCl	IR
S	Fused with LiBO ₂ and dissolved in HNO ₃	ICP/AES
	Fused with VO ₅ and dissolved in HCl	IR

Abbreviations: AAS - Atomic Absorption Spectrometry
 ICP/AES - Inductively Coupled Plasma Atomic Emission Spectrometry
 IR - Infrared spectroscopy

TRACE ELEMENT ANALYSES

Element	Extraction	Method
Ag	HF-HCl-HNO ₃ -HClO ₄	AAS
As	Aqua regia with La(OH) ₃ precipitate	AA-SiO ₂
Au	Aqua regia and Methylisobutyl ketone	AA-graphite furnace
B	NaOH fusion	ICP/AES
Ba	HNO ₃ -HF-HClO ₄ -HCl	ICP/AES
Be	HNO ₃ -HF-HClO ₄ -HCl	ICP/AES
Co	HNO ₃ -HF-HClO ₄ -HCl	ICP/AES
Cr	HNO ₃ -HF-HClO ₄ -HCl	ICP/AES
Cu	HNO ₃ -HF-HClO ₄ -HCl	ICP/AES
La	HNO ₃ -HF-HClO ₄ -HCl	ICP/AES
Mo	NaOH Fusion	ICP/AES
Ni	HNO ₃ -HF-HClO ₄ -HCl	ICP/AES
Pb	HF-HCl-HNO ₃ -HClO ₄	AAS
Sb	HNO ₃ -HF-HClO ₄ -HCl	ICP/AES
Se	Aqua regia with La(OH) ₃ precipitate	AA-SiO ₂
V	HNO ₃ -HF-HClO ₄ -HCl	ICP/AES
W	NaOH Fusion	ICP/AES
Yb	HNO ₃ -HF-HClO ₄ -HCl	ICP/AES
Zn	HNO ₃ -HF-HClO ₄ -HCl	ICP/AES

Abbreviations: AA - Atomic Absorption Spectrometry
 ICP/AES - Inductively Coupled Plasma Atomic Emission Spectrometry
 IR - infrared spectroscopy

Estimate of Validity of Results

ELEMENT	+/-	(ABSOLUTE	+	RELATIVE)
SiO ₂	+/-	0.4 %	+	2% of CONCENTRATION
TiO ₂		0.02	+	" "
Al ₂ O ₃		0.2	+	" "
Fe ₂ O ₃ (t)		0.1	+	" "
MnO		0.01	+	" "
MgO		0.1	+	" "
CaO		0.1	+	" "
Na ₂ O		0.1	+	" "
K ₂ O		0.1	+	" "
FeO		0.2	+	5% of CONCENTRATION
H ₂ O(t)		0.1	+	" "
CO ₂		0.1	+	3% of CONCENTRATION
C				
P ₂ O ₅		0.02	+	1% of CONCENTRATION
S(t)		0.04	+	5% of CONCENTRATION
LOI				
Ba	+/-	20 ppm	+	5% of CONCENTRATION
Be		0.5	+	" "
Co		5	+	" "
Cr		10	+	" "
Cu		10	+	" "
La		10	+	" "
Ni		10	+	" "
Pb		20	+	10% of CONCENTRATION
V		5	+	5% of CONCENTRATION
Yb		0.5	+	" "
Zn		5	+	" "
Au		1 ppb	+	10% of CONCENTRATION

Whole rock and Trace Element Geochemistry.

Whole rock data is presented as a percent and trace element data is reported as parts per million (ppm) except where indicated.

Sample Rock	86-01 Mudstone	86-02 Mudstone	86-03 Mudstone	86-05 Shale	86-07 Quartz Vein	86-08 Shale	86-09 Shale	86-10 Basalt	86-11 Basalt	86-13 Quartz Vein
SiO ₂	63.9	54.1	49.7	67.7	98.2	67.3	60.2	48.4	44.8	85.8
TiO ₂	0.56	0.94	0.82	0.39	0.03	0.43	0.52	0.62	0.88	0.35
Al ₂ O ₃	14.7	18.2	15.7	15.8	1.3	13.7	16.4	12.7	13.8	5.54
Fe ₂ O ₃	5.48	11.0	9.80	4.21	0.26	4.24	6.04	7.99	11.0	2.58
MnO	0.09	0.12	0.16	0	0.01	0	0	0.24	0.23	0.02
MgO	3.43	4.59	4.90	0.30	0.14	0.29	0.33	5.94	3.84	0.07
CaO	2.29	1.43	3.59	0.21	0.08	0.20	0.25	8.33	8.61	0.67
Na ₂ O	1.93	0.95	1.50	1.16	0.06	0.83	1.21	2.96	2.69	1.87
K ₂ O	1.86	2.00	2.43	2.39	0.15	2.21	2.41	0.33	0.89	0.30
H ₂ O	2.70	5.50	0	0	0.50	0	0	2.3	0	0
C	0	0.3	0.3	5.1	0.2	5.3	6.2	0.1	0	0.2
CO ₂	3.6	1.8	5.3	0	0	0	0	12.4	13.0	0.9*
P ₂ O ₅	0.10	0.14	0.13	0.14	0.03	0.13	0.17	0.07	0.07	0.07
S	0.04	0.39	7.41	3.14	0.14	3.02	4.62	0.42	2.80	1.00

	333	360	390	550	0	480	600	20	180	30
Ba										
Ag										
Be	1.2	1.1	0.9	1.6	0.1	1.6	1.6	0.4	0.6	0.2
Co	25	44	41	25	3	42	71	34	45	19
Cr	110	210	180	53	7	76	88	140	80	41
Cu	54	71	110	120	16	180	360	88	130	50
La	22	17	16	30	4	26	33	3	3	4
Ni	73	160	140	91	13	130	200	53	65	47
Pb	32	4	11	33	6	43	34	0	1	10
V	110	230	170	54	7	67	82	190	240	1100
Yb	1.4	2.1	1.9	1.3	0.2	1.4	2.0	1.4	1.8	0
Zn	78	500	440	170	140	460	310	87	130	39
Au (ppb)	3.4	12.0	14.1	101.0	2.7	77.6	502.1	89.3	471.2	895.0
B	28.5	46.0	180.1	57.8	13.5	49.4	52.8	15.3	50.1	3.1
Mo	1.1	1.4	1.5	5.3	1.6	6.0	9.0	0.8	1.4	1.0
W	<1.0	<1.0	<1.0	<1.0	2.7	<1.0	7.7	9.0	17.0	15.0
As	38.2	58.9	46.8	104.0	6.6	163.4	300.1	56.4	188.3	134.9
Sb	<0.5	<0.5	0.9	3.7	<0.5	4.4	6.4	<0.5	1.1	0.6
Total	100.3	101.6	101.9	100.7	101.1	97.8	99.0	102.1	102.7	100.2

Sample Rock	86-15 Shale	86-17 Mudstone	86-18 Mudstone	86-20 Shale	86-22 Shale	86-23 Shale	86-25 Mudstone	86-26 Mudstone	86-27 Carbonate Vein	86-28 Mudstone
SiO ₂	59.5	54.0	50.2	62.9	68.7	73.0	49.1	49.3	40.6	64.9
TiO ₂	0.50	1.34	0.90	0.46	0.48	0.38	0.82	0.91	0.76	0.64
Al ₂ O ₃	15.9	25.0	17.9	15.8	14.2	11.6	15.9	15.6	7.86	15.0
Fe ₂ O ₃	3.11	8.24	10.2	3.38	2.27	1.83	9.21	10.6	11.1	5.97
MnO	0	0.01	0.13	0.01	0.00	0.00	0.14	0.14	0.39	0.08
MgO	0.48	2.62	3.04	0.35	0.67	0.37	3.20	3.50	7.11	3.57
CaO	0.30	0.17	3.98	0.36	0.20	0.16	4.47	3.34	11.5	1.95
Na ₂ O	1.12	1.08	0.83	1.83	0.65	0.55	1.36	1.22	0.26	1.85
K ₂ O	1.84	2.08	3.16	2.02	3.02	2.52	2.90	3.17	1.58	2.20
H ₂ O	0	0	0	0	0	0	0	0	0	3.2
C	9.8	0.5	0.3	5.5	4.2	4.2	0.6	0.3	0.0	0.1
CO ₂	0	0	6.0	0	0.2	0.2	6.0	4.4	14.5	2.2
P ₂ O ₅	0.15	0.03	0.15	0.16	0.18	0.13	0.11	0.13	1.06	0.12
S	1.90	3.40	7.50	2.30	1.66	1.21	6.61	7.56	5.77	0.03
Ba	460	410	540	470	500	400	440	530	240	400
Ag	-	-	-	-	1	0	1	0	0	0
Be	1.3	1.4	1.0	1.0	1.2	1.1	1.1	1.0	0.8	1.3
Co	44	147	35	39	40	38	30	42	46	23
Cr	63	260	170	66	58	46	160	140	250	72
Cu	140	260	85	180	300	180	79	69	66	46
Fe	31	21	13	24	32	17	13	16	62	20
Ni	170	130	110	130	100	79	120	120	190	60
Pb	41	16	11	34	18	20	14	11	13	3
V	67	270	190	70	74	52	180	180	140	110
Yb	2.3	2.6	1.7	1.7	1.8	0.8	1.2	1.7	1.7	1.1
Zn	3200	160	52	1300	57	69	1500	350	84	78
Au (ppb)	62.8	847.8	5.4	11.4	52.2	41.8	28.3	13.2	14.6	2.3
B	66.9	217.1	347.0	53.8	1140.3	370.3	338.8	192.2	11.0	30.5
Mo	7.0	2.0	1.7	6.7	5.9	7.0	1.5	0.7	0.7	0.7
W	5.0	20.0	<1.0	1.2	5.1	4.4	3.4	2.1	5.1	1.9
As	124.0	329.0	64.9	85.6	114.0	116.9	35.5	61.2	426.0	43.2
Sb	3.9	1.4	5.6	2.6	3.7	3.5	1.6	1.0	0.8	0
Total	95.0	98.6	104.4	95.3	96.6	96.3	100.7	100.3	102.6	101.9

Sample Rock	86-29 Mudstone	86-30 Mudstone	86-31 Mudstone	86-32 Shale	86-33 Quartz Vein	86-34 Mudstone	86-35 Mudstone	86-36 Shale	86-38 Shale	86-39 Shale
SiO ₂	58.0	57.7	56.3	51.7	99.4	42.4	52.3	53.2	56.3	55.9
TiO ₂	0.85	0.72	0.74	0.90	0.01	1.17	0.79	0.52	0.53	0.31
Al ₂ O ₃	17.3	15.1	16.8	17.6	0.61	22.6	16.3	15.6	14.7	14.9
Fe ₂ O ₃	9.17	7.76	8.18	11.2	0.14	15.7	8.92	5.85	7.19	3.29
MnO	0.06	0.16	0.13	0.02	0.01	0.01	0.17	0.00	0.00	0.00
MgO	4.54	3.93	4.00	4.11	0.05	0.90	3.58	0.50	0.42	0.49
CaO	1.14	2.89	1.72	0.30	0.08	0.38	3.72	0.31	0.30	0.27
Na ₂ O	1.35	3.42	1.95	3.17	0.04	1.11	2.07	0.79	0.80	2.00
K ₂ O	2.30	1.37	2.30	2.43	0.11	5.55	2.99	2.81	2.26	2.89
H ₂ O	4.9	3.0	4.0	0	0.1	0	0	0	0	0
C	0.2	0.3	0.3	0.3	0.0	0.4	0.2	13.0	8.9	14.8
CO ₂	1.0	3.5	2.0	0.2	0.2	0.2	5.3	0.2	0.2	0.2
P ₂ O ₅	0.15	0.12	0.12	0.12	0.01	0.12	0.10	0.13	0.13	0.14
S	0.27	0.42	0.56	7.23	0.00	10.4	3.61	4.09	5.32	2.30
Ba	420	230	390	390	0	890	460	590	520	550
Ag	0	0	0	0	0	0	0	1	0	2
Be	1.3	0.8	1.1	0.9	0.0	1.7	1.2	1.3	1.4	1.2
Co	18	33	32	44	1	53	44	55	82	45
Cr	120	83	120	140	3	230	80	58	83	22
Cu	66	69	68	120	3	130	99	350	430	460
La	18	16	17	18	1	18	20	26	31	40
Ni	92	90	86	140	4	160	120	190	250	140
Pb	4	6	3	7	0	4	4	44	51	39
V	170	150	170	210	5	260	170	81	78	60
Yb	1.3	1.6	1.6	1.6	0.0	2.1	1.7	1.6	2.1	1.9
Zn	160	83	130	250	0	250	59	1200	2300	1100
Au (ppb)	4.3	2.0	2.3	5.9	0	7.3	3.8	79.7	92.2	81.4
B	47.7	24.6	37.9	110.4	15.4	454.1	43.0	59.4	36.5	36.5
Mo	<0.5	0.9	1.2	1.2	<0.5	2.3	1.4	9.4	9.3	6.8
W	<1.0	1.7	2.0	2.9	<1.0	4.3	2.4	4.3	3.5	3.1
As	11.9	54.1	48.7	165.0	4.2	11.7	112.5	274.1	382.8	175.7
Sb	<0.5	<0.5	<0.5	1.7	<0.5	2.5	0.9	7.2	9.8	5.5
Total	101.4	100.5	99.2	99.4	100.7	101.1	100.2	97.3	97.4	97.7

Sample Rock Type	86-40 Basalt	86-41 Mudstone	86-42 Mudstone	86-43 Arkasic Sacke	86-44 Mudstone	86-45 Mudstone	86-46 Mudstone	86-47 Basalt	86-48 Basalt	86-49 Calcite Vein
SiO ₂	45.9	47.5	55.2	57.6	58.7	55.6	57.5	54.8	42.2	47.8
TiO ₂	0.69	0.80	1.01	0.80	0.81	0.63	0.83	0.96	0.81	0.18
Al ₂ O ₃	12.4	14.6	17.3	14.2	15.1	12.8	15.8	17.2	13.9	5.06
Fe ₂ O ₃	8.98	9.17	11.3	9.48	9.29	6.53	9.80	11.0	13.1	4.44
MnO	0.22	0.17	0.11	0.14	0.10	0.28	0.11	0.11	0.19	0.35
MgO	5.09	3.93	5.00	4.11	4.19	3.53	4.53	4.50	5.86	4.35
CaO	9.45	4.89	0.93	4.23	1.45	6.33	2.07	1.81	6.82	17.1
Na ₂ O	2.10	1.31	3.43	2.69	3.55	3.58	2.48	1.48	1.25	0.28
K ₂ O	0.75	2.99	1.62	1.31	1.25	1.68	1.83	2.47	1.82	1.27
H ₂ O	0	0	4.4	3.7	3.6	1.6	3.8	4.5	3.9	0.7
C	0.1	0.3	0.1	0.1	0.1	0.0	0.1	0.3	0.0	0.1
CO ₂	12.8	6.7	0.5	3.0	1.3	8.9	2.4	2.0	10.1	19.7
P ₂ O ₅	0.06	0.10	0.12	0.10	0.09	0.10	0.10	0.12	0.06	0.05
S	2.72	6.94	0.15	0.24	0.20	0.72	0.12	0.34	0.45	0.06
Ba	80	480	330	220	250	250	310	340	190	290
Ag	1	1	0	0	0	0	0	0	0	0
Be	0.7	1.0	1.1	0.8	1.1	1.1	1.1	1.1	0.6	0.4
Co	45	45	44	32	33	25	35	45	49	16
Cr	98	100	130	120	110	92	87	130	34	22
Cu	100	95	97	70	77	94	72	71	120	27
La	3	13	15	14	13	14	16	18	3	5
Ni	65	130	130	94	100	74	99	130	67	37
Pb	7	10	9	15	17	17	1	2	0	9
V	220	190	230	160	180	130	180	210	270	90
Yb	1.3	1.6	1.9	1.5	1.5	1.6	1.6	2.0	1.7	0.9
Zn	49	550	120	91	93	38	86	130	120	25
Au (ppb)	649.3	14.3	2.9	3.4	2.9	23.3	9.0	43.5	4.4	26.5
B	36.7	245.1	54.2	18.5	18.6	18.1	25.9	205.1	571.0	56.0
Mo	0.5	1.1	1.7	1.0	0.5	1.4	1.0	1.1	0.5	0.5
W	29.5	2.9	2.2	8.5	1.9	3.8	4.9	5.4	2.7	10.6
As	290.8	39.8	24.4	28.1	34.6	30.9	43.1	80.6	82.7	26.4
Sb	1.3	1.8	0.9	1.1	1.0	5.6	0.5	0.5	0.9	0.5
Total	101.3	99.8	101.3	101.8	100.3	102.4	101.6	101.7	100.5	101.4

Sample Rock Type	86-50 Arkasic Wacke	86-51 Basalt	86-52 Basalt	86-53 Basalt	86-54E Quartz Vein	86-54W Basalt	86-55 Mudstone	86-56 Mudstone	86-57 Shale	86-58 Mudstone
SiO ₂	61.8	46.9	45.8	41.4	100.6	43.5	48.4	56.4	66.9	55.2
TiO ₂	0.83	0.61	0.54	0.56	0.01	0.66	1.44	1.03	0.35	0.86
Al ₂ O ₃	16.2	12.5	11.8	12.6	0.54	12.0	23.9	18.8	12.3	16.9
Fe ₂ O ₃	8.97	8.49	7.96	6.92	0.16	8.81	9.23	9.29	3.30	11.2
MnO	0.03	0.20	0.20	0.16	0.01	0.24	0.01	0.02	0.01	0.01
MgO	3.85	5.93	5.58	4.84	0.10	5.26	0.40	2.94	0.46	3.11
CaO	0.31	7.82	9.70	11.9	0.04	8.97	0.16	0.13	0.28	0.29
Na ₂ O	2.64	2.99	2.98	2.37	0.08	3.19	1.38	0.84	0.55	0.86
K ₂ O	1.89	0.46	0.49	0.75	0.38	0.94	3.17	2.53	2.89	3.44
H ₂ O	4.0	2.9	2.2	1.7	0.1	0	0	0	0	0
C	0.4	0.0	0.0	0.0	0.0	0.0	0.6	0.3	6.2	0.2
CO ₂	0.0	10.5	13.4	16.7	0.1	13.6	0.1	0.1	0.0	0.1
P ₂ O ₅	0.13	0.04	0.05	0.04	0.02	0.05	0.02	0.03	0.09	0.12
S	0.67	0.04	0.10	0.43	0.00	1.61	7.31	3.93	2.35	8.56
Ba	290	20	50	50	0	80	470	360	520	470
Ag	0	0	1	1	2	1	0	1	1	0
Be	0.9	0.4	0.3	0.4	0.0	0.4	1.6	1.3	1.2	1.1
Co	31	25	27	39	1	43	57	50	27	50
Cr	120	110	120	100	7	100	190	140	49	120
Cu	67	97	98	72	2	97	100	174	91	82
La	18	3	3	3	1	3	20	20	21	16
Ni	84	80	61	80	5	81	140	110	92	130
Pb	9	4	0	6	6	7	21	19	24	11
V	160	210	130	190	5	210	280	220	51	210
Yb	1.6	0.9	1.1	1.0	0.0	1.0	2.4	2.1	1.1	1.7
Zn	96	55	46	31	0	56	50	170	1100	220
Au (ppb)	1.3	8.1	2.2	7.8	89.6	20949.1	297.8	1004.3	19.5	1.1
B	25.2	15.3	18.2	41.6	2.9	17.7	178.6	93.6	73.3	189.2
Mo	1.1	<0.5	<0.5	0.7	<0.5	<0.5	2.0	2.6	2.8	1.4
W	1.9	4.9	2.2	2.1	<1.0	18.8	33.5	16.9	1.9	1.7
As	15.7	31.2	58.8	58.7	8.4	985.3	617.8	363.5	87.5	54.8
Sb	0.9	0.5	<0.5	<0.5	<0.5	1.1	0.5	<0.5	1.2	3.2
Total	101.8	99.4	100.9	100.4	102.1	98.8	96.2	96.5	95.9	101.0

Sample Rock Type	86-59 Mudstone	86-60 Mudstone	86-61 Shale	86-62 Mudstone	86-63 Mudstone	86-64 Mudstone	86-66 Mudstone	86-67 Basalt	86-N04 Quartzose Breccia
SiO ₂	59.5	65.8	56.2	59.8	61.0	57.6	55.0	46.6	72.4
TiO ₂	0.87	0.59	0.39	0.76	0.53	0.45	0.91	0.66	0.74
Al ₂ O ₃	171	15.9	12.5	17.9	14.9	6.04	18.2	14.5	8.61
Fe ₂ O ₃	835	5.68	12.8	7.43	4.98	5.74	12.0	5.43	6.76
MnO	005	0.01	0.01	0.02	0.08	0.14	0.02	0.23	0.03
MgO	302	3.04	0.37	0.64	2.85	5.50	4.24	5.13	3.05
CaO	069	0.22	0.34	0.52	3.94	8.58	0.20	11.1	0.80
Na ₂ O	108	1.76	1.77	0.55	0.97	0.25	0.37	1.88	0.38
K ₂ O	347	3.06	2.34	4.21	3.44	1.84	3.41	0.98	0.91
H ₂ O	0	0	0	0	0	0	0	1.9	0
C	0.4	0.1	4.7	2.1	0.1	0.0	0.3	0.1	0.1
CO ₂	0.4	0.0	0.1	0.0	5.7	12.3	0.0	15.5	0.5
P ₂ O ₅	0.12	0.11	0.13	0.15	0.10	0.42	0.13	0.07	0.03
S	6.44	4.78	10.7	5.19	3.87	4.24	6.90	0.06	2.31
Ba	460	430	370	690	430	180	570	170	70
Ag	1	1	2	1	1	1	1	1	1.8
Be	1.1	1.3	0.9	1.4	1.4	0.6	1.0	0.5	0.6
Co	48	27	41	38	22	32	34	46	38
Cr	130	67	51	150	51	91	130	95	80
Cu	93	49	650	85	50	14	30	120	12
La	15	19	24	24	21	44	13	2	1
Ni	130	70	150	120	57	79	120	82	75
Pb	2	16	68	9	15	1	6	3	0
V	200	110	58	150	97	77	220	220	220
Yb	1.8	1.3	1.1	1.6	1.1	1.3	1.7	1.4	0.3
Zn	260	200	1200	790	90	24	180	50	41
Au (ppb)	1.2	1.1	38.1	7.2	7.3	0	1.9	67.2	14021.9
B	133.4	66.2	56.3	483.1	72.8	20.1	155.6	42.1	16.0
Mo	1.2	1.1	6.8	3.5	1.3	1.0	1.5	0.5	<2
W	<1.0	<1.0	2.3	1.8	1.5	2.9	<1.0	1.2	52
As	46.3	32.0	333.8	181.7	271.7	73.9	52.2	294.5	703.2
Sb	2.5	6.3	12.3	4.9	2.9	1.4	1.5	0.8	0.9
Total	101.6	101.1	102.6	99.4	102.5	103.1	101.8	104.2	96.7

Sample Rock Type	80-04-11 Mudstone	80-04-12 Shale	80-04-13 Mudstone	80-04-14 Mudstone	80-15 Komatiite	80-17 Komatiite	H15-04-1 Mudstone	H15-04-2 Shale	H15-04-3 Shale	H15-10-1 Mudstone	H15-10-2 Shale
S ₁₀₂	47.5	28.5	51.3	53.3	66.6	70.8	41.9	51.1	52.5	42.3	60.3
Ti ₁₀₂	0.46	0.10	0.67	0.45	0.36	0.33	0.70	0.48	0.51	1.03	0.44
Al ₂ O ₃	15.0	3.46	13.6	16.1	12.8	11.8	12.1	14.6	14.8	9.60	13.0
Fe ₂ O ₃	7.80	36.1	6.25	3.23	4.28	2.26	9.70	5.34	7.06	11.8	6.19
MnO	0.10	0.07	0.30	0.17	0.02	0.03	0.21	0.06	0.01	0.16	0.01
MgO	2.88	2.14	3.32	2.84	0.50	0.45	4.64	0.71	0.91	1.54	0.98
CaO	4.43	3.45	6.27	4.82	1.49	2.82	8.09	6.21	1.76	11.9	1.18
Na ₂ O ₄	1.17	0.22	3.47	4.88	3.00	2.39	0.20	0.24	0.28	1.77	2.04
K ₂ O	2.90	0.78	1.95	2.29	2.25	2.24	3.55	4.18	4.12	2.26	2.81
H ₂ O	0	0	2.0	0	0	0	0	0	0	0	0
C	3.5	1.4	0.0	2.6	3.1	2.5	0.4	5.8	9.0	0.4	6.6
CO ₂	6.2	5.0	9.3	6.4	0.8	2.5	11.4	4.6	1.1	10.2	0.6
P ₂ O ₅	0.13	0.03	0.11	0.15	0.11	0.13	0.06	0.15	0.11	0.07	0.12
S	5.67	29.8	0.18	2.46	3.23	1.79	6.80	4.13	5.66	9.05	4.72
Ba	330	60	250	350	280	330	250	400	380	90	260
Ag	1.4	8.4	0.5	0.6	<0.5	<0.5	<0.5	0.9	0.9	<0.5	1.0
Be	1.2	0.3	1.0	1.2	1.0	1.1	0.9	1.4	1.3	0.9	1.0
Co	38	24	27	25	23	23	48	56	44	31	32
Cr	49	0	150	65	54	47	52	72	44	15	38
Cu	320	290	85	110	55	93	140	550	230	47	190
La	30	8	18	28	21	25	5	39	36	5	34
Ni	120	56	86	89	75	100	64	160	140	47	120
Pb	68	349	<5	21	22	18	<5	31	36	18	42
V	71	17	150	83	54	40	240	72	77	290	79
Yb	1.9	0.0	2.0	1.5	0.7	1.2	1.5	2.2	2.6	2.9	2.5
Zn	250	73	46	610	120	760	220	2300	2600	26	2200
Au (ppb)	351.8	4956.5	2.8	12.6	8.0	8.9	73.9	31.5	32.2	26.0	67.6
B	280.0	37.5	70.5	17.9	20.5	17.5	91.9	62.4	1382.0	22.1	1752.0
Mo	4	3	<2	2	3	4	<2	6	7	<2	5
W	<4	<4	<4	<4	<4	<4	<4	<4	<4	5	<4
As	300.6	690.0	12.5	127.2	245.7	154.6	52.9	255.9	226.7	30.1	197.5
Sb	10.3	54.2	0.7	4.7	5.1	3.1	7.6	34.3	30.4	12.4	37.3
Total	97.9	111.1	98.8	99.9	98.7	100.2	99.9	98.0	98.2	102.1	99.3

Sample Rock Type	80-04-1 Arkosic Wacke	80-04-2 Mudstone	80-04-3 Mudstone	80-04-4 Mudstone	80-04-5 Mudstone	80-04-6 Mudstone	80-04-7 Quartz Vein	80-04-8 Quartz Vein	80-04-9 Mudstone	80-04-10 Shale
SiO ₂	57.5	56.6	67.0	57.3	99.0	55.2	89.2	96.3	39.9	50.4
TiO ₂	0.77	0.85	0.59	0.85	0.0	0.61	0.07	0.01	0.92	0.70
Al ₂ O ₃	14.1	14.3	11.1	16.3	0.75	12.7	1.72	1.14	16.5	14.2
Fe ₂ O ₃	8.92	9.23	7.05	9.90	0.03	7.62	0.92	0.75	9.14	8.60
MnO	0.10	0.09	0.14	0.13	0.00	0.15	0.04	0.01	0.21	0.13
MgO	3.73	4.35	3.04	4.31	0.04	4.03	0.53	0.18	3.91	3.00
CaO	2.61	2.84	3.18	2.66	0.05	4.33	1.06	0.07	6.91	4.69
Na ₂ O	3.01	2.34	2.58	2.16	0.02	2.93	0.28	0.00	1.60	1.49
K ₂ O	1.27	1.44	1.04	2.16	0.22	1.33	0.26	0.22	2.90	2.29
H ₂ O	3.6	3.9	2.5	3.9	0.1	0	0.3	0.3	0	0
C	0.0	0.1	0.0	0.0	0.0	0.4	0.0	0.1	0.7	0.5
CO ₂	2.2	2.9	3.6	3.7	0.0	6.2	1.4	0.0	9.9	6.6
P ₂ O ₅	0.11	0.10	0.11	0.09	0.02	0.09	0.02	0.03	0.14	0.10
S	0.57	0.04	0.39	0.00	0.03	1.24	0.37	0.16	6.06	6.05
Ba	230	220	100	210	0	160	0	0	410	180
Ag	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Be	0.9	0.9	0.7	1.0	0.0	0.7	0.0	0.0	1.4	1.1
Co	39	38	29	35	0	26	6	2	43	38
Cr	180	190	130	180	1	150	11	3	220	160
Cu	78	190	56	71	0	82	2	55	53	83
La	16	15	15	14	0	13	0	0	18	17
Ni	90	110	79	100	2	69	10	13	120	100
Pb	<5	<5	<5	<5	<5	<5	<5	<5	14	20
Y	170	190	130	180	7	140	25	6	200	170
Yb	1.3	1.5	1.1	1.5	0.0	1.6	0.0	0.0	2.0	1.6
Zn	98	100	73	110	4	97	37	57	100	55
Au (ppb)	2.4	2.2	5.7	2.9	1.1	48.9	1539.1	2702.9	351.8	76.7
B	18.3	29.2	18.5	32.1	2.0	32.0	4.5	1.9	65.4	76.5
Mo	<2	<2	<2	<2	<2	<2	<2	<2	<2	3
W	<4	<4	<4	<4	<4	6	<4	<4	8	<4
As	11.2	17.9	17.6	36.0	1.2	825.4	53.0	7.3	410.5	186.5
Sb	0	0	0	0	0	0.7	0	0	1.8	3.7
Total	98.6	99.2	102.3	103.6	100.3	96.9	96.2	99.3	98.9	98.9

Sample	80-02-1	80-02-2	80-02-3	80-12-1	80-12-2	80-12-3	80-12-4	80-12-5
Rock	Mudstone	Mudstone	Mudstone	Arkagic Wacke	Mudstone	Mudstone	Mudstone	Tuff
SiO ₂	62.3	67.7	66.1	76.0	51.2	53.1	32.8	37.8
TiO ₂	0.37	0.34	0.46	0.12	0.93	0.83	1.17	0.99
Al ₂ O ₃	12.2	15.4	17.5	5.96	18.7	16.6	25.6	15.7
Fe ₂ O ₃	6.59	2.53	3.18	2.32	12.7	9.44	9.60	10.8
MnO	0.06	0.06	0.01	0.11	0.08	0.16	0.15	0.19
MgO	1.15	1.44	0.65	1.47	4.84	4.83	4.01	4.95
CaO	4.08	1.70	0.76	5.39	1.51	3.49	7.58	9.60
Na ₂ O	0.70	1.48	2.32	1.72	3.98	2.79	2.57	3.03
K ₂ O	2.13	2.60	2.86	0.44	0.87	1.25	2.99	1.07
H ₂ O	0	0	0	0.70	0	3.30	-	-
C	3.1	3.1	4.3	0.9	0.8	0.2	0.5	0.1
CO ₂	4.0	2.3	0.5	6.3	2.0	5.3	11.2	14.7
P ₂ O ₅	0.12	0.11	0.19	0.03	0.13	0.13	0.03	0.03
S	4.80	1.90	2.40	0.80	3.30	0.61	4.40	4.60
Ba	480	600	680	80	180	230	530	200
Ag	-	-	-	-	-	-	-	-
Be	1.1	1.3	1.4	0.3	0.7	0.7	1.7	1.7
Co	28	18	22	11	43	36	45	54
Cr	32	37	54	18	190	170	230	67
Cu	120	81	92	24	70	46	29	94
La	25	39	33	4	14	14	17	2
Ni	98	93	110	34	130	110	150	89
Pb	44	33	41	15	12	15	25	14
V	53	43	57	22	210	180	270	270
Yb	1.6	1.2	1.1	0.4	1.9	2.0	2.3	1.5
Zn	1300	230	200	210	160	93	39	93
Au (ppb)	51.2	4.7	57.0	123.4	280.2	15.5	4901.2	4839.5
B	118.2	40.2	36.7	19.8	61.6	35.7	124.6	39.8
Mo	6.0	5.1	4.5	3.0	2.0	1.3	3.0	0.6
W	2.7	<1.0	5.0	1.1	16.0	6.0	109.0	116.0
As	252.7	87.3	226.1	78.7	214.1	126.3	746.6	3184.9
Sb	5.5	1.5	4.7	<0.5	0.6	<0.5	2.4	5.9
Total	101.8	100.8	101.4	102.3	101.1	101.3	102.7	103.6

Geochemistry of Pyrite Separates

Fe_2O_3 , MnO and S data reported as percentage. Trace elements reported as parts per million.

Sample	80-13	80-17	80-12-4	86-05	86-10	86-11	86-14	86-17	86-18	86-25
Rock	Basalt	Komatilita	Mudstone	Shale	Basalt	Basalt	Massive Sulphide	Mudstone	Mudstone	Mudstone
Type										
Fe ₂ O ₃	65.8	61.1	0	61.9	62.3	63.2	58.6	84.4	72.1	83.5
MnO	0.10	0.07	0	0.01	0.07	0.06	0.02	0.01	0.01	0.07
S	0	0	0	0	0	45.8	41.5	52.1	0	47.5
Ba	70	30	0	60	50	60	50	40	40	60
Be	0.0	0.2	0	0.2	0.0	0.1	0.4	0.0	0	0.1
Co	380	160	0	290	130	180	35	320	220	64
Cr	0	0	0	0	0	0	0	0	0	0
Cu	220	320	0	480	370	290	370	270	410	560
La	2	4	0	31	2	4	9	6	18	13
Ni	910	400	0	930	140	210	170	700	650	260
V	0	24	0	0	22	76	11	0	1	0
Y	4	5	0	17	6	8	2	4	17	8
Yb	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zn	100	150	0	190	38	57	150	23	85	160
Pb	28	-	29	145	-	49	362	24	49	67
Au	4.5	11.1	130.6	1.3	0.5	3	2	9.3	-	211
As	1046.7	8178.9	7828.4	1339.2	2238.6	3011	658.2	3592	483.8	176.6
Sb	15.1	15.5	3.9	18.4	1.7	8.5	56.4	2.4	25.1	8.3
Se	35.3	9.8	4.6	29.8	13.6	8.5	23.1	22.4	8.3	2.9
Te	3.6	1.8	14.9	3.7	2.1	4.6	2.1	11.4	0.6	0.8
Ag	3	3	18	2	-	5	9	6	-	-

[illegible]

Sample Rock Type	86-55 Mudstone	86-57 Shale	86-58 Arkose Wacke	86-61 Shale	86-63 Mudstone	86-66 Mudstone	86-HWY Basalt	86-N04 Quartzose Breccia
Fe ₂ O ₃	73.1	53.7	54.8	61.2	72.5	79.6	-	67.4
MnO	0.01	0.01	0.01	0.01	0.02	0.01	-	0.17
S	53.1	40.1	50.8	45.0	0	54.0	-	0
Ba	40	30	40	70	50	50	-	50
Be	0.0	0.3	0.0	0.1	0.1	0.0	-	0.2
Co	290	280	210	120	240	64	-	420
Cr	0	0	0	0	140	0	-	0
Cu	120	250	300	680	450	120	-	83
La	6	15	6	27	69	5	-	3
NI	820	1100	590	520	580	450	-	740
V	0	2	44	0	0	0	-	63
Y	5	25	4	22	20	4	-	9
Yb	0.0	0.1	0.3	0.0	0.0	0.0	-	0.0
Zn	35	140	91	160	470	79	-	50
Pb	27	211	32	287	140	25	121	-
Au	7.1	0.4	-	0.2	0.2	-	1756	347.5
As	4179.8	1518.9	232.4	1215.9	2659.3	139	317.2	8068.7
Sb	2.3	21.5	8.9	50.3	14.8	1.8	19.6	2.9
Se	15.5	32.6	4.9	24.2	3	1.7	9.8	4.9
Te	7.6	6.2	-	4.1	-	-	0.8	2
Ag	3	4	-	6	-	-	3	78

APPENDIX V: Carbon and Oxygen Isotope Data

Sample Number	Rock Type	^{13}C	^{18}O
OC-86-N01	Calcite vein	-8.19	+10.61
OC-86-N02	Calcite vein	-8.17	+11.18
OC-86-N02a	Calcite vein	-7.84	+10.91
OC-86-N03	Ankerite vein	-7.22	+11.32
OC-86-5bE1	Carbonaceous shale	-33.1	-
OC-86-5bE2	Carbonaceous shale	-33.4	-

APPENDIX VI: Sulphur isotope data, after Elliott
(1984).

Sample	Host Rock	Pyrite type	$\delta^{34}\text{S}$ (per mil)
OWL-01	Shale	E	+1.2
OWL-02	Arkosic Wacke	E	+2.8
OWL-03	Shale	E	+0.4
OWL-04	Arkosic Wacke	E	+3.2
OWL-05	Arkosic Wacke	E	+2.2
OWL-06	Shale	E	+2.7
OWL-07	Basalt	E	+2.5
OWL-08	Basalt	E	+2.1
OWL-09	Basalt	E	+1.9
OWL-10	Basalt	E	+2.9
OWL-11	Basalt	E	+1.8
OWL-12	Basalt	E	+1.8
OWL-13	Basalt	E	+3.3
OWL-14	Shale	N	+3.5
OWL-15	Mudstone	B	-1.0
OWL-16	Mudstone	B	-1.4
OWL-17	Arkosic Wacke	E	+2.2
OWL-18	Shale	N	-0.6
OWL-19	Shale	N	-2.7
OWL-21	Shale	N	+2.3
OWL-22	Shale	N	-2.2
OWL-23	Shale	N	+2.7
OWL-24	Shale	N	+0.1
OWL-25	Shale	N	-1.5
OWL-26	Shale	MS	+2.8
OWL-27	Shale	MS	+2.9
OWL-28	Basalt	E	+2.0
OWL-29	Basalt	E	+2.3
OWL-30	Shale	N	-0.7
OWL-31	Shale	MS	+4.3

Greywacke

High gr content but rocks
remain competent (not sheared)

Graphitic shale (siltstone)

Black graphitic shale
(gouge)

Dec in gr content
Inc in avg grain size
Inc in % of
siltstone laminae
Inc in competence

Black gr rich shale

60%

ON

Y

inc

uh

260/85N

(1mm)

2 mm

siltstone)

(5mm)

Y (3-4%)

black

of grey-black

wide)

Massive mafic volcanics
- buff colour, carbonatized

Massive mafic volcanics (grey
with sigmoidal qtz veins
carbonatized, sericite
- euh py up to 10 mm (avg 3 mm)
Py conc from 2-4% N to S
largest cubes at N and S contacts
- rare vfg py < 1 mm in thin
qtz vein (1-5 mm)

"Stretched" pillow basalts
- stretching in 2D S1 to S11
- selvages of chlorite and qtz
- large euh py (5 mm) in selvage
- to 10% py
- no good tops indicators
- carbonate alteration

Pillowed to massive mafic volcanics
- carbonate, sericite alteration
- 5 mm euh py in local shears (10-15 mm wide)
- rare 15 mm euh py, vfg py in thin, + 5 mm
white qtz vein.

Sheared grey volcanics
- 4-5% qtz + calcite conc no py
- 3% euh py, avg 3-4 mm
- 30% calcite to 20% 275°

Dec in % of pillows

Py inc from 2-4% N to S
 largest cubes at N end & contacts
 rare vfg py (1-5 mm) thin
 qtz vein (1-5 mm)

"Stretched" pillow basalt
 - stretching in 2D S1 to S1
 - selvages of chlorite and qtz
 - large euh. py (15 mm) in selvage
 - 5-10% py
 - no good top indicators
 - carbonate alteration

Pillowed to massive mafic volcanics
 - carbonate, seafite alteration
 - 5 mm euh. py in local shears (10-15 mm wide)
 - rare 15 mm euh. py, vfg py in thin (1-5 mm) white qtz veins

Sheared grey volcanics
 - 4-5% qtz & calcite veins, no py
 - 3% euh. py avg size 5 mm
 - isoclinal fold - T 075°
 P 300°E

Grey-buff massive volcanics
 - weakly carbonatized, many small
 (1x10 mm) barren grey qtz veins // S1
 - rare calcite in qtz veins
 - 2-3% euh. py (5 mm)

Grey sediments, siltstone with 1-2 mm
 euh. py, gouge at N contact

Fig grey wacke with deep orange weathered
 surface

- 2-3% euh. py (4-5 mm) at south;
 1% euh. py (1-2 mm) at north end

Greywacke
 - 5-10% euh. py, 5-12 mm
 - minor calcite veins (240/12 N);
 some have euh. py (3-4 mm)
 - avg grain size inc to north
 - unit has 1-10 cm laminac at

→ N

South end, gradually becomes massive
to the north

Si: 090/89 S

319/13 NW

x
42

Si: 206/82 W

x
43

180/43 W

Zone of subhorizontal calcite veins
(in greywacke)
- white and pink calcite veins (up
to 10%), 5-10 mm x 10 cm - 3 m
veins always pinch out at ends

Figure 4. Geology of 5 bench west

cored M Volcanics

5% euh py, 5 mm

ss gr then main gr shear

v are both concordant and

ordant to joint planes

contain fragments of

t rock

1-10 mm, avg 5 mm

py in post-shear

cal/dol veinlets, < 1 mm

High % of euh py →

and ...

strongly jointed

Massive Mafic Volcanics

from S to N

no ... size of ... up to ...

in % of euh py

} weak to mod trends

Alteration

pyrite, carbonate and pyrite

nonhorizontal QV is zoned (white center

grey edges)

main euh py 1-2 mm / at white grey contact

... gouge material ...

... of ...

QV white centre with grey ...

vfg py 1-2 mm, at contact

cal/dol veinlets up to 4 x 100

mm in joints

OWL CREEK

WEST FACE OF NUMBER 5 BENCH

D.M. KINGSTON

Figure 5. Geology of 5 be

N ↑

bench east

OWL CREEK
5 BENCH EAST
D.M. KINGSTON

0m 5m

Figure 3. Geology of 4 bench

Black graphitic shale
(gouge)

west

- Stretching
- stretching
- selivages
- large eu
- 10%
- no gose
- carbonat
- Pillowed to
- carbonat
- 5mm eu
- rare 15m
- white qtz
- Shear
- 4-5% eu
- 3% eu
- isoclinal
- Grey buff
- weakly c
- (1x10 mm)
- rare cal
- 2-3%
- Grey sedim
- eu py
- Fg grey
- surface
- 2-3% eu
- 1% eu
- Greywack
- 1%
- minor c
- some h
- avg. gr

unit n
south e
to the

SI: 090/89 S

319/13 NW

x
42

SI: 206/82 W

180/43 W

Zone of subhorizontal calcite veins
(in greywacke)

white and pink calcite veins (up
to 10%), 5-10 mm x 10 cm - 3 m
veins always pinch out at ends

OWL CREEK

WEST WALL

D.M. KINGSTON

0m 5m

3

of/de

3

Resolution is determined by the number of lines per inch.

Metro

Resolution is determined by the number of lines per inch.

N < -

Figure 6. Geology of 4 bench east

green
shale

Grey, relatively
gr-poor shale

Grey graphitic
shale

Black
graphitic shale

Grey graphitic shale
rare rounded py nod with
qtz pr sh (up to 10 mm long)
between laminae

Black
graphitic
shale

Black-grey
shale

Grey shale

Black graphitic shale

Gradual increase
in silt beds, decrease
in gr-rich laminae

4-6% ex py (<1mm)
sericite in py rich bands
2% py - in bands
2% ex py (2-5mm)

- lithologically very similar
to subunit to north
- 0.5-1% vfg (<1mm)
dissem py and rare nod
- thin white qtz veins (≤1cm)
|| S₂
- sericite

Four fabrics observed
on north facing S₁
joint/bedding plane:
i) S₂, subvertical 277/73N
ii) S₃, subhoriz 072/37N
iii) S₃, 357/66E
iv) cren cleavage caused by
intersection of S₂ and S₃

Dec in py
rich bands to
2-3% py

2% dissem vfg
py (not localized
in bands)
- white qtz veinlets
(≤2mm wide) || S₁

Distinctive cren cleavage
Py occurs as: i) round
oval nod (8±2mm) with
qtz pr sh (total length of
30-40mm);
ii) qtz py veinlets (3-5
mm - up to 10cm,
iii) dissem vfg pin point

1 ≤0.5% py as veinlets (3-5mm
x 5-10um) with white qtz. Beds
are tight to isoclinaly folded
Folds trend 090±005°, plunge
15-20°E.
- few py nod (rounded, diam.
<5mm) with qtz pr sh

2 Tightly folded unit with many
local faults 2% py, as nod
and as qtz-py band || S₁
(≤5mm thick) Rounded nod
(2-5mm) are at N end, py-
qtz veinlets and stretched nod
(5-1) in south half

15% py alternating between
vfg dissem py in black sh
laminae and cont-discont
"wavy" bands (3-5mm wide)
of massive py possible
Boudinage of massive py bands
- southmost 30cm has only
fg dissem py in sh (sharp
N and S contacts) (277/12N)

are gradational
ent dec north and
All subunits are
nodules are near
up to 41 (2x0.5cm)

Gradual increase
in silt weds, decrease
in gr rich laminae

Black graphitic shale Grey, relatively py poor shale Grey graphitic shale Black graphitic shale Grey shale Black graphitic shale

Grey graphitic shale
rare rounded py nod with
qtz pr sh (up to 10 mm long)
between laminae
Black graphitic shale

Four fabrics observed
on north facing S_1
joint/bedding plane
i) S_2 , subvertical 277/73N
ii) S_3 , subhoriz 072/37N
iii) S_3 , 357/66E
iv) cren cleavage caused by
intersection of S_2 and S_3

Distinctive cren cleavage
Py. occurs as: i) round to
oval nod (8 ± 2 mm) with
qtz pr sh (total length of
30-40 mm);
ii) qtz-py veinlets (3-5
mm - up to 10 cm)
iii) dissem vfg pin point py

- lithologically very similar
to subunit to north
- 0.5-1% vfg (< 1 mm)
dissem py and rare nod
- thin white qtz veins (5 cm)
|| S_2
- sericite

2% dissem vfg
py (not localized
in bands)
- white qtz veinlets
(≤ 2 mm wide) || S_1

15% py alternating between
vfg dissem py in black shl
laminae and cont-discont
"wavy" bands (3-5 mm wide)
of massive py: possible
boudinage of massive py bands
- southwest 30 cm has only
fvg dissem py in shl (sharp
N and S contacts) (277/12 N)

1. $\leq 0.5\%$ py as veinlets (3-5 mm
x 5-10 cm) with white qtz. Beds
are tight to isoclinally folded
Folds trend $090 \pm 005^\circ$, plunge
15-20°E.

- few py. nod (rounded, diam
 < 5 mm) with qtz pr sh

2. Tightly folded unit with many
local faults. 2% py, as nod
and as qtz-py band || S_1
(≤ 5 mm thick). Rounded nod
(2-5 mm) are at N end, py-
qtz veinlets and stretched nod
(5-1) in south half

4-6% can py (2-5 mm)
sericite in py rich bands
- 2% py - in nod.
- 2% can py (2-5 mm)

e are gradational
int dec north and
all subunits are
adules are near
py to 4 1 (2x0.5cm)

Blue-grey shale-siltstone

<1% py, and

4-0.5 cm to 10 x 0.4 cm,

long axis parallel to S_2

4 sets of qtz veins: 094/74 S (4 to 2), 081/82 S

- S_2 112/42 N

blue-grey graphitic shale

Poorly exposed
greywacke

2% py, as

5-15 mm euh py

64

Qtz veins 3mm x 2m

- some zoned, white qtz

± euh py in centre and

black ptz clays, 1-2%

subhedral euh py (2mm)

63

274/
70W

2-3% euh py (1mm)

dissem in seas

py and qtz "worms"

1 cm x 2-3 mm appear

subhorizontal fabric

(S_3) is now weak

Intermittent beds
with 1-2% vfg
py (<1mm)

Black-grey siltstone

<1% py, as euh py (1-2mm),

massive lenses (5 x 2 mm to
10 x 3 mm) and veinlets (2-100 mm)

py % is greatest in 1-2 m
adjacent to greywacke

65

OWL CREEK

4 BENCH EAST

D.M. KINGSTON

0m 5m

FIGURE 25. SURF

LEGEND

- 7 Diabase
- 6 Quartz feldspar Porphyry
- 5 Carbonaceous Shale
- 4 Arkosic Wacke
- 3 Fe Tholeiite
- 2 Mg Tholeiite
- 1 Komatiite
- Fault
- o Drill hole collar

FACE GEOLOGY OWL CREEK - HOYLE POND AREA

E GEOLOGY OWL CREEK - HOYLE POND AREA

END

29.06.88

FIN