GEOLOGY, STRUCTURE AND GEOCHEMISTRY
OF GOLD MINERALIZATION IN THE
GERALDTON AREA, NORTHWESTERN ONTARIO

CAROLYN DIANE ANGLIN

GEOLOGY, STRUCTURE AND GEOCHEMISTRY OF GOLD
MINERALIZATION IN THE GERALDTON AREA, NORTHWESTERN
ONTARIO.

by
© Carolyn Diane Anglin

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science

Department of Earth Sciences
Memorial University of Newfoundland
1987

St. John's   Newfoundland

ABSTRACT

Gold mineralization in the Beardmore-Geraldton area occurs in a major, long-lived deformation zone, spatially coincident with the boundary between the Wabigoon subprovince to the north and the Quetico subprovince to the south.

Regionally, the deposits are linearly distributed (east-west) parallel to the strata of the southern margin of the Wabigoon belt. Virtually all rock types host gold mineralization, except for the youngest intrusions, diabase and lamprophyre dykes.

Gold mineralization in the Geraldton area occurs; 1) in quartz and quartz-carbonate veins in; fractured greywacke, felsic and mafic intrusions and mafic volcanic rocks, 2) in disseminated sulphide-bearing, highly fractured, zones in greywacke and quartz-feldspar porphyry, and 3) in massive quartz-sulphide lenses in oxide iron formation.

There is no primary sulphide or carbonate facies iron formation in the belt. All sulphide and carbonate minerals in iron formation are secondary alteration features associated with gold mineralization. The

alteration is characterized by addition of CO_2, S, As, K, Ba and H_2O, and loss of Sr. There is no primary enrichment of gold in any of the rocks, background gold content of all rock types is less than 10 ppb.

Gold-bearing veins occur in relatively young structures that crosscut all local Archean rock, and overprint several earlier phases of deformation. The major control on emplacement of veins is cleavage- and foliation-parallel fractures and dilations, and zones of intense deformation localized at the contacts of rocks of differing ductility.

The U/Pb zircon age of felsic porphyry intrusions in the Geraldton area is 2691 +3/-2 Ma, significantly younger than volcanic rocks in the Onaman Lake area to the north, which are 2769 +6/-5 Ma.

The age of gold mineralization is 2556 +72/-76 Ma as determined by a lead isochron on pyrite from mineralized felsic porphyries. This age is approximately 130 Ma younger than the age of the felsic porphyritic rocks and therefore there does not appear to be a direct magmatic-hydrothermal link between these intrusive rocks and the gold mineralization.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION AND REGIONAL GEOLOGY

1.0 Introduction

Gold mineralization in the Geraldton area occurs; 1) in quartz and quartz-carbonate veins in fractured greywacke, quartz-feldspar porphyry, gabbro and volcanic rocks, 2) in disseminated sulphide-bearing, highly fractured, zones in greywacke and quartz-feldspar porphyry, and 3) in massive quartz-sulphide lenses in oxide iron formation.

1.0.1 Purpose of study

The purpose of this study is; 1) to characterize the geological environment in which the gold occurs, 2) to determine the timing of emplacement of and the controls on the site of the gold mineralization, 3) to determine the nature and importance of the relationship between gold mineralization and iron formation and 4) to asses the relationship of the felsic intrusive rocks to the gold mineralization.

This study was conducted primarily south of Geraldton in an area approximately 15 kilometres long by 5 kilometres wide comprising the southern half of Errington Township and the southwestern quarter of Ashmore Township in the District of Thunder Bay (Figures 1 and 2). Within
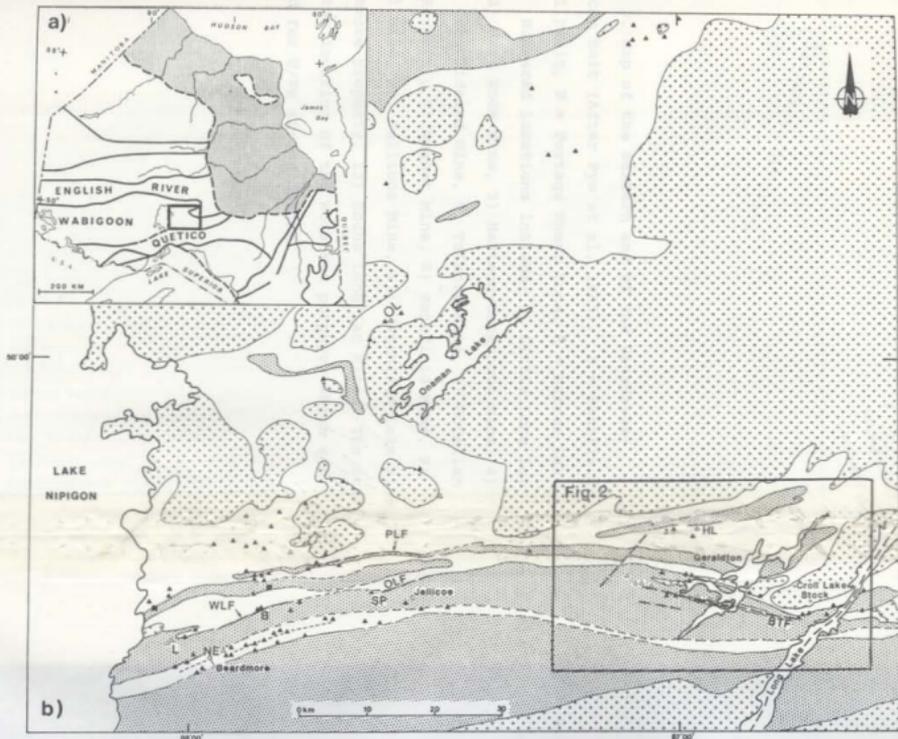
LEGEND

⬚ Felsic Intrusives		B	Bema Property (Watson Lake)
▦ Mafic Intrusives		HL	Hutchison Lake Mine
▨ Metasedimentary Rocks		L	Leitch Mine
☐ Metavolcanic Rocks		NE	Northern Empire Mine
		SP	Solomon's Pillars (Oremond Property)
⌒ Geological Boundary		WLF	Watson Lake Fault
− − − Faults		PLF	Paint Lake Fault
⋯⋯⋯ Lineament (Probable Fault)		OLF	Oxaline Lake Fault
▲ Gold Occurrences		BTF	Bankfield~Tombill Fault
△ Past Producing Mines			

Figure 1. a) Map of Northern Ontario showing the English River, Wabigoon and Quetico belts in central Superior Province of the Canadian Shield. The stipple pattern indicates Phanerozoic rocks. The Beardmore-Geraldton area is outlined in the black rectangle. b) Map of the eastern Wabigoon belt. The subprovince boundary between the Wabigoon metavolcanic-plutonic subprovince and the Quetico metasedimentary subprovince is presently defined as the southern boundary of the southernmost linear metavolcanic belt (Williams, 1986). Gold past-producers and occurrences are marked by open and closed triangles, respectively. The Onaman Lake massive sulphide property is marked OL.

Figure 2. Map of the eastern end of the Beardmore-Geraldton belt (After Pye et al, 1965). B = Bankfield-Tombill Fault, P = Portage Shear Zone, M = Marron Lake Fault. Numbered locations include; 1) Little Long Lac Mine, 2) Hard Rock Mine, 3) MacLeod-Cockshutt Mine, 4) Mosher Consolidated Mine, 5) Talmora Mine, 6) McLellan Mine (Roxmark), 7) Magnet Mine, 8) Bankfield Mine, 9) Tombill Mine, 10) Jellicoe Mine, 11) Hutchison Lake Mine, 12) Ashmore property, 13) Roche Long Lac Mine. The star marks the location of the Wods-Mac porphyry which was sampled for U/Pb zircon dating.

LEGEND

Felsic Intrusions
Mafic Intrusions
Mafic Volcanic Rocks
Wabigoon Sedimentary Rocks
Quetico Sedimentary Rocks
Fault, IF Iron formation
Gold Past Producers
Gold Occurrences
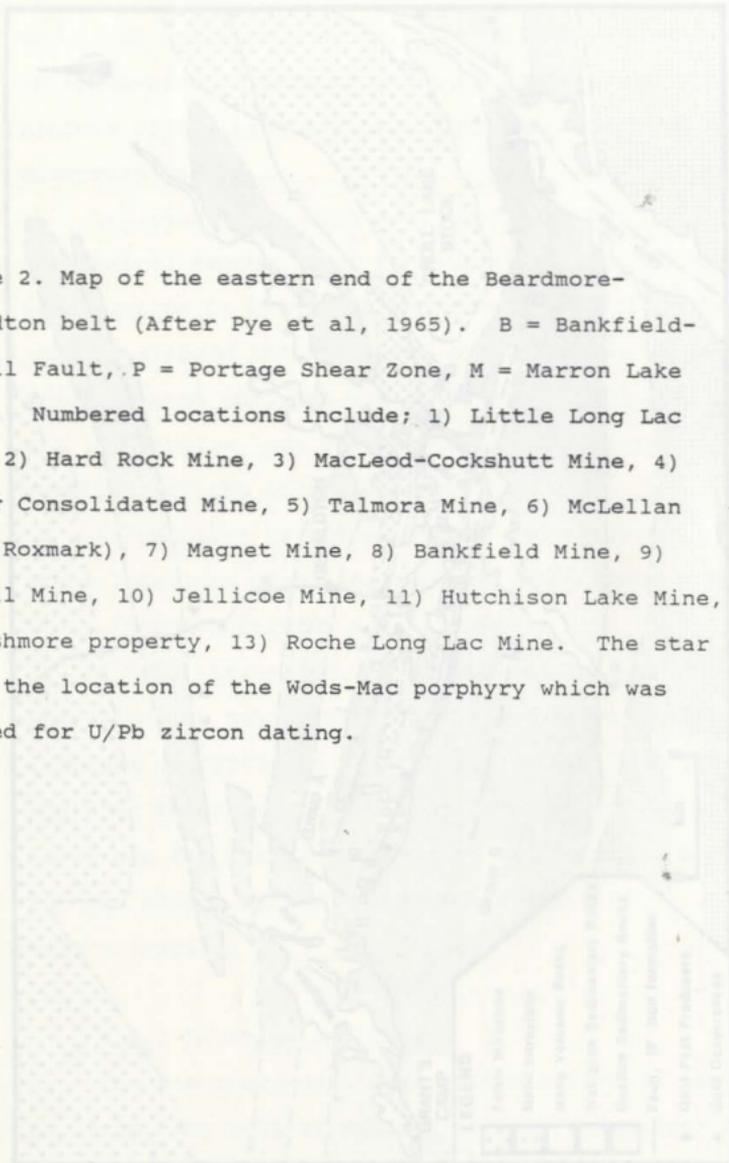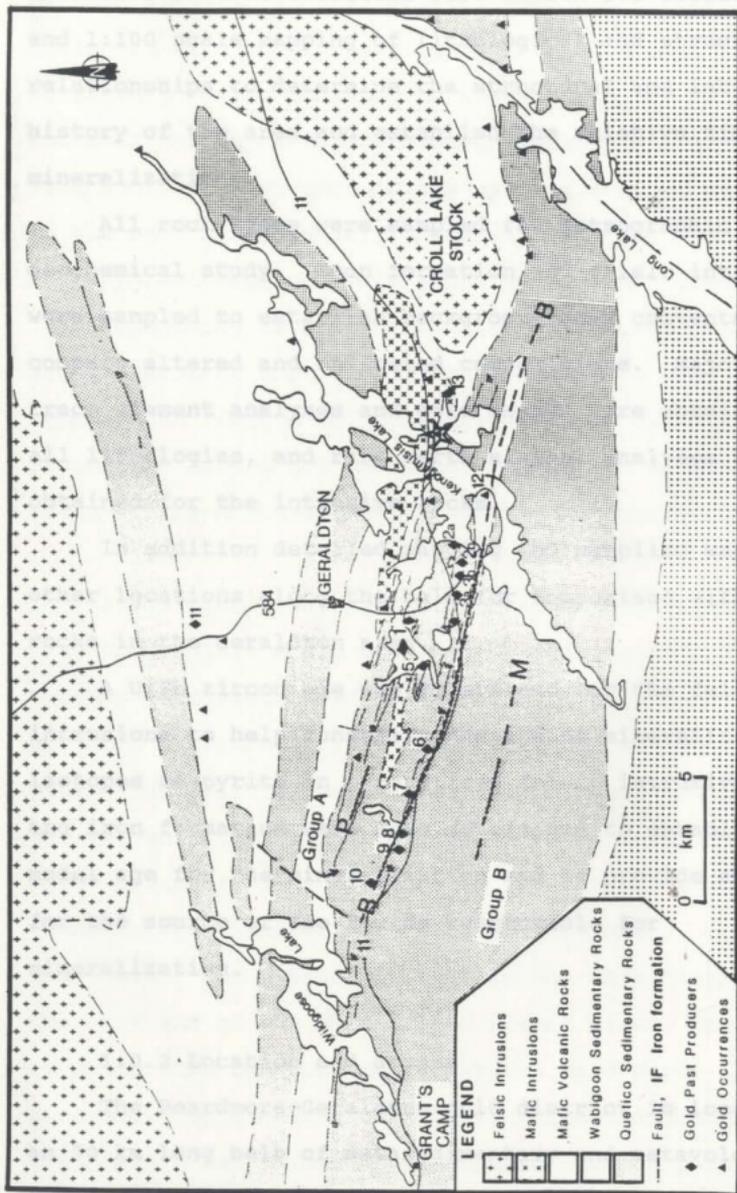
this area several locations were chosen for detailed 1:500
and 1:100 scale mapping of lithological and structural
relationships to determine the structural and intrusive
history of the area and establish the relative timing of
mineralization.

All rock types were sampled for petrographic and
geochemical study. Iron formation and felsic intrusions
were sampled to establish background gold contents, and to
compare altered and unaltered compositions. Major and
trace element analyses and gold assays were obtained for
all lithologies, and rare earth element analyses were
obtained for the intrusive rocks.

In addition detailed mapping and sampling was done at
other locations along the belt for comparison with the
rocks in the Geraldton area.

A U/Pb zircon age was determined for the felsic
intrusions to help constrain the age of mineralization. Pb
isotopes of pyrite in mineralized felsic intrusive rocks
and iron formation were also determined to establish a
model age for the mineralization and to provide evidence
for the source of the fluids responsible for
mineralization.

1.0.2 Location and access

The Beardmore-Geraldton gold district is located in
an 90 km long belt of metasedimentary and metavolcanic
rocks (the prefix meta will subsequently be omitted), east

of Lake Nipigon, approximately 160 to 250 kilometres
northeast of Thunder Bay (Figure 1a). The belt is
relatively easily accessed by Highway 11, the northern
route of the Trans-Canada Highway, which follows the belt
from south of Beardmore in the west to east of Geraldton
in the east (Figure 1b). Several north-south secondary
highways and logging roads allow additional access.

Topography is moderately flat with numerous swampy
areas. Much of the belt is drift-covered. Good outcrop
exposure is limited to highway rock cuts, old mine
properties (where not obscured by waste or tailings) and
areas stripped and trenched recently by prospectors.

1.0.3 History and geological setting of the deposits

In the 1920's and 30's gold-bearing quartz vein
systems were discovered in the area, and gold has been
produced intermittently for the past 50 years, from 18
mines (Table 1). Numerous gold occurrences are located in
the volcanic terrain to the north of the area, but the
major producers were all located in a narrow east-west
trending zone between Geraldton and Beardmore.
Sedimentary and intrusive rocks in the Geraldton area at
the east end of the belt hosted eleven mines, the largest
of which were the MacLeod-Cockshutt, Hard Rock, Little
Long Lac, Magnet Consolidated, Consolidated Mosher and
Bankfield mines. This area produced, over a period of 34
years, approx 2,900,000 ounces of gold with an average

Table 1. Production statistics for the Beardmore-Geraldton area (modified after Mason et al., 1985)

Mine	Years in Production	Ounces Gold	Ounces Silver	Tons of Ore Milled	Average Au Grade oz/ton	Average Ag Grade oz/ton	Host Lithology	References
GERALDTON AREA:								
MacLeod-Cockshutt	1938-68	1,973,728	101,388	10,337,229	0.14	0.09	greywacke porphyry iron formation	Horwood and Pye (1955)
Little Long Lac	1934-36 1956	605,449	52,750	1,780,516	0.34	0.03	greywacke quartzwacke (iron formation)	Bruce (1936, 1937) Pye (1932)
Mosher Longlac	1962-66	330,265	39,604	2,710,657	0.12	0.01	diorite iron formation porphyry greywacke	Pye (1932)
Hard Rock	1938-51	269,081	9,009	1,938,373	0.18	0.01	greywacke iron formation porphyry	Matheson and Douglas (1948) Horwood and Pye (1955)
Magnet Consolidated	1938-63 1946-52	152,089	16,879	359,912	0.42	0.05	greywacke iron formation	Pye (1952)
Tombill	1938-42 1955	69,120	8,595	190,622	0.36	0.05	greywacke porphyry	Matheson (1948) Pye (1952)
Bankfield	1937-42 1944-47	66,417	7,290	231,009	0.29	0.03	greywacke porphyry iron formation gabbro	Matheson (1948) Pye (1952)
Theresa	1935-38 1941-43, 45 1950-55, 55	4,785	202	26,120	0.18	0.01	quartz diorite mafic to intermediate volcanic	Johnson (1981)
Jellicoe Talmora Longlac	1939-41 1942, 48	3620 1417	145 36	14,000 6,634	0.40 0.21	0.01 0.01	greywacke greywacke gabbro	Matheson (1948) Pye (1952)
BEARDMORE AREA:								
Leitch	1936-68	847,690	31,802	920,745	0.92	0.03	greywacke lean iron formation	McKay et al. (1948)
Northern Empire	1934-41 1949	149,493	19,803	425,866	0.35	0.05	mafic to intermediate volcanics Titcomb (1948)	Benedict and Titcomb (1948)

grade of 0.1 oz/ton. In the Beardmore area at the west
end of the belt (Figure 1b), gold production was largely
from an area of sedimentary rocks (the largest being the
Leitch and Sand River mines) and one mine hosted in
volcanic rocks (the Northern Empire Mine). This area
produced over 1,135,000 ounces with an average grade of
0.66 oz/ton (Mason and McConnell, 1982).

On a regional scale the deposits are linearly
distributed in an east-west direction broadly parallel to
the strike of the sedimentary and volcanic stratigraphy
(Figure 1b), and concentrated along the southern margin of
the Wabigoon greenstone belt. Virtually all rock types in
the belt contain mineralization, except for the youngest
intrusive units, diabase and lamprophyre dykes.

The gold occurs predominantly in quartz and quartz-
carbonate vein systems in greywacke, felsic porphyritic
rocks, and conglomerate, as well as in silicified
sulphidic fracture zones in the above rock types and
hornblende gabbros, and sulphidic zones in iron formation.

1.1 Regional Geology

1.1.1 Regional setting

The Beardmore-Geraldton area is in the eastern end of
the Wabigoon Subprovince, a major subdivision of the
Superior province of the Canadian Shield (Figure 1a).
Wabigoon Subprovince extends in an east-west direction for

approximately 900 km and attains widths up to 150 km. It emerges from under Phanerozoic cover just west of the Manitoba-Ontario border and extends eastward under Lake Nipigon (aeromagnetic data ODM-GSC 1970a) past Longlac, where it again passes under Phanerozoic cover (Blackburn et al.,1985) (Figure 1a).

The Wabigoon Subprovince is a typical granite-greenstone terrain of Archean age, consisting of a supracrustal assemblage of predominantly volcanic rocks and lesser amounts of sedimentary rocks, into which were emplaced plutons varying in composition from granite, to syenite and gabbro (Card, 1983; Blackburn et al, 1985). To the north, the Wabigoon Subprovince is bounded by the English River Subprovince, and to the south by the Quetico Subprovince, both of which consist predominantly of "Couchiching type" turbiditic sedimentary rocks, and migmatites, as well as granitoid rocks of both anatectic and magmatic derivation (McGlynn, 1970; Blackburn et al, 1985).

1.1.1.1 Interpretations of stratigraphy

Ayres (1978) interpreted the Wabigoon Subprovince to be the dismembered and deformed remnant of a linear chain of volcanic islands whose lower and middle parts coalesced to form a continuous unit. The chain was bounded on the south by a penecontemporaneous turbidite sedimentary basin now represented by the Quetico Subprovince. Within the

western Wabigoon Subprovince, Blackburn et al (1985)
suggested that "...there was a consistent development
through time from initial, thick mafic, tholeiitic,
quiescent submarine flows, with little or no associated
clastic sediments, to more silicic, calc-alkaline,
pyroclastic, violent, in part subaerial, volcanism.
Clastic sedimentation associated with the latter was
widespread, and consisted of proximal alluvial fan,
braided river, and lacustrine facies, and distal submarine
facies." Ayres (1978) stated that the original volcanic
chain is now highly deformed and dismembered.

1.1.1.2 Structure

The Wabigoon granite-greenstone terrain is dominated
by elliptical to amoeboid domal structures, which are
related to batholith emplacement. The supracrustal rocks
are distributed in arcuate patterns that wrap around the
domes (Figure 1). The ends of these arcuate zones are
strongly attenuated, but in the interiors of the
supracrustal areas there are zones of relatively coherent
volcano-sedimentary assemblages (Blackburn, et al, 1985).
The Beardmore-Geraldton belt corresponds to the latter.
There the rocks strike dominantly east to east-northeast,
whereas in the north part of the Wabigoon, the strike
directions are much more variable and tend to warp around
the granitoid plutonic bodies (Figure 1b). In the south

part of the eastern Wabigoon, east-west trending
lineaments and faults are prominent structures.

1.1.1.3 Metamorphism

The Wabigoon subprovince is characterized by low
greenschist facies assemblages, with metamorphic grade
increasing rather abruptly to amphibolite facies at the
margins of plutonic and batholithic bodies. Ayres (1978)
noted that the increase in grade toward the granitic
batholiths is probably a contact metamorphic effect. The
relatively low metamorphic grades in the interior of the
belts indicate a relatively shallow burial, probably less
than 10 km (Ayres, 1978).

1.1.2 The Beardmore-Geraldton Belt

The Beardmore-Geraldton belt is at the southern
margin of the Wabigoon Subprovince (Figure 1b). In this
study the Beardmore-Geraldton belt is defined as the
southern part of the Wabigoon greenstone belt, where the
strike of the supracrustal units is predominantly east-
west, and the volcanic rocks are predominantly mafic in
composition. Felsic intrusive and extrusive units are
volumetrically minimal. In contrast, the volcanic rocks
to the north range from mafic through intermediate to
felsic in composition. Granitic intrusions are also a
major component of this part of the Wabigoon greenstone
belt.

In the Beardmore-Geraldton belt the rocks are distributed in lens-shaped elongate panels which alternate between domains dominated by mafic volcanic rocks and those dominated by sedimentary rocks (Figure 1b).

Within Errington and Ashmore townships, Pye (1952) and Horwood and Pye (1955) divided the greywacke unit south of Geraldton into two distinct sedimentary assemblages. The northern assemblage consists of greywacke, quartz-rich greywacke, siltstone, polymict conglomerate and iron formation, with a minor amount of mafic volcanic strata in the southeast part of Ashmore Township. They named this assemblage 'group A'. To the south of group A, the sedimentary assemblage consists of a very homogeneous, laterally extensive sequence of interbedded, medium to fine grained greywacke and siltstone. This southern package, 'group B', is notably lacking in iron formation and contains only very minor conglomerate.

The group A sedimentary sequence is intruded by hornblende gabbro, felsic porphyritic rocks and Proterozoic diabase dykes. Intrusive rocks, other than Proterozoic dykes, are absent in group B.

These two distinctive sedimentary groups (A and B) are continuous along the strike length of the belt. The iron formation-bearing strata are continuous along the entire belt from east of Geraldton, west to Beardmore and southwest under Lake Nipigon to north of Thunder Bay. The

Geraldton area has an anomalous proportion of iron formation relative to the rest of the belt. This may result from tectonic thickening of the iron formation in this highly deformed area (see Chapter 3). Tectonic thickening and thinning of units most certainly takes place at the outcrop scale. However, this greater development of iron formation in the Geraldton area may also be due to a change in depositional environment along the belt.

Conglomerate beds throughout the Beardmore-Geraldton belt also occur typically as narrow, laterally extensive units, confined to the northern heterogeneous sedimentary sequence. These conglomeratic horizons are commonly located near and parallel to sedimentary-volcanic rock contacts and/or fault contacts (Bruce, 1937a; Bruce, 1937b).

Numerous east-west striking faults are identified throughout the area. Many of the contacts between sedimentary rock- and volcanic rock-dominant terrains are occupied by faults, for example the Paint Lake Fault and the Watson Lake Fault (Figure 1b). Bruce (1937a) described schistose contacts between sedimentary and volcanic rocks at several locations in the belt. He suggested that movement had occurred along these zones obliterating all primary contact relationships.

In addition to east-west faults, the Beardmore-Geraldton belt is characterized by isoclinal folding.

Kehlenbeck (1986) identified the entire Beardmore-Geraldton belt as a complex folded terrain. He observed that the rocks of the southern part of the belt form a series of isoclinal antiforms and synforms. Fold axes are generally parallel to the strike of the units. Minor fold hinge lines and bedding (S_0)/ cleavage (S_1) intersection lineations vary both in trend and plunge along the strike of the belt. Beds dip steeply to vertically and strike dominantly east-west.

Deformation in the belt is most intense in the east around Geraldton, where Pye (1952) and Horwood and Pye (1955) identified in the south part of Errington and Ashmore townships, an elliptical zone of intense deformation, to the north of a major strike-slip fault (Figure 1b, and Figure 2). The deformation zone extends along strike for over 15 km and may attain widths up to 5 km (Buck and Williams, 1984).

Author's Note: The work for this thesis was done at the same time that the Ontario Geological Survey had several geologists working in the Beardmore - Geraldton area (Macdonald 1983, 1984; Lavigne, 1983; Kehlenbeck, 1984, 1986; Barrett and Fralick, 1985; and, Buck and Williams, 1984). Other than the occasional mutual exchange of ideas, all of the observations and conclusions in this thesis (except where referenced) were based on my own, independent, field and laboratory work.

CHAPTER 2

GENERAL GEOLOGY - DESCRIPTION OF ROCKTYPES

2.0 Introduction

The thesis area, which measures approximately 15
kilometres east-west by 5 kilometres north-south, is
located in the southern half of Errington and southwestern
quarter of Ashmore Townships, centred on Horwood and Pye's
(1955) southern sedimentary belt, groups A and B (Figures
2 and 3).

2.1 Sequence of lithologies

A generalized sequence of the lithologies is
presented in Table 2. Although the absolute timing of
events is poorly constrained, the relative timing of
intrusive, and deformational events has been well
established through field observations. Intrusive
relationships will be discussed with respect to each
intrusive lithology. The relationship between the
sedimentary and the volcanic rocks is unknown. No primary
contacts were observed. (See chapter 3 for more
discussion of this relationship.)

TABLE 2. Table of Formations

<u>Proterozoic</u>

Proterozoic diabase dykes
        intrusive contact

<u>Archean</u>
Quartz feldspar and feldspar porphyry intrusions
        intrusive contact

Chlorite schist
      ?

Intrusions of intermediate composition
      ?

Hornblende gabbro and gabbro intrusions
        intrusive contact

Sedimentary rocks: Group A; greywacke (sandstone-siltstone)
                            conglomerate, iron formation and,
                            Group B; greywacke, siltstone

    ?

Volcanic rocks: mafic pillowed flows, massive and fragmental flows

(Note: ? = contact relationships are unknown)

Figure 3. Map of the southern half of Errington and part of Ashmore Townships (after Pye, 1952, and Horwood and Pye, 1955). Locations of detailed maps are outlined in black and labelled with their respective figure numbers.

LEGEND

Diabase dykes

QFP Quartz feldspar porphyry

Chlorite schist

GBR Gabbro, hornblende gabbro

Intermediate intrusion

CGL Conglomerate

Iron formation

Greywacke – siltstone

Mafic volcanics

Geological contact: known, assumed

Fault: Known, approximate, assumed

Bedding, dip: Overturned bedding; Graded bedding, tops

Cleavage, dip: Vertical cleavage

Sense and plunge of minor folds

Inferred axis of mesoscopic isoclinal folds

Highway, main road: secondary road

Barton Bay

Algoma Trenches

Fig. 9a,b

LLLF

Lake Kenogamisis

N

GBR

GBR

GBR

Mosher Lake

Fig. 6

QFP

Mosher West

Mosher East

Hard Rock Open Stope
Figs. 33, 57-61

QFP

MacLeod-Cockshutt

CGL

CGL

DGL

Figs 19, 29
Fault Rock Outcrop

Porphyry Hill

Scale

0   5000 feet

0   1 kilometre

2.2 Mafic volcanic rocks

Within the Geraldton area, mafic volcanic rocks occur
in the southeast part of Ashmore township (in the group A
belt), and in the two linear east-west panels to the north
of the central sedimentary belt (Figures 2 and 3). Though
the volcanic rocks were not studied in detail, a few
representative samples were taken for petrographic
examination. These rocks are fine to medium grained,
light to dark green, with some outcrops pillowed and some
showing remnant amygdules. Interbedded with the flows are
beds of agglomerate and well-layered tuff which, along
with the pillows, indicate a submarine depositional
environment. The mineral assemblage is typical of lower
greenschist grade mafic rocks, consisting of varying
amounts of Na-plagioclase, fibrous amphibole, chlorite,
epidote, sericite, and carbonate, with minor quartz and
biotite.

2.3 Sedimentary rocks

The sedimentary rocks were studied in the Geraldton
area where deformation was least intense, (Figure 3); and,
along highway 11, at Grant's Cabins and at several
outcrops east of Jellicoe (Figure 2 and 1b), where group B
rocks are exposed. The classification scheme used for
naming these rocks follows that of Pettijohn, (1957).

2.3.1 Group B greywacke-siltstone

The sedimentary rocks of group B are composed primarily of a homogeneous sequence of fine to medium grained feldspathic greywacke interbedded with fine-grained chloritic siltstone. Minor thin lenses of intraformational conglomerate have been reported (Pye,1952). The coarser beds, which weather a light grey to white, typically vary in thickness from 10 to 30 cm, and are locally up to approximately one metre thick. The fine-grained beds, which weather a darker grey-green, due to their higher chlorite content, locally attain thicknesses of up to a metre, but on average they are 1 to 3 cm thick (Figure 4a,b,c).

The thicker beds are commonly massive (Figure 4d), but in many places they have regular variations in grain size from a coarse gritty to pebbly base, through to a finer-grained, slaty, top (Figure 4a, b). Rip-up clasts, flame structures, and poorly-developed cross-laminations are present. The coarser, sandy beds commonly have very sharp bases (Figure 4a,b,d). Rootless folds in two outcrops along Highway 11 are in strata that are not correspondingly deformed. These are probably soft sedimentary folds, indicative of tectonic instability during sedimentation.

Petrographically, the coarser grained layers consist mainly of angular quartz and feldspar grains with minor

Figure 4.   Photographs of group B greywacke and siltstone.
Photographs were taken at Grant's Camp on Highway 11 and in
each case the top of the photograph is to the northeast.

4a. Flame structure and small rip-up clasts of shale
in overlying coarse-based graded greywacke bed.

4b. Rhythmic graded bed sequence with thin sandy bases
that grade stratigraphically upward into shale.   The
sequence in the photo is capped by a massive greywacke bed.

4c. Scours of coarser greywacke into laminated shale
layer.

4d. Load casts of coarse greywacke into finer
greywacke. Note the shear zone with sigmoidal fractures
cross-cutting layering.
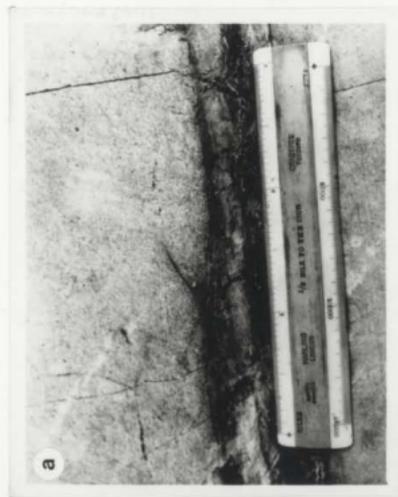
chert fragments. No lithic fragments were observed. The quartz and feldspar grains range from 0.3 to 0.8 mm. The feldspar grains are fresh, and like the quartz, are angular to subangular. Some of the quartz grains are composite and some are strained, even though the rock has only a faint foliation. The matrix, which comprises 30 to 50% of the rock, is a fine-grained groundmass of quartz and altered feldspar, plus chlorite, sericite and carbonate. Minor magnetite is present.

The finer grained layers have essentially the same constituents as the coarser layers, but in different proportions. The chlorite content is up to 35% in the fine-grained layers. The foliation in these layers is much more pronounced, with the chlorite and sericite in preferred dimensional alignment, wrapping around the larger quartz and feldspar grains.

2.3.2 Group A sedimentary rocks

This group consists of interlayered greywacke and slate, polymict, sandy conglomerate lenses and oxide iron formation. These rocks were intruded by hornblende gabbro, diorite and quartz and feldspar porphyritic felsic intrusions. In addition, local zones of chlorite schist are developed along faults and contacts of different rock types.

2.3.2.1 Greywacke and siltstone

Greywacke and siltstone are the most abundant lithologies of the group A panel. They vary from relatively coarse, massive sandy feldspathic greywacke to finely-laminated chloritic siltstone. The coarse layers weather light grey to white, commonly with a pebbly surface due to differential weathering of the more resistant quartz and feldspar fragments. The finer-grained layers weather a darker grey due to their higher chlorite content. In some outcrops, the chloritic layers contain abundant magnetite which imparts a darker colour.

On the island in Barton Bay (Figure 3) well-graded, 10-15 cm thick, greywacke siltstone beds were observed, tops to the south (Figure 5a). In one outcrop area on the south shore of Barton Bay, just west of the Little Long Lac mine property (Figure 3), the greywacke beds are up to approximately a metre thick, with coarse pebbly bases (clasts up to 2cm long). These beds have rip-up features at their bases, and they grade up through a massive sandy interval into very fine, magnetite-rich chloritic tops, the magnetite laminae being no thicker than one cm, and usually less (Figure 5b). In the same area, features similar to load casts are seen in sandy greywacke where it overlies 3 to 4 cm thick magnetite layers (Figure 5c). These features have been accentuated by deformation.

In other locations, such as the hydro line exposure west of Mosher Lake (Figures 3 and 6) individual beds are

Figure 5. Photographs of group A greywacke and siltstone.

5a. Graded sandy greywacke beds. Photograph of outcrop on the island in Barton Bay. Top of photograph is to the south.

5b. Greywacke bed, 80cm thick, grading from massive sandy base into finer siltstone, with a very fine, magnetite-rich top. Overlying bed repeats sequence of siltstone to magnetite over a 10cm interval. Note the magnificent refracted cleavage.

5c. Load casts of sandy greywacke into finer-grained, magnetite-rich, siltstone.

Figure 6. Detailed map of the Henker East hydbulline exposure (east of Henker Lake). (Note: Sample numbers, gold assays and respective rock types are keyed in the column on the right.)
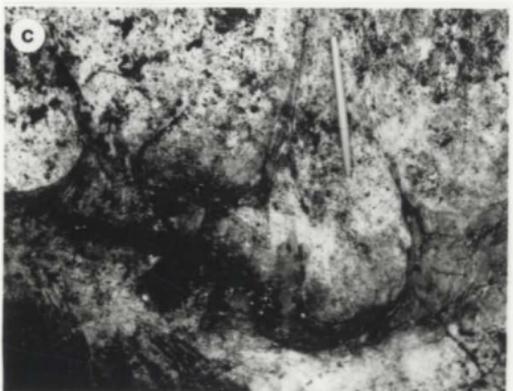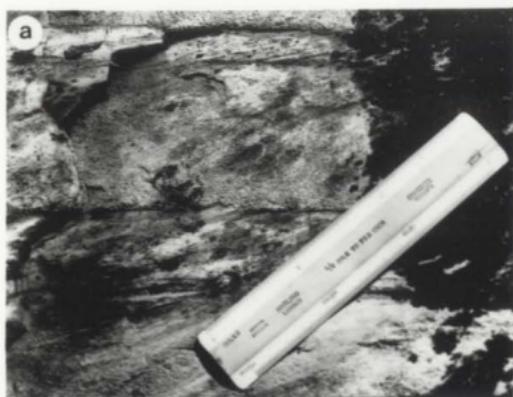
thinner, ranging from several cm to several tens of cm
thick and finer-grained than those described above. They
are composed dominantly of sandy and silty greywacke with
a significant portion of oxide iron formation. Where it
is most abundant, over an interval of several metres, the
magnetite layers are up to 30 cm thick. These layers are
actually compound units of narrow magnetite laminae with
very minor chert and very narrow siltstone laminae.
Individual laminae are usually less than a few mm thick.
In addition, narrow interbeds of green, fine-grained
chloritic layers, contain abundant disseminated magnetite
grains. These may be mafic tuffaceous interlayers.

Petrographically, the greywacke and siltstone of
group A are very similar to those of group B. The
principal difference is the generally coarser-grained
nature of the greywacke, and the high proportion of
magnetite in some of the chloritic slaty layers, of group
A. These sedimentary rocks are composed of angular to
subangular quartz and feldspar grains, 0.15 to 0.5 mm in
size, in a variable fine grained matrix of quartz, highly
altered feldspar (to sericite), chlorite, sericite and
carbonate.

Horwood and Pye (1955) and Pye (1952) distinguished a
separate lithology in the group A panel that they called
arkose. In thin section this unit is coarser-grained, with
more quartz grains and less matrix than the greywackes.
Quartz greywacke is probably a more appropriate term for

this rock than arkose because in the sections examined the
rock contained at least 15% matrix.

2.3.2.2 Conglomerate

Elongate, narrow, locally lensoid, conglomerate
horizons extend across Errington and Ashmore townships
within the group A panel (Figure 3). Good exposures are
present on the Bankfield property, on Highway 11 south of
the McLellan property (now Roxmark mines), on the east-
west hydroline right-of-way, west of Mosher lake (Mosher
West), and on Highway 11 at the entrance to the old
Mosher-Consolidated property (Mosher East) (Figure 3).

The conglomerate units are polymict, clast-supported
and matrix-supported pebble-cobble beds, and alternate
with sandy to silty greywacke beds. At the Roxmark
property the individual sandy beds are from 5 to 20 cm
wide and the conglomeratic layers average 50 cm in
thickness but may attain thicknesses of up to 1 metre. The
matrix here is very sandy (Figures 3 and 7a).

On the Bankfield property, conglomerate is exposed at
both the northern and southern edges of the outcrop area.
The conglomerate here is more massive and occurs in
thicker beds, up to 2 metres wide, which are bounded on
either side by massive greywacke beds.

Individual conglomeratic beds are moderately sorted
with respect to size of clasts, but there is a wide
variation in clast size between beds. In some outcrops

Figure 7.   Photographs of conglomerate in the group A
sequence.

7a. Conglomerate with sandy interbeds, on Highway 11
south of Roxmark trenches. Note the lens cap for scale.

7b. Deformed conglomerate layers with finer-grained
matrix and stretched-out volcanic clasts, Mosher West.

7c. Deformed conglomerate, southeast of Mosher Lake,
east of "Gabbro Fault Rock" outcrop. Note the consistent
asymmetry to the minor folds.
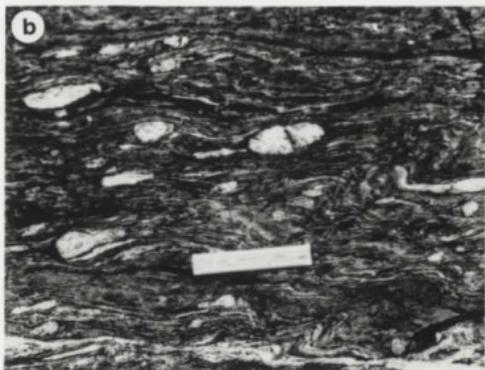
maximum clast size is 2-3 cm in diameter, for example south of Highway 11 between Little Long Lac and Eldee Lake, whereas, at the Bankfield and Roxmark properties the clasts attain sizes of 10 to 15 cm in the long dimension (even longer in the case of deformed mafic volcanic clasts). There appears to also be some variation in clast sizes along the strike of the beds.

Clast lithologies are very variable: granitic, granodioritic and quartz feldspar porphyritic clasts appear to be the most abundant, followed by mafic volcanic (and some felsic volcanic), quartz and a few chert and jasper pebbles. It may be that the intrusive lithologies appear to be more abundant than the extrusive ones because the latter are obscured somewhat by deformation (Figure 7b,c) and, especially in the case of the mafic clasts which are difficult to distinguish from the matrix of the conglomerate. The petrography and provenance of these clasts were not studied in detail.

The shape of the clasts depends on the composition and amount of deformation. Felsic plutonic and quartzitic clasts are typically more spherical than other clast types, and may have length to width ratios from 1:1 to 5:1. Felsic volcanic clasts tend to be more elongate, parallel to foliation, whereas the mafic volcanic clasts are stretched by as much as 15:1. Clasts are typically oblate spheroids ("pancakes") flattened in the N-S dimension and elongate E-W and vertically.

Petrographically, the matrix of these conglomerates is the same as the enclosing greywacke, varying from fine to medium grained, from slaty (schistose) to massive, and from chloritic to sandy (quartzitic and feldspathic). The matrix is composed dominantly of subrounded to angular quartz grains (some composite) and variable amounts of plagioclase, chlorite, carbonate, sericite and minor magnetite.

2.3.2.3 Alteration of clastic sedimentary rocks

Where these rocks are crosscut by quartz or quartz-carbonate veins the sedimentary rocks in some cases develop a chloritic-pyritic-sericitic selvedge on the veins, and in others a sericite-carbonate selvedge. This seems to depend on the original composition of the rock with the finer-grained sediments tending to develop chloritic selvedges, which commonly contain fine-grained pyrite. In all instances the alteration selvedges on the veins are very narrow and are seldom greater than the width of the veins themselves.

Extreme carbonate alteration of sedimentary rocks is developed at the open stope exposure on the Hard Rock property. Here, the rocks are so extensively altered that it is difficult in hand specimen and in thin section to determine their primary composition. These rocks are identified as sedimentary however because of their stratiform association with iron formation, and the

presence of what appears to be bedding in one short drill core. These rocks have also been extensively deformed and transposition of bedding has been extreme along the south side of the open stope (see Chapter 3).

2.3.2.4 Iron formation

The most distinctive member of the sedimentary sequence is iron formation which occurs at a number of stratigraphic levels within the sedimentary rocks of group A, interbedded with sandy and silty greywacke (Figure 3, 8a,b,c and d). Sedimentary sequences containing magnetite occur at several discrete, fairly laterally continuous horizons, however, it is evident from Figure 3 that many of the stratigraphic occurrences of iron formation are due to fold repetition. Structural thickening and thinning of the sedimentary package and frequent repetition of the sequence occurs at centimetre and metre scale (Figure 8c,d).

At the outcrop scale, these bands, which are composite units composed of alternating magnetite and clastic sedimentary laminae 10's of centimetres to metres wide, are traceable for 100's of metres. Similar to the distribution of the conglomerate, however, the iron formation actually appears to have a lensoid local distribution, with individual laminae thinning out rapidly along strike.

Figure 8. Photographs of iron formation in group A
sequence.

8a. Magnetite and hematite-rich iron formation
interlaminated with fine-grained silstone in trench on
island in Barton Bay.

8b. Deformed magnetite-rich layers 5 to 10 cm wide in
greywacke, Roxmark property.

8c. Highly deformed magnetite-rich layers in
greywacke and silstone, Mosher East (hydroline exposure
east of Mosher Lake.

8d. Very narrow magnetite-rich laminae in greywacke-
silstone beds, Mosher East. Note isoclinal folding of
sedimentary layers.

The iron formation varies from an almost purely chemical (Figure 8a), to an almost entirely clastic end-member (Figure 8d). The chemical end-member consists of magnetite(-hematite)-rich intervals intercalated with minor siltstone beds. The best exposure of this type is on an island in Barton Bay (Figure 3), where the iron formation has been exposed in a pit and trench (Figure 9a,b, Algoma trenches). Finely laminated bands of magnetite and hematite, with minor reddish jasper bands, are intercalated with narrow siltstone laminae (Figure 8a). These laminae form compound iron-oxide dominated packages which are interlayered with more coarse-grained clastic laminae.

In thin section, the Barton Bay iron formation consists of fine-grained magnetite-dominated and hematite-dominated layers, interlaminated with very fine-grained quartz-rich siliciclastic layers or narrow chert and jasper bands. The hematite grains have a tabular habit and are oriented with their long dimensions parallel to cleavage. Magnetite grains are generally equant and coarser-grained than the hematite grains (Figure 10). The iron oxide-rich bands are made up of many individual laminae with varying proportions of iron oxide and siliceous material. Individual beds tend to be discontinuous.

A complete spectrum of compositions exists between the two end-members. At the Roxmark property, Mosher

LEGEND

- Outline of outcrop
- Outline of trench
- Magnetite – hematite – jasper
- Greywacke – siltstone
- Gwke with minor mt laminae
- 68 Bedding, dip
- Graded bedding, tops, dip
- 70 Cleavage, dip
- Vertical cleavage
- S_c Bedding
- Structural lines
- Sense and plunge of minor folds
- +45 Sample location
- ☐ Fig.5a Photograph location and figure number.
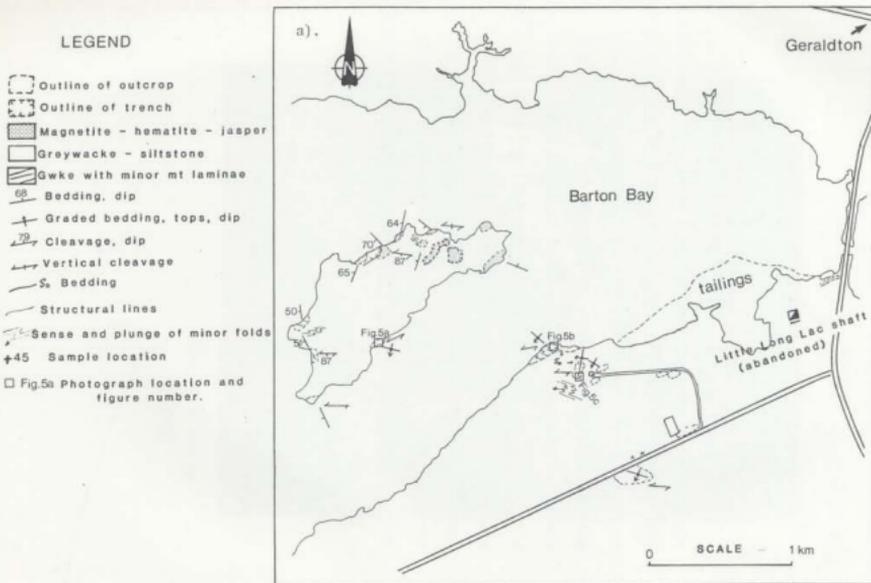
Figure 9. a) Map of the island in and shoreline of Barton Bay; and, b) Detailed structural map of the Algoma trenches. Sample locations are marked with crosses. Photograph locations are outlined by small squares and labelled with their respective figure numbers.
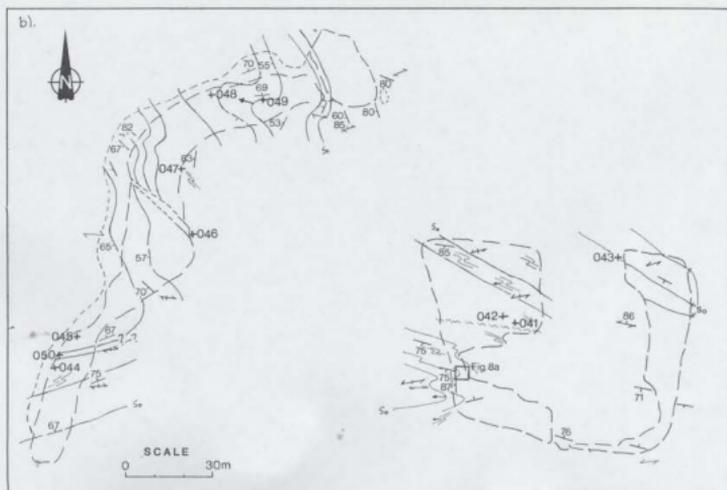
Figure 10. Photomicrograph of iron formation sample 045.
This sample is from the western Algoma trench on the island
in Barton Bay. The photograph was taken under transmitted,
polarized light at 2 X 2.5 magnification. Magnetite-
dominated and hematite-dominated layers are interlaminated
with very fine-grained quartz-rich siliciclastic or chert
and jasper bands. The magnetite grains are generally
equant and coarser than the hematite grains which have a
tabular habit. Note the cleavage perpendicular to layering
and the very slight offset of layering along this cleavage.

1mm

East, and the Bankfield property, the magnetite-rich laminae are intercalated with more clastic-rich beds resulting in the intermediate member (Figures 3, 8b).

In the south part of the Mosher East section (Figure 6), magnetite laminae (<1 centimetre wide) are intercalated with sandy-silty greywacke beds (these are actually representative of the clastic-dominated end-member). The next 65 metres of section to the north (some structural repetition is present) consists only of siliciclastic material. The next 60 metres of section contains more magnetite-rich beds. These beds are up to 20 centimetres wide composed of finely laminated magnetite (described above). The section alternates from being entirely clastic-dominated to being dominated by magnetite layers.

The clastic-dominated iron formation (LIF for lean iron formation) is characterized by laminae of almost pure magnetite which occur at the uppermost, finest-grained parts of thick, graded, greywacke-siltstone units, as seen in outcrops on the shore of Barton Bay just west of the site of the old Little Long Lac mine shaft, and east of the island. These were described above under group A greywacke and siltstone.

In the clastic-dominated sections, chert and jasper bands are absent. This is different from the more characteristic magnetite-hematite-chert interbanding of Algoma-type iron formation as described by Gross (1965).

In the Geraldton area, magnetite laminae often form the tops of graded greywacke beds. Graded bedding is seen in thin section (Figure 11), with the amount of magnetite increasing as grain-size of the clastic material decreases. Laminae of almost pure magnetite may occur at the tops of these units (Shegelski, 1978). What appear to be scour marks or load casts of siliciclastic material into magnetite layers are preserved in some samples (Figure 12a,b).

2.3.2.5 Alteration of iron formation

In no place were primary carbonate, silicate or sulphide facies of iron formation observed in the Geraldton area. However, carbonate and sulphide alteration is common on the selvedges of quartz-carbonate veins that crosscut the iron formation. Hand specimen photographs and photomicrographs clearly illustrate the replacement and overgrowth textures of carbonate and sulphide minerals in the oxide iron formation (Figures 13a,b 14 and 15). The carbonate minerals weather an orange-brown, and have variable relief in thin section, suggesting that they are iron carbonates, but the exact composition is unknown.

Sulphide and carbonate alteration of iron formation is very pronounced at the Open Stope exposure. Where veins are parallel to the bedding in iron formation the secondary nature of the sulphides is difficult to see;

Figure 11. Composite photomicrograph of iron formation siltstone sample 004. Note graded nature of sample from darker coarse-grained fragmental material to finer-grained magnetite and quartz-rich material at the tops of beds. The photographs were taken under transmitted, plane light. The scale bar is 1.0mm.

1 mm
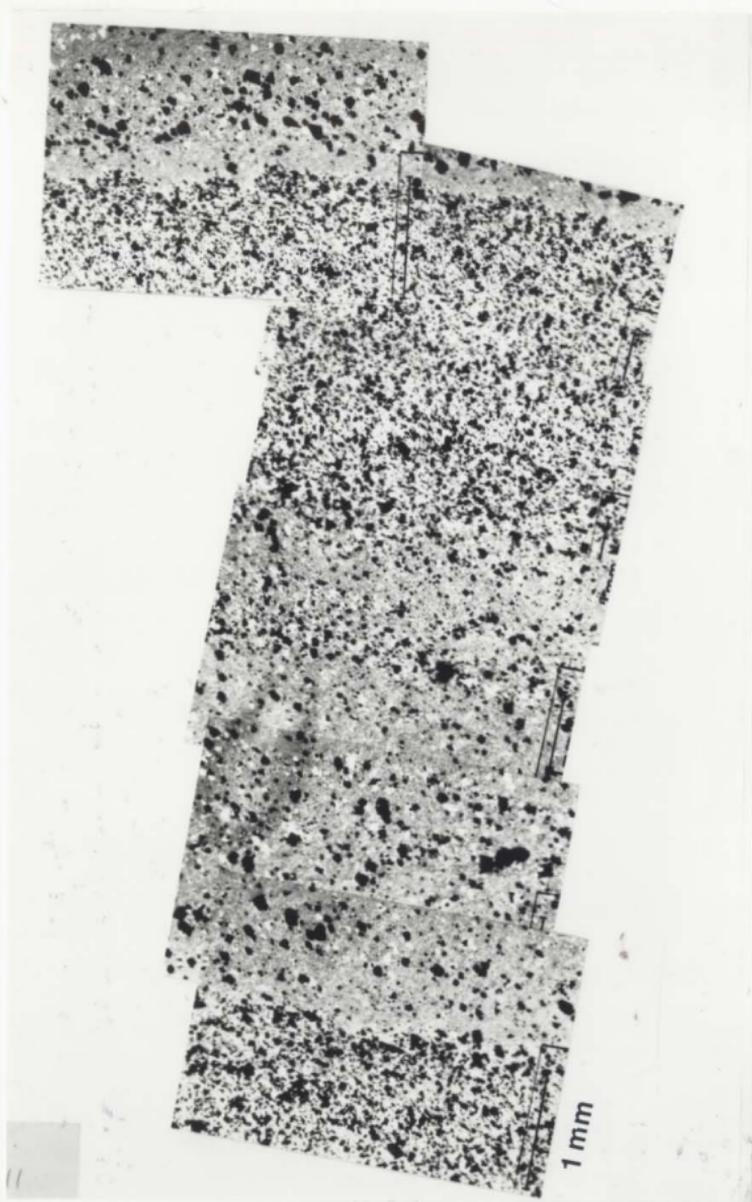
Figure 12. Photomicrographs of sedimentary structures in iron formation sample 153; a) scour marks, and b) load casts, of siliceous clastic material into magnetite-rich laminae. The photographs were taken in transmitted light. The scale bar is 1.0mm.
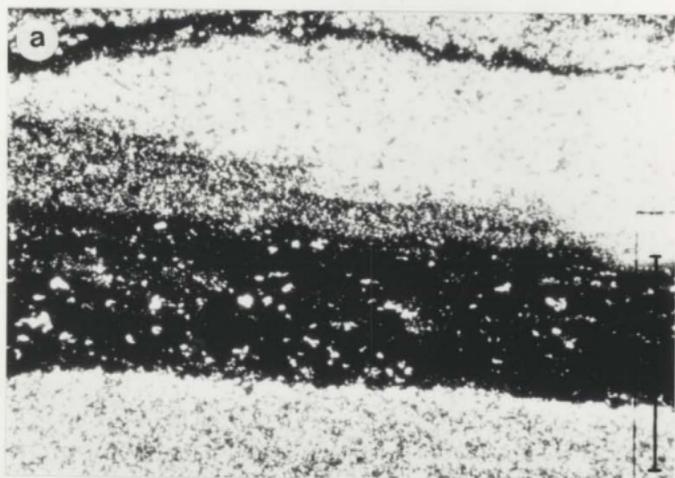
1 mm

Figure 13. Photographs of sulphide replacement of iron formation in hand samples; a) A sample of thin-banded magnetite-hematite-jasper-siltstone iron formation from the Solomon's Pillars property northwest of Jellico (see Figure 1b). Sulphides (pyrite with minor arsenopyrite) replace the iron oxide minerals outwards from a small crosscutting quartz-carbonate vein. (Photograph courtesy of A.J. Macdonald, Ontario Geological Survey, Toronto, Ontario.), b) A sample of banded magnetite-hematite-siltstone iron formation from the Hard Rock dump. Sulphides (pyrite and arsenopyrite) replace oxide minerals along and across folded bedding. Small quartz veinlets are hosted in fractures parallel to the axial plane of the minor folds.

10 cm

2 cm

a

b
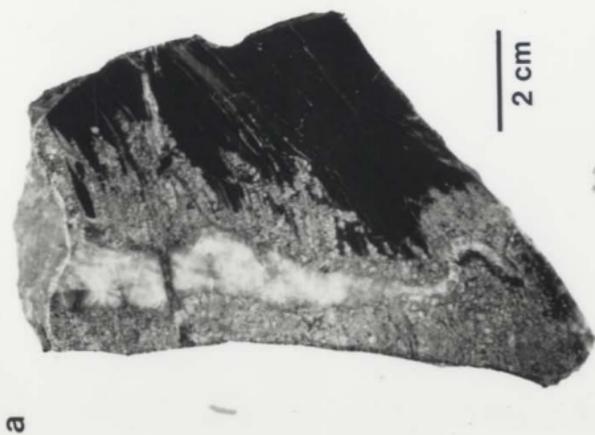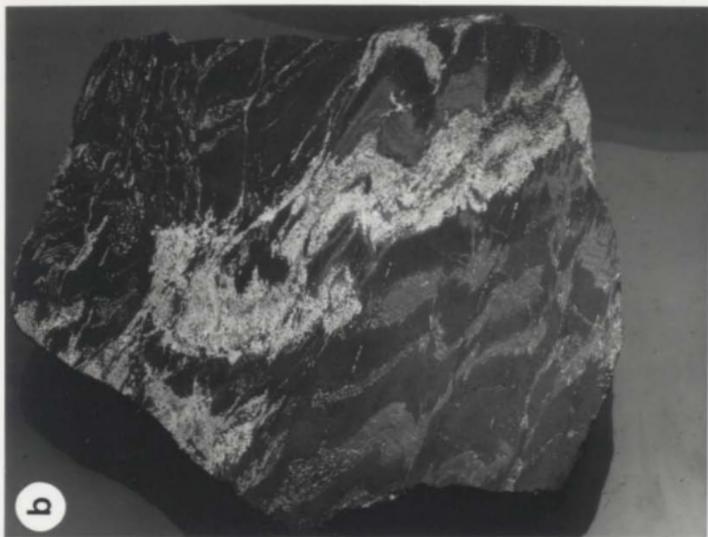
Figure 14. Photomicrographs of sulphides replacing oxide
iron formation; a) from the Open Stope exposure on the
Hard Rock property. Sulphides (pyrite with very minor
arsenopyrite and pyrrhotite) replace magnetite along
bedding, outwards from a cross-cutting quartz vein (dark
area to left of the large pyrite grain). Note how the
replacement front appears to be localized along the
contact between the magnetite and the darker clastic
laminae (right hand part of the photograph). This sample
assayed at greater than 10,000 ppb.; b) from the Roxmark
property. Pyrite porphyroblasts overgrow fine-grained
magnetite in an iron-rich chloritic slate. This sample
assayed at 4400 ppb Au.
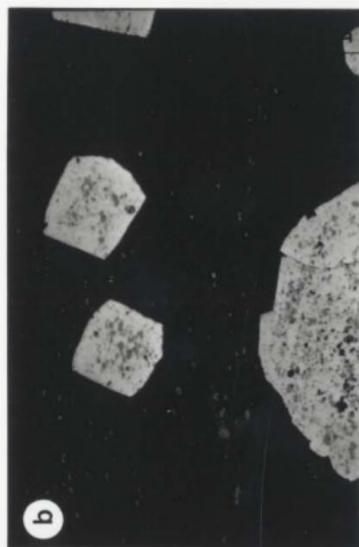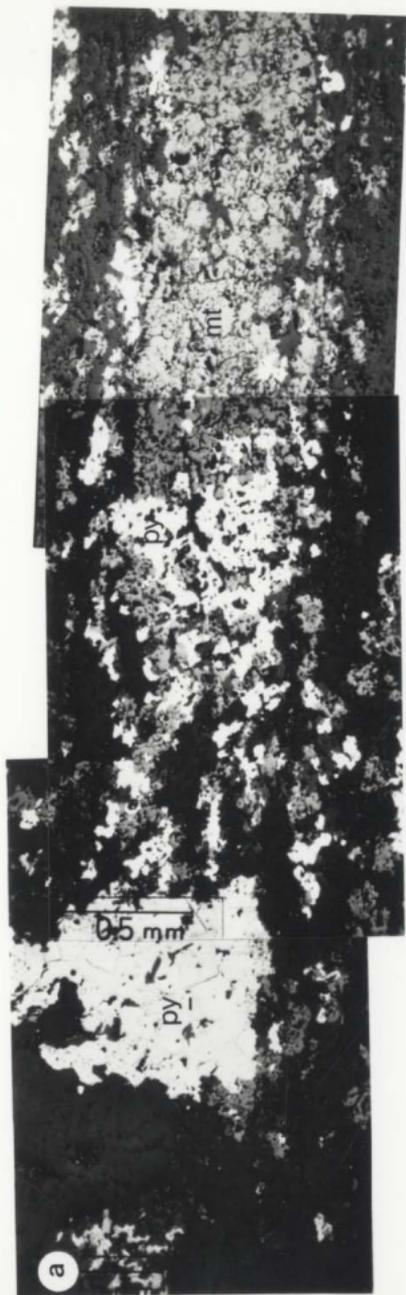
0.5 mm

Figure 15. Photomicrograph of quartz-carbonate vein
crosscutting thin-banded iron formation. This sample is
from the Open Stope exposure on the Hard Rock property.
The photograph was taken in transmitted light. The scale
bar is 0.5 mm.

0.5 mm

qtz ± cbt vein
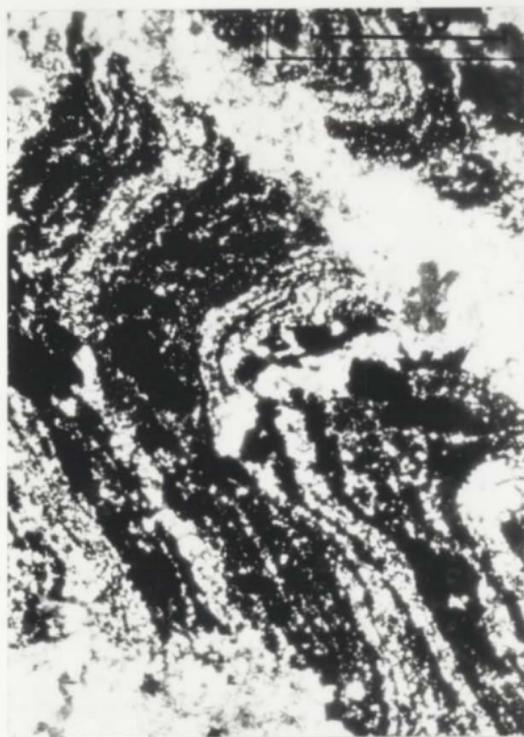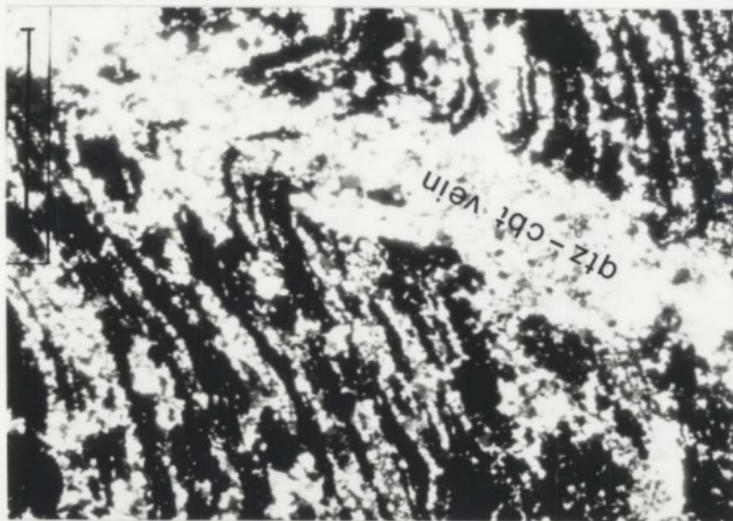
however, where veins cut the layering at a high angle the replacement nature of the sulphides is clear (Figures 13a,b ,15). In photomicrographs of sulphides from the open stope, pyrite and arsenopyrite progressively replace magnetite-hematite layers away from quartz veins (Figure 14a). The magnetite layers were first replaced along their contacts with siliceous layers, clastic or chert. The sulphides selectively replaced the magnetite layers. Pyrite grains overgrow smaller magnetite grains in slaty iron formation from the Roxmark property (Figure 14b).

2.3.3 Sedimentological summary of the sedimentary rocks in the Geraldton area

Due to limited outcrop and extensive deformation in the Geraldton area, sedimentary structures and stratigraphic relationships tend to be obscured. However, the associations of certain lithologies may be used to fit the area into a generalized sedimentological model.

The greywacke described from both group A and B sequences fits Walker's (1979) model of turbidite sediments. Turbidite beds are laterally extensive, tend to be parallel-sided and vary little in thickness laterally (Walker, 1979). The group B and group A sedimentary rocks appear to be comprised of A and E beds of the Bouma model. Several other facies which Walker (1979) stated are commonly associated with classical turbidites are observed in the group A sequence. These

include, pebbly sandstones, and clast-and matrix-supported
conglomerates. This association of rock types fits the
Resedimented (Turbidite) Facies Association described by
Ojakangas (1985) for Archean sedimentary rocks. In this
model, the turbidite sequences are developed on a
submarine fan. These turbidites are commonly interbedded
with conglomerate that is graded and lacks cross-bedding,
and represents resedimented conglomerates deposited from
mass flows.

The occurrence of iron formation in turbidites was
noted as early as 1936 by Rittenhouse (Shegelski, 1978)
who observed magnetite bands occurring in the top layer of
a graded sequence, which passed from greywacke through
argillite to iron formation. Shegelski (1978) noted that
the turbidite-hosted iron formation commonly occurs
between turbidite beds and is finely laminated. He called
this type "laminated iron formation" and interpreted
these layers to be equivalent to the ambient pelagic
sedimentation in the deeper water turbidite environments.
Only oxide facies iron formation was observed in the
Geraldton area.

There are two distinct sedimentary environments in
the Geraldton area. The group A sediments consist of
graded greywacke-siltstone (mudstone) turbidites with
minor coarse greywacke, polymict matrix-supported
conglomerate and iron formation, consistent with a
proximal, turbidite fan environment. To the south, the

group B sequence consists entirely of graded greywacke-siltstone mudstone with no conglomerate or iron formation, indicating a more distal turbidite environment. The lack of iron formation in the group B assemblage indicates that there was either no source of iron chemical precipitate in this area, or the deposition rates were higher and/or more consistent so that no distinctive iron-sediments were produced.

2.4 Mafic intrusive rocks

Large mafic bodies, several kilometres in length, intrude the volcanic rocks to the north of Geraldton. Similar, but smaller bodies intrude the sedimentary and volcanic rocks of the group A panel. There is an anomalous concentration of mafic intrusions in the Geraldton area relative to the rest of the Beardmore-Geraldton belt (Figure 1a). Horwood and Pye (1955, p16) noted that exposures of the mafic intrusions are more numerous and more extensive in the volcanic belts than in the sedimentary belts and no outcrops have been found in either the sedimentary belt underlying the town of Geraldton or in the southern group B part of the southern sedimentary belt. However, numerous intrusions are found in the group A sedimentary belt.

Outcrops of the mafic intrusions were examined on the Bankfield property, outcrops west and south of Mosher

Lake, on the Ashmore and Roche Long Lac properties at the east end of the study area, and several other outcrops to the north of the highway.

The mafic intrusions are dyke-like and sill-like masses that vary from a few centimetres to approximately 1500 metres in width (Horwood and Pye 1955). Their contacts are generally parallel to the sedimentary units which they intrude. However, crosscutting relationships were observed on the Bankfield Mines property, where mafic sills crosscut the sedimentary strata at low angles (Figure 16, 17a).

On the Bankfield property the mafic bodies range from a knobby-weathering, dark green variety (the "knobs" being blocky hornblende crystals) (Figure 17b); to a finer-grained dark greenish-grey rock which forms narrow sill-like bodies. In some outcrops the matrix surrounding the hornblende crystals weathers almost white rather than the normal greyish-green due to epidotization of the plagioclase in the matrix. The mafic intrusions are cut by narrow albitized zones which in turn are cross-cut by thin hematite-bearing fractures. The hematite-filled fractures are cut by small felsic dykes (Figure 17c). Within the central part of the mafic bodies, these dykes have variable strikes, that locally occur at high angles to the regional foliation.

The interiors of the mafic intrusions are relatively massive with foliation increasing toward the margin

Figure 16. Detailed geology map of the Bankfield
property. Sample locations are marked with crosses. Note
the crosscutting relationships of the mafic intrusions
into the sedimentary rocks, and the felsic intrusions into
both the sedimentary rocks and the mafic intrusions.

Outline of waste pile

Foundations of old mill building

Road to highway 11

LEGEND

P	Quartz feldspar porphyry
CS	Chlorite schist
M	Hornblende gabbro
S	Sedimentary rocks – greywacke, siltstone
IFe	Iron formation (magnetite layers)
C	Conglomerate

qv— Quartz vein

——— Geological boundary (known, approximate, assumed)

Outcrop boundary   small outcrop

257 •   Sample no. and location

SCALE

0   10   20   30   metres

Figure 17. Photographs of mafic intrusions on the Bankfield property.

17a. Mafic sill crosscutting greywacke. The intrusive contact is located just above the lens cap and is marked with two small black arrows. A fragment of banded oxide iron formation (marked IF) is included within the mafic intrusion.

17b. Coarse-grained hornblende crystals in the centre of a mafic sill, away from its deformed margins (see 17d).

17c. Felsic intrusive material crosscutting coarse-grained relatively undeformed gabbro.

17d. Chlorite schist developed at the margins of a mafic intrusion. Note the lighter material in the vicinity of the lens cap at the bottom of the photograph. This is felsic material that has been deformed subsequent to crosscutting the mafic sill.

(Figure 17d). Where the intrusions have been subjected to intense deformation, they are transformed into a strongly foliated, rubbly-weathering chlorite schist (Figure 17d). Similarly, at the margins of the mafic intrusions the cross-cutting felsic dykes are rotated to be sub-parallel with the foliation, and where felsic dykes are caught up in the schist zones, they form boudinaged lenses surrounded by chloritic, mafic material (Figure 17d).

Petrographically, the mafic intrusive rocks consist of stubby to elongate crystals of hornblende, which impart a porphyritic texture, and twinned plagioclase laths, in a fine grained matrix of altered plagioclase, epidote, sericite, carbonate, and locally fine-grained biotite and quartz (Figure 18a,b). In samples where the hornblende crystals are elongate, they have an ophitic texture with plagioclase laths of approximately the same size (Figure 18a). The hornblende in these rocks is commonly partially altered to chlorite and minor carbonate. In one sample (228) remnants of clinopyroxene were observed in the interiors of several of the stubby hornblende crystals. In some samples, the plagioclase is almost entirely altered to epidote, carbonate and sericite. Opaques consist of less than 5% magnetite and less than 2% sulphide in most sections. The magnetite contains abundant ilmenite intergrowths.

Figure 18. Photomicrographs of mafic intrusions.

18a. Coarse-grained equigranular plagioclase and hornblende crystals with ophitic texture.

18b. Very coarse hornblende crystals in fine grained plagioclase-quartz matrix.

Some remnant pyroxene within hornblende was observed in one thin section. Most of the hornblende is now altering to chlorite.

1 mm

2.5 Chlorite schists

Chlorite schist units occur as: 1) narrow layers at the contacts of mafic intrusions with other rock types, as on the Bankfield property (above); 2) as narrow bands entirely enclosed within massive hornblende gabbro; and, 3) at the contacts of felsic intrusions and sedimentary rocks . Outcrops of this schist were examined immediately south of the Bankfield-Tombill Fault, on the Roxmark property; associated with gabbroic intrusions in outcrops on the hydroline exposure west of Mosher Lake and south of the lake to outcrops on Highway 11; and, further southeastward along strike to an area south of the MacLeod-Cockshutt and Hard Rock properties (Figure 3).

In the series of outcrops from west of Mosher Lake southwest to south of the Hard Rock property, lenses and layers of chlorite schist are intercalated with coarse-grained hornblende gabbro (Figure 19a,b,c,d). These rocks outcrop along a narrow zone that is parallel to the strike of the enclosing sedimentary rocks and the Bankfield-Tombill Fault (BTF), and in several places appears to enclose the fault. Similar to the chlorite schist units at the margins of the gabbroic intrusives on the Bankfield property, these are dark green, highly foliated, schistose, rubbly-weathering outcrops (Figure 19d), interbanded with very finely laminated, highly chloritic, material (Figure 19c). At this location, however, the

Figure 19. Photographs of hornblende gabbro and chlorite schist from the Fault Rock Outcrop.

19a. Fairly massive, coarse-grained hornblende gabbro.

19b. Slightly foliated hornblende gabbro. Narrow chloritic seams are developed parallel to foliation direction.

19c. Strongly folitaed gabbro with prominent chloritic laminae and boudinaged and rotated quartz veins parallel to foliation direction.

19d. Extremely foliated, rubbly-weathering, chlorite schist zone with narrow, discontinuous, quartz lenses.

Deformation and alteration of massive hornblende gabbro.
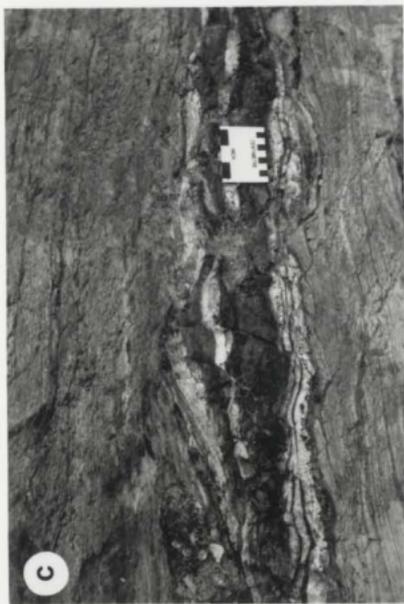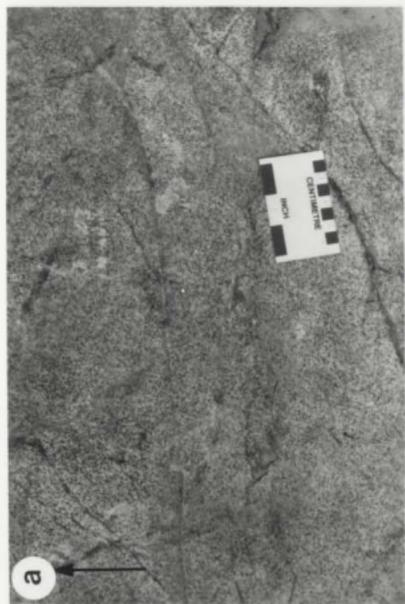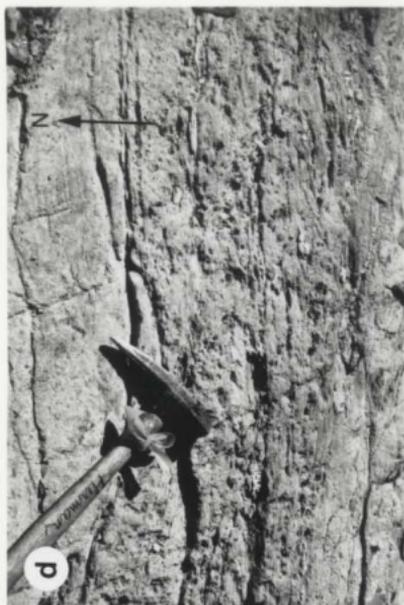
chlorite schist units are more extensive, up to several metres wide. They are not exclusively localized at contacts of different rock types but are enclosed entirely by gabbro, and locally are at gabbro-sediment contacts.

These outcrops were originally mapped by Horwood and Pye (1955) and Pye (1952) as tuff and volcanic breccia, intruded by gabbro. Pye (1952, p13-14) interpreted the rubbly-weathered outcrops to be volcanic breccia, composed of highly altered, schistose elliptical fragments. The finely banded schist that is interbanded with the "fragmentals" he interpreted to be waterlain tuffs, the banding being due to more abundant chlorite in some layers than in others. In thin sections Pye observed that the two rocks had a similar mineral assemblage; chlorite, altered plagioclase, quartz, and small amounts of sericite, carbonate and epidote; however, the "tuff" bands had constituent minerals arranged in parallel laminae, with chlorite-dominated laminae alternating with those containing dominantly quartz and feldspar.

Detailed examination of this series of outcrops indicates that these "fragmental" and "tuffaceous" units are actually gradational into the surrounding gabbro bodies which were thought, by the above authors, to be intrusive into them. It is postulated that these chlorite schist zones are not a primary rock type as suggested by Horwood and Pye (1955), but were derived from the deformation and alteration of massive hornblende gabbro.

Massive gabbro (Figure 19a) may be followed across
strike into moderately foliated gabbro where the
hornblende phenocrysts start to become elongated and
parallel (Figure 19b) . This transition continues into
more foliated rock in which narrow (less than 1 cm)
anastomosing chloritic "sheared" zones have developed
(Figure 19c), and finally into the intensely foliated,
rubbly weathering schist and the very finely laminated
bands (Figure 19d). This entire transition may take place
within 2 or 3 metres.

The gradational nature of these chlorite schists with
massive gabbro is also documented in thin sections. The
sequence from massive hornblende gabbro to chlorite schist
is represented by progressive destruction of the
hornblende crystals by alteration to chlorite and minor
epidote, and by progressive decrease in grain size.
Plagioclase is altered to epidote, carbonate and chlorite.
As the rock becomes finer-grained, chlorite, carbonate and
quartz become dominant, with the chlorite forming almost
monomineralic dark bands. In the most schistose sections
irregular streaks of dusty-brown semi-opaque material form
parallel to the chlorite. In reflected light these masses
are a semi-opaque bluish-grey and are probably hematite +
titanium oxides, probably leucoxene, formed as an
alteration of ilmenite-magnetite intergrowths. Sulphides
are minor in abundance, less than 2%, and consist of
pyrite and chalcopyrite.

Geochemical analysis and mass balance calculations were done to further test the hypothesis that the chlorite schist was derived directly from the hornblende gabbro (see Chapter 4). The presence of texturally and mineralogically similar-looking chlorite schists at the contacts of hornblende gabbro on the Bankfield property described above supports this hypothesis. The presence of leucoxene also indicates that they probably underwent a major hydrothermal alteration as leucoxene is not typically a primary igneous phase.

Although some of the chlorite schist, that Horwood and Pye (1955) and Pye (1952) mapped as tuff and agglomerate, was originally gabbro, on the Ashmore property there are true tuff and agglomerate units interbedded with mafic flows. Thus some of the chlorite schist along the fault zone may be volcanic material that has been deformed in a major fault , but not all the chlorite schist units along the fault in the study area can be explained as primary, intercalated, volcanic strata. This interpretation would relieve the difficulty Horwood and Pye (1955) had in explaining the relationship of these "tuff and breccia" zones to the surrounding sedimentary rocks. Many of the chlorite schist zones in the area may be fault zones. The mechanism by which these units were formed is discussed in Chapter 3 (shear zones and faults).

2.6 Intermediate intrusive rocks

A suite of intrusions that are petrographically and geochemically "intermediate" between the mafic and felsic intrusive rocks occur in a few outcrops within the Geraldton area. The relative age of these rocks with respect to the felsic intrusions is unknown from this study as cross-cutting relationships were not observed, but they are grouped with the mafic intrusions because of their close spatial association with these rocks.

Contacts of this rock type with the surrounding rocks are exposed only on the Ashmore property. Here the intrusion cuts across mafic volcanic rocks and a mafic gabbroic intrusion. According to Pye (1952), they are generally small bodies, either narrow sills or dykes intrusive into sedimentary rock, or larger masses spatially associated with gabbroic intrusions.

In outcrop these bodies are massive, fine to medium grained, greyish-white on the weathered surface, and darker grey with white plagioclase crystals visible on the fresh surface. In some outcrops they are porphyritic in others they are essentially equigranular. In two locations (the Roxmark and Ashmore properties) these bodies contain up to 7% arsenopyrite and a few samples contain anomalous gold values.

2.7 Felsic intrusive rocks

Felsic porphyritic rocks outcrop along a narrow zone restricted to the group A sedimentary belt in the west, and the southern part of the volcanic belt in the east (Figures 3). This roughly linear distribution is spatially coincident with the distribution of the mines in the area, with the BTF, and to some degree also with the mafic intrusions.

The porphyry bodies in all areas crosscut all other rock types except the diabase and lamprophyre dykes. (Their relationship to the intermediate intrusions is unknown.) Underground at the MacLeod-Cockshutt Mine the porphyry truncates folded sedimentary rocks, implying some deformation prior to intrusion (Pye,1952). Similarly, included fragments of highly foliated gabbro suggests that the latter rock type had undergone some deformation prior to and/or during intrusion of the porphyries. The porphyries themselves are intensely deformed in some places and therefore must have been emplaced prior to the end of deformation.

In most outcrops the porphyry contacts are conformable with the enclosing stratigraphy. Very few cross-cutting relationships are exposed. This led to confusion in the past as to the intrusive nature of this rock. For example, Reid (1945) suggested that the porphyry was of sedimentary origin because of; 1) its

generally conformable nature, "interbedded" with greywacke
and iron formation; and, 2) its similarity in appearance
to an arkosic sedimentary rock.

However, cross-cutting relationships are exposed on
the Bankfield property (Figures 3,16, 20a) and on the
hydroline exposure west of Mosher Lake (Figures 3, and
20 a,b). At the latter location a 30 centimetre long
fragment of greywacke, with interbedded folded iron
formation, is enclosed entirely within porphyry (Figure
20b). The fragment may have originated from a few 10's of
centimetres away, where the porphyry is in contact with the
sediments. Throughout the remainder of this outcrop area
the porphyry contacts are conformable with the enclosing
sedimentary rocks.

On the Bankfield property the porphyry crosscuts
greywacke and lean iron formation at a high angle, with
very irregular margins (Figure 20 a). Narrow felsic dykes
cut the hornblende gabbro at a relatively high angle to
the foliation, and a small fragment of highly foliated
gabbro is included within a porphyry dyke. Commonly these
contacts are the site of development of chlorite schist
and also of quartz veins and some associated pyrite
deposition.

Based on field evidence and spatial distribution the
felsic porphyritic rocks are divided into two distinct
groups; the western porphyries and the eastern porphyries.

Figure 20. Photographs of intrusive nature of the
Geraldton quartz feldspar porphyry.

20a. Quartz feldspar porphyry nose crosscuts banded
oxide iron formation and greywacke at the Bankfield
property. No evidence of a chilled margin was observed on
the border of the porphyry.

20b. Quartz feldspar porphyry crosscuts iron
formation and greywacke on the Mosher West hydroline
exposure (west of Mosher Lake). Note the fragment of iron
formation included within porphyry in the left centre part
of the photograph.

IF

a

QFP

b

QFP

IF
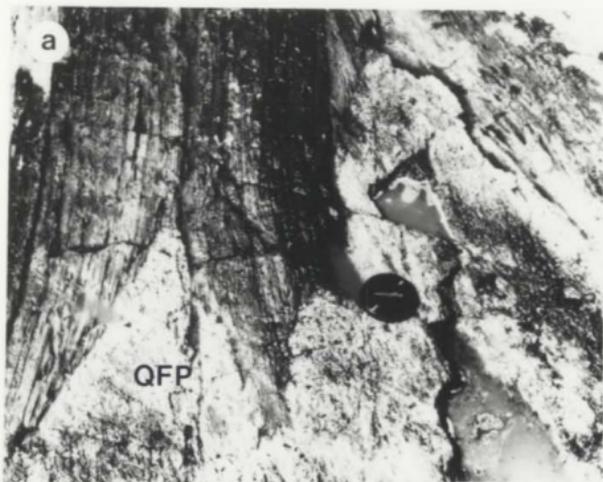
2.7.1 Western porphyries (WP)

The porphyries in the western area, west of Lake Kenogamisis, form sheet-like intrusions which are oriented parallel to the regional foliation and orientation of the stratigraphy. The western porphyries weather a light grey to white and are commonly fine-grained. Phenocrysts of both quartz and feldspar are visible, but they are usually small and rounded, and not conspicuous on the weathered surface. This rock is easily mistaken for a sedimentary rock, especially where a strong foliation has developed, giving it a "bedded" appearance.

The intensity of foliation varies considerably between outcrops. The grain size of these rocks is also variable. On the Bankfield property, in an outcrop just north of Highway 11, is a fairly coarse grained exposure with abundant, relatively large, quartz phenocrysts (up to 8-10 mm). In contrast, the small felsic dykes that crosscut the hornblende gabbro in outcrops to the north on the Bankfield Property are equigranular.

Weathering colour and texture are variable depending on the intensity of deformation and alteration. Where deformation has been intense a distinct foliation is developed. Most of the porphyries in the western group are moderately to extremely foliated. The more highly foliated rocks tend to assume a greenish colour, due to an increase in white mica.

The western porphyries contain variable proportions of quartz and albite phenocrysts (Figure 21a,b,c,d). Phenocryst size may vary from 2 to 8 mm in diameter, with an average of 3.5mm, and they may comprise anywhere from 15 to 50 % of the rock. The albite phenocrysts are nearly pure albite (Ab_{96-100}) (Table 3), and are very homogeneous in composition. Many of the plagioclase phenocrysts are twinned, but none show any evidence of zonation. The quartz phenocrysts often have corroded margins.

The matrix is fine crystalline material composed of quartz and plagioclase and is homogeneous. Two small K-feldspar grains were analysed during probe analysis of the phenocrysts, but they were very small and very rare. Samples of all the porphyries were stained for K-feldspar and only the granitic stock to the east, the Croll Lake Stock, gave a positive indication of K-feldspar.

All of the WP show evidence of alteration. A variable amount of sericite and carbonate alteration of both phenocrysts and groundmass is present. In some samples up to 85% of the rock consists of carbonate and sericite. Bands of sericite impart a foliation to many of these rocks. In many samples the fabric penetrates the albite phenocrysts. There is no foliation developed in the quartz phenocrysts but they commonly show undulose extinction and development of pressure shadows, evidence of their having been strained.

Figure 21. Photomicrographs of western felsic porphyritic intrusive rocks. All photographs were taken in transmitted light under crossed nicols. Black lines on photos b, and d are ink outline guides for microprobe analysis. The scale bar is 1 mm. The photographs were all taken at the same scale.

21a. Twinned albite phenocrysts in fine-grained quartz-plagioclase-sericite-carbonate matrix. Sample from the Bankfield property.

21b. Twinned and untwinned albite phenocrysts in fine-grained, moderately foliated matrix. Sample from the Mosher East area.

21c. Quartz and albite phenocrysts in altered, moderately foliated, fine-grained matrix of quartz, plagioclase, carbonate and sericite, and minor pyrite. The section is cut by a small quartz veinlet which has been slightly deformed. The sample is from the Porphyry Hill outcrop.

21d. Highly altered and foliated porphyry. Pyrite and arsenopyrite are abundant in this rock. This sample is also from the Porphyry Hill outcrop.
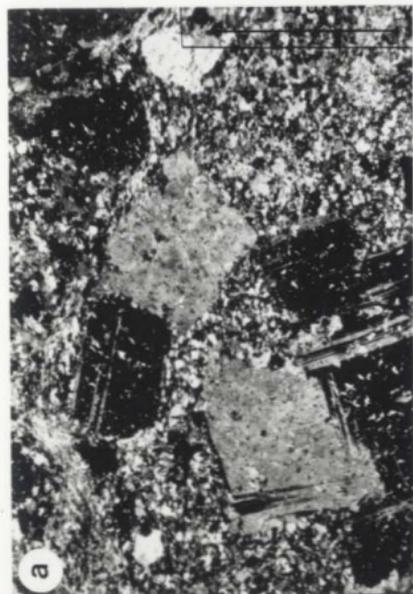
Table 3. Electron microprobe analyses of western quartz-feldspar porphyries.

	PLAGIOCLASE						
Sample	011	011	214	214	220	220	220
N *	8	3	8	4	5	1	3
	phenos	(a)	phenos	matrix	phenos	(a)	matrix
wt %							
SiO_2	67.40	64.96	67.52	67.34	68.34	63.37	68.37
Al_2O_3	20.30	18.96	20.12	20.07	20.06	18.89	19.69
FeO	0.11	0.09	0.05	0.11	0.05	0.00	0.03
CaO	0.15	0.07	0.33	0.24	0.31	0.20	0.16
Na_2O	11.60	0.34	11.54	11.32	11.42	0.00	11.31
K_2O	0.49	15.97	0.14	0.30	0.12	15.80	0.51
TOTAL	100.05	100.39	99.69	99.37	100.3	98.26	100.7
WT % PROPORTIONS							
AN	0.7	0.4	1.6	1.2	1.5	1.0	0.8
AB	98.1	2.9	97.7	95.7	96.7	0.0	95.7
OR	2.9	94.4	0.8	1.8	0.7	93.4	3.0
TOTAL	101.8	97.7	100.1	98.7	98.9	94.4	99.5

a = one small grain analysed.

	SERICITE			CHLORITE	CARBONATE	
Sample	011	214	220	011	214	220
N *	3	6	4	5	6	2
wt %						
SiO_2	46.02	47.63	49.52	25.97	0.01	0.01
TiO_2	0.36	0.45	0.41	0.13	0.00	0.00
Al_2O_3	34.50	35.46	28.82	19.09	0.00	0.00
Cr_2O_3	0.01	0.03	0.01	0.06	0.00	0.00
FeO	4.06	1.77	5.42	31.42	14.95	0.22
MnO	0.01	0.02	0.02	0.02	0.23	0.11
MgO	2.04	1.39	3.02	11.63	13.88	0.61
CaO	0.02	0.22	0.01	0.06	27.03	54.90
Na_2O	0.75	1.00	0.15	0.00	0.00	0.00
K_2O	7.35	7.49	8.05	0.00	0.00	0.00
TOTAL	95.13	95.45	95.43	88.44	56.11	55.84
PROPORTIONS						
Fe	52.63	60.16	50.15	60.16	20.12	0.31
Mg	47.10	39.69	49.70	39.69	33.28	1.51
Ca	0.28	0.16	0.15	0.16	46.60	98.19
FM Ratio	0.53	0.60	0.50	0.60	0.37	0.16

(Values reported are averages of N number of analyses.)

Electron microprobe analyses of carbonate composition in two samples are given in Table 3. In one sample the carbonate was almost pure calcite, while in the other it was ankerite. The variation in carbonate species with rock type or degree of alteration was not studied in detail but is an important area for further study of these rocks. The ferromagnesian mineral in these rocks consists of a minor amount of chlorite (and epidote). Electron microprobe data on chlorite in one sample indicates that it is iron-rich (Table 3). No biotite or hornblende was observed in these rocks.

2.7.2 Eastern porphyries (EP)

The porphyries to the east of Lake Kenogamisis intrude sedimentary and volcanic rocks and massive gabbro (Figure 2). The contacts of the porphyry here are more irregular than where they intrude sedimentary rocks in the west. On the Roche Long Lac property to the east their strike varies from N70W to N80E (Horwood and Pye, 1955 p97).

The eastern porphyries are darker grey in colour on the fresh and weathered surface than the western porphyries. Phenocrysts are an off-white colour and consist entirely of plagioclase. The groundmass of these rocks contains more ferromagnesian minerals than the western porphyries. At Wods-Mac the ferromagnesian

mineral is dominantly chlorite, while at Roche Long Lac it
is biotite.

The EP consist of large (5-8 mm) plagioclase
phenocrysts that make up 20-40% of the rock (Figure
22a,b,c,d,) set in a fine-grained groundmass. The
phenocrysts are both twinned and untwinned, and zoned and
unzoned. The zoning is oscillatory, and compositions vary
from approx Ab_{66} to Ab_{75}. Electron microprobe results on
phenocryst and matrix compositions are given in Table 4.
The phenocrysts are generally very angular, retaining
their primary igneous texture, but they are variably
altered to sericite and minor carbonate. The carbonate
composition of one sample is Ca-Mg rich ankerite. The
groundmass, which makes up approximately 50-60% of the
rock, is composed of fine grained quartz and plagioclase,
with minor sericite and carbonate. Chlorite and biotite
make up approximately 10% of the groundmass and are
coarser grained than the other groundmass constituents.

Alteration of these samples appears to be weak to
moderate. They are only weakly foliated, and thus do not
seem to have undergone nearly as much deformation or
alteration as those porphyries to the west.

2.7.3 Interpretation of the origin of the two
porphyry groups

These two groups may represent a fractionation trend
from more ferromagnesian in the east to more siliceous in

Figure 22. Photomicrographs of eastern felsic porphyritic intrusive rocks. Black lines are ink guides for microprobe analyses. The scale bar is 1 mm. All photographs were taken at the same scale.

22a. Twinned and zoned An30 plagioclase phenocrysts in fine-grained plagioclase-quartz-chlorite matrix. The zoning is oscillatory. The plagioclase is altering slightly to sericite and minor carbonate. This sample is from the Wods-Mac Porphyry. The photograph was taken under transmitted, plane light.

22b. Photograph of the same section as 22a, taken under polarized light.

22c. Twinned and zoned phenocrysts of An30 composition in a fine-grained matrix of quartz-plagioclase-biotite. This sample is only weakly altered, with some sericite forming at the expense of the plagioclase. This sample is from the Roche Long Lac property. The photograph was taken under transmitted, plane light.

22d. Photograph of the same section as 22c, taken under polarized light.
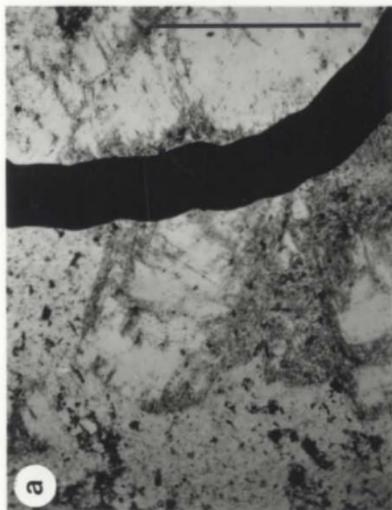
Table 4. Electron microprobe analyses of eastern quartz-feldspar porphyries.

	PLAGIOCLASE							
Sample No.	207	207	207	209	209	209	209	209
N *	5	5	8	9	7	8	4	4
	1 pheno osc. zon.	same grain	1 pheno osc. zon.	2 phenos osc.zon.	2 phenos osc.zon.	1 pheno osc.zon.	1 pheno osc.zon.	matrix
wt %								
SiO$_2$	60.61	60.02	58.03	61.09	60.83	59.89	59.47	64.93
Al$_2$O$_3$	25.08	25.38	26.42	24.67	24.67	25.49	25.44	21.97
FeO	0.16	0.10	0.10	0.18	0.16	0.14	0.10	0.18
CaO	5.84	6.15	7.37	5.56	5.57	6.38	6.29	2.78
Na$_2$O	8.55	8.35	7.43	8.46	8.50	8.02	7.92	9.66
K$_2$O	0.14	0.11	0.12	0.19	0.15	0.12	0.11	0.60
TOTAL	100.37	100.11	99.47	100.16	99.88	100.04	99.32	100.12
WT % PROPORTIONS								
AN	29.0	30.5	36.5	27.6	27.6	31.6	31.2	13.8
AB	72.3	70.6	62.9	71.6	71.9	67.9	67.0	81.7
OR	0.8	0.7	0.7	1.1	0.9	0.7	0.6	3.5
TOTAL	102.1	101.8	100.1	100.3	100.4	100.2	98.8	99.0

	BIOTITE	CHLORITE
Sample	207	209
N *	5	5
wt %		
SiO$_2$	37.84	26.72
TiO$_2$	1.95	0.11
Al$_2$O$_3$	16.78	20.73
Cr$_2$O$_3$	0.02	0.09
FeO	18.81	23.94
MnO	0.16	0.21
MgO	12.33	17.51
CaO	0.00	0.10
Na$_2$O	0.00	0.00
K$_2$O	9.15	0.03
TOTAL	97.04	89.46
PROPORTIONS		
Fe	46.12	43.30
Mg	53.88	56.46
Ca	0.00	0.24
FM Ratio	0.46	0.43

(Values reported are averages of N number of analyses.)

the west, or the western porphyry may represent an alteration of the eastern porphyry, or both of the above; or they may be two entirely unrelated rocks.

The outcrop appearance and relative timing of the two porphyry groups are similar. Both porphyries are cut by quartz veins which carry gold. However, the western porphyries have a lower ferromagnesian component than the eastern porphyries, and contain phenocrysts of both quartz and albite, whereas the eastern porphyries have only feldspar phenocrysts of oligoclase composition. This suggests that either a fractionation trend exists between the two rock types, or they have been derived form two different sources.

On the other hand, the western porphyry have variable amounts of sericite-carbonate alteration. In addition the feldspar phenocrysts in the WP are homogeneous in composition (which can not be a primary igneous composition), while those in the EP have oscillatory zoning from An 25 to An 33, suggesting that the western porphyries are more altered rocks than the eastern porphyries (Figure 23). The relationships will be explored further through examination of the chemical composition of these rocks (Chapter 4).

Probe results on feldspar phenocryst composition of sample 209 (Eastern Porphyry) and sample 214 (Western Porphyry)
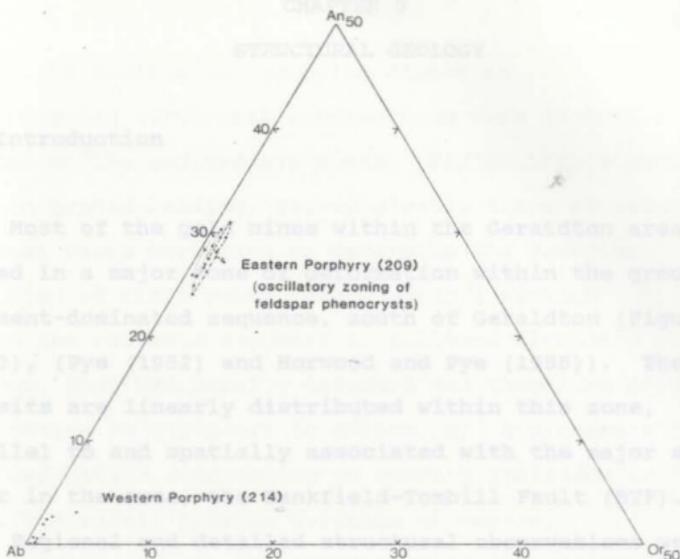
Figure 23. Ternary Ab-An-Or plot of electron microprobe analyses of plagioclase phenocrysts in Eastern and Western felsic porphyritic intrusions.

CHAPTER 3

STRUCTURAL GEOLOGY

3.0 Introduction

Most of the gold mines within the Geraldton area were
hosted in a major zone of deformation within the group A,
sediment-dominated sequence, south of Geraldton (Figures 2
and 3), (Pye (1952) and Horwood and Pye (1955)). The
deposits are linearly distributed within this zone,
parallel to and spatially associated with the major strike
fault in the area, the Bankfield-Tombill Fault (BTF).

Regional and detailed structural observations were
made to 1) describe the structural style in the Geraldton
area, 2) to determine the relative timing of structural
events and emplacement of quartz veins (gold) and, 3) the
degree to which structural conditions controlled the
emplacement of the gold. These observations were made in
part through detailed mapping of selected areas, usually
near gold mineralization, and also by detailed examination
of selected outcrops along Highway 11 and other properties
west of the main study area.

3.1 Structural observations in the Geraldton area

3.1.1 Bedding and younging direction

Detailed structural observations were generally
limited to the sedimentary rocks. Sedimentary structures
such as graded bedding, rip-up clasts, flame structures
and load casts were used to determine the younging
direction of these rocks (see Chapter 2 section 2.2).
Within the volcanic succession, pillowed flows are common,
however, they are usually deformed and therefore primary
orientation is difficult to determine. Agglomerate beds
give definitive information on bedding attitudes in these
rocks but rarely provide evidence of way-up.

Bedding, S_o, is well preserved in the sedimentary
succession, particularly in the southern and western parts
of the Beardmore -Geraldton belt where deformation is not
extreme. Toward the Quetico belt to the south, primary
bedding surfaces become progressively subordinate to a
schistosity, into which bedding appears to be transposed
(Kehlenbeck, 1984).

Where observed, bedding in the Geraldton area
consistently dips steeply to vertically and strikes
approximately east to east-southeast. Within much of the
thesis area, particularly in the group A sedimentary
rocks, deformation has largely obliterated any sedimentary
structures, so younging directions were only determined in

a few localities (Figure 3). (See section 3.2.3
Structural facing).

3.1.2 Cleavage

Two cleavages are developed in the rocks in the
Geraldton area. An earlier, penetrative cleavage, S_1, is
ubiquitous throughout all the Archean age rocks in the
Beardmore-Geraldton belt. The orientation of the dominant
cleavage is 260-270°, and is commonly co-planar with the
axial surfaces of folds (Figure 24a,b), but is also
observed to transect folds (Figure 24c).

The cleavage is defined by the parallel alignment of
mica and chlorite, and the flattening of grains, fragments
and crystals within the various rock types.   Refraction
of cleavage is commonly observed in graded beds where
ductility differs from the coarse to the fine grained
portions of the beds (Figure 24d). The coarser-grained
sedimentary layers tend to develop a spaced cleavage, but
finer, more chloritic layers tend to develop a penetrative
cleavage.

In most outcrops the cleavage is close to, or,
bedding-parallel. which, as deformation increases, makes
it difficult to determine original bedding. A
characteristic feature of the deformation in the Geraldton
area is the transposition and disruption of sedimentary
layering, giving rise to a "stripey" cleavage which upon
cursory examination appears to be bedding, but upon closer

Figure 24. Photographs of cleavage in sedimentary rocks.

24a. Cleavage oriented 260-270°, axial planar to the mesoscopic fold. Grant's Camp outcrops.

24b. Photomicrograph of sample FRA063 (scale bar is 1 mm). Isoclinal fold in greywacke-siltstone unit with thin magnetite bands.

24c. Sketch map of greywacke outcrop on the north side of Highway 11, approximately 1 km east of Jellicoe, illustrating cleavage crosscutting earlier isoclinal fold.

24d. Cleavage refraction in thin, graded, greywacke-siltstone beds with small pressure solution, or displacements along, cleavage, at Grant's Camp outcrops.

24e. Two cleavages in greywacke from the Mosher West hydroline exposure. The earlier cleavage, which is approximately horizontal in the photo, is kinked by a later cleavage which makes and angle of approximately 75° with the earlier one.

24e,f. Highly deformed sedimentary rocks at the Roxmark property. What appears to be bedding is actually transposed lenses of coarser-grained (lighter-coloured) material in highly deformed (darker) silty matrix, which is equivalent to the S_1 cleavage. The S_2 cleavage is axial planar to the minor kink/chevron folds. Note the Z-asymmetry of these later folds.

CLEAVAGE AXIAL PLANAR
TO SMALL FOLDS

FOLD TRANSECTED BY CLEAVAGE
SHOWING REVERSAL IN FACING DIRECTION
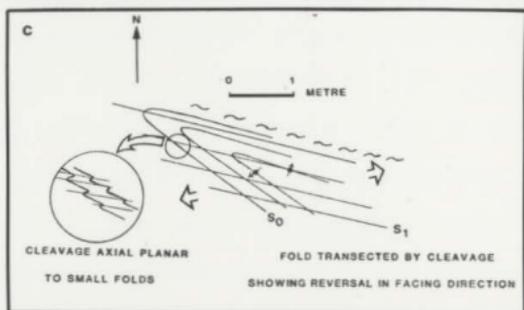
examination reveals elongate, narrow lenses of coarser-grained sedimentary material within a matrix of intensely deformed finer-grained sedimentary material (Figures 24 f,g). Note the slight transposition of layering along cleavage in Figure 24 d. This process taken to an extreme could produce the features observed in Figures 24 f and g.

Another common feature of the deformation in the Geraldton area is its inhomogeneity with well-preserved sedimentary packages juxtaposed against strongly disrupted packages. This inhomogeneity of deformation is also observed within originally homogeneous rocks such as gabbroic intrusions (see section 3.2.5 Shear zones).

In zones of intense deformation, particularly along the Bankfield-Tombill Fault Zone, a second cleavage, S_2, is developed which overprints the earlier cleavage and is consistent with the axial planar orientation of minor asymmetric folds (see Section 3.2.4.1) and small kink folds (Figure 24 e,f,g). In one outcrop, a small dyke (less than a few cm wide) of porphyry intrusion was observed which contained an earlier cleavage and was folded by an asymmetric fold consistent with the second cleavage. This places intrusion of the porphyry as prior to much of the tectonic deformation.

No evidence of stretching lineations was observed in outcrops in the Geraldton area. In the conglomerates the pebbles are flattened in the plane of the cleavage, and do

not show evidence of greater stretching in one direction than another within this plane.

3.1.3 Structural facing

Bedding, cleavage and younging relationships were used to determine the structural facing of the stratigraphic sequence. Structural facing is defined as the younging direction of strata at the hinge of a fold (Cummins and Shackleton, 1955;). Borradaile (1976) showed that the structural facing of a fold can be determined at any point on a folded surface by projecting the younging direction at that point onto the axial planar cleavage. This observation can be very useful in polydeformed terrains (Poulsen, et al,1980) as the structural facing of later folds may be obtained by projecting local younging directions onto their accompanying axial planar cleavage. Reversals in the structural facing may indicate areas where the strata was affected by an earlier deformational event (Kehlenbeck,1985).

Structural facing measurements were made locally along the Beardmore-Geraldton belt. Opposing facing directions are developed at several locations within the sedimentary sequences of the belt (Figure 25). Within the group A sedimentary rocks in the Geraldton area a consistent westward structural facing was observed in outcrops north of the Bankfield-Tombill Fault (BTF)
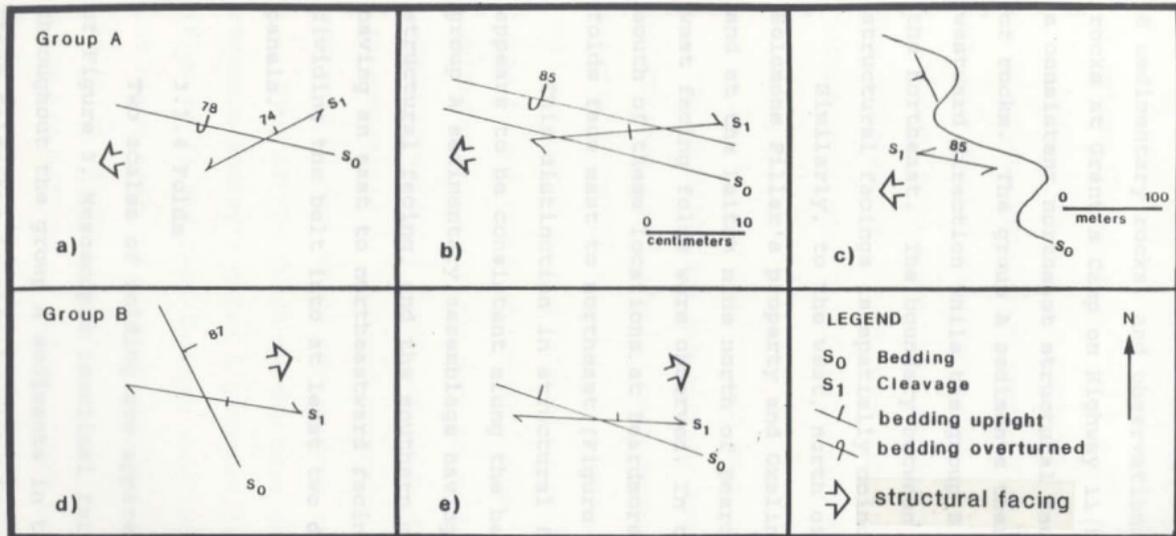
Figure 25. Sketch illustration of bedding-cleavage-structural facing relationships from selected localities along the Beardmore-Geraldton Belt; a) Leitch Mine, b) Oxaline Lake, c) Little Long Lac Mine, d) Highway 11 outcrops at Jellicoe, and e) Grant's Camp outcrops.

(Figure 25c). Horwood and Pye's observations on the group B sedimentary rocks, and observations on the sedimentary rocks at Grant's Camp on Highway 11 (Figure 25e), document a consistent northeast structural facing for this package of rocks. The group A sediments therefore young in a westward direction while the group B sediments young to the northeast. The boundary between these two differing structural facings is spatially coincident with the BTF.

Similarly, to the west, north of Jellicoe at the Solomons Pillar's property and Oxaline Lake (Figure 25b), and at the Leitch mine north of Beardmore (Figure 25a), west facing folds were observed. In the greywacke to the south of these locations at Beardmore and Jellicoe, the folds face east to northeast (Figure 25d).

This distinction in structural facing direction appears to be consistent along the belt, with the northern group A sedimentary assemblage having a westward structural facing, and the southern group B assemblage having an east to northeastward facing direction, thus dividing the belt into at least two discrete structural panels.

3.1.4 Folds

Two scales of folding are apparent from examination of Figure 3. Mesoscopic isoclinal folds are developed throughout the group A sediments in the Geraldton area. These folds are isoclinal, with hinge axes parallel to the

regional strike of the stratigraphy. At Geraldton the
hinge spacing of these folds is on the order of hundreds
of metres (Figure 3).

Within the group A package north of the BTF and in
lithologies immediately south of the fault, minor folds
are extensively developed. Some of these folds are
consistent with the mesoscopic isoclinal folds, but they
are dominated by z-asymmetry which is in places
inconsistent with the larger-scale fold structures.

3.1.4.1 Description of minor folds

Minor folds are extensively developed within the
sedimentary and volcanic rocks immediately adjacent to the
Bankfield-Tombill Fault in the Geraldton area. They are
well-developed in the heterogeneous assemblage of rock
types to the north of the BTF, especially in finely
laminated layered rocks such as oxide iron formation, and
finely interbedded sandy and silty greywacke. These folds
are dominantly of Z-shaped asymmetry, with a gentle
westward plunge, which varies from 30-60°.

Many of the folds in the Geraldton area strongly
resemble Ramsay's Class 2 geometry of similar folds
(Figures 26 and 27a) in that they tend to be thickened in
the hinge zone and thinned on the limbs, and the shape of
the folds is repeated from one layer to the next. Similar
folds are defined by Ramsay (1967) as having parallel dip
isogons, i.e. "the changes of curvature of the surfaces of

Figure 26. Photographs of folds.

26a. Similar-looking folds in thinly laminated
greywacke-siltstone-magnetite iron formation at the
Roxmark property. Note the thinning of the limbs and the
thickening of the hinge zones of the folds.

26b. Photomicrograph of sample FRA045 from the west
trench on the island in Barton Bay. The photo is
approximately 2 mm wide.

26c, e, f. Iron formation exposed northwest of the
Roxmark trenches. Similar-looking folds with neutral to
Z-asymmetry.

26d. Closeup of area in 24c. These folds show
evidence of two cleavages. An earlier "stripey" cleavage
(especially noticeable in the darker silty layers) is
folded by the asymmetric minor folds. The very dark layer
at the top of the photo is magnetite.
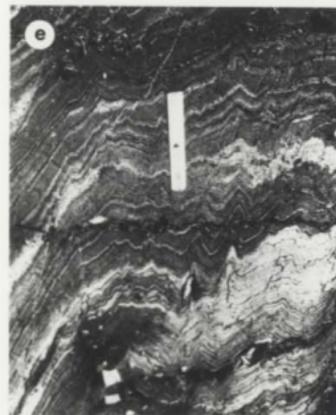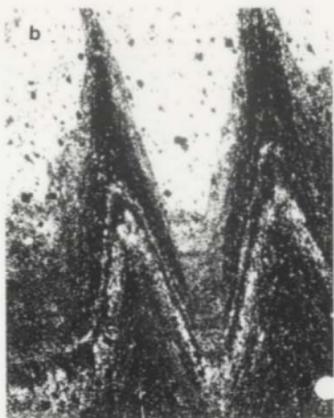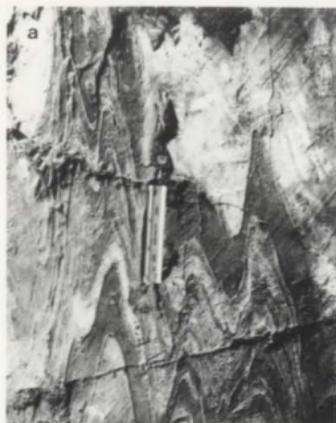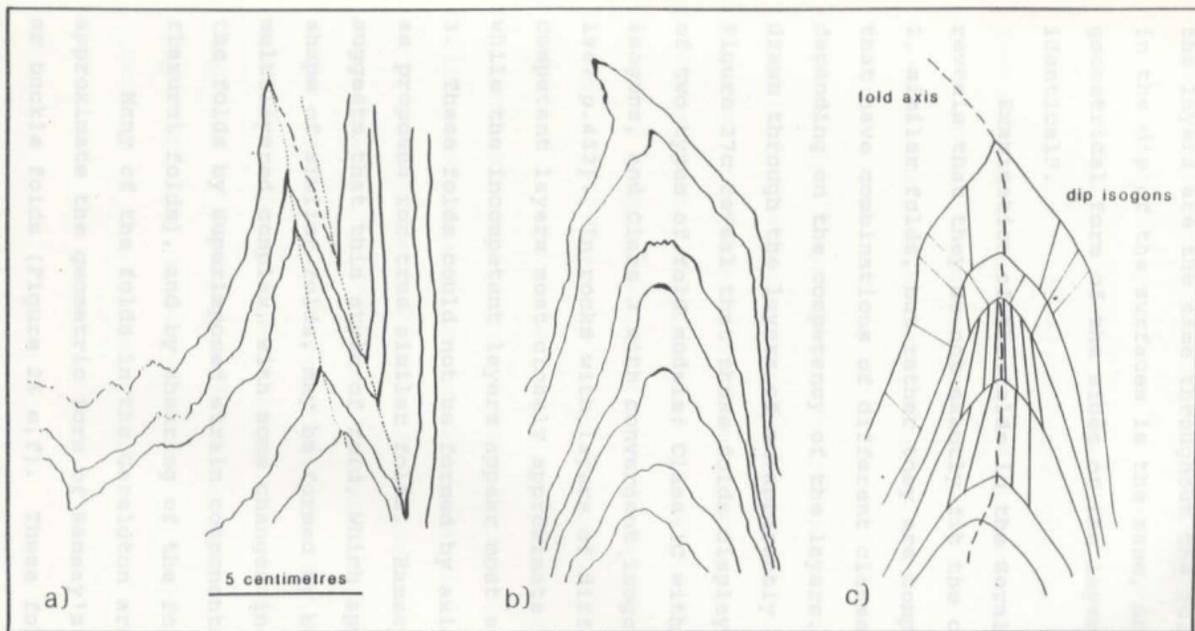
Figure 27. Tracings of folds from hand samples of banded oxide iron formation. a) Hard Rock property. Note the slight offset of some layers along narrow zones parallel to the axial plane of the folds. The plane of this section is at 30° to the plunge of the folds. b) MacLeod-Cockshutt property. The plane of this section is perpendicular to the plunge of the fold. c) Idealized fold tracing based on (b). Dip isogons (Ramsay, 1967) are sketched for compound packages of magnetite-hematite-siltstone-chert layers. The scatter of the isogons broadly represents the behaviour of the layers on a millimetre scale.

the layers are the same throughout the fold, the variation in the dip of the surfaces is the same, and the geometrical form of the sides of the layers are identical".

Examination of the folds in the Geraldton area reveals that they do not exactly fit the criteria of Class 2, similar folds, but rather they are composed of folds that have combinations of different classes of folds, depending on the competency of the layers. Dip isogons drawn through the layers of an apparently similar fold in Figure 27c reveal that these folds display a combination of two types of fold models; Class 1C with divergent dip isogons, and Class 3 with convergent isogons (see Ramsay, 1967 p.432). In rocks with layers of differing ductility, competent layers most closely approximate the Class 1C while the incompetent layers appear most similar to Class 3. These folds could not be formed by axial-surface flow as proposed for true similar folds. Ramsay (1967) suggests that this style of fold, which approximates the shape of similar folds, may be formed by buckling a multilayered complex, with some changes in the shapes of the folds by superimposed strain components (flattened flexural folds), and by shearing of the fold limbs.

Many of the folds in the Geraldton area more closely approximate the geometric form of Ramsay's Class 1B folds or buckle folds (Figure 26 e,f). These folds are formed by a compressive stress acting along the length of the

layers. In rocks with strong competency contrasts, the more competent layers tend to buckle, while the less competent layers take a different form. Many fold shapes were observed that were intermediate between buckle and similar-looking folds, suggesting that the similar-looking folds in the Geraldton area may have been formed by a progressive flattening of what were initially buckle folds.

A significant feature of the folds in the Geraldton area is the development of distinct shear discontinuities parallel to the axial surfaces of the folds. Slip along these surfaces is common and may displace fold hinges very slightly (Figure 27a, 28a,b) or in extreme cases, bedding is entirely transposed along cleavage, juxtaposing unrelated layers (Figure 24 f,g). These shear discontinuities occur at both thin section and outcrop scale, and probably on a much larger scale. Thus bedding on a local scale cannot be used to determine stratigraphy.

In addition to the asymmetric z-folds there are folds which appear to be refolded (Figure 28 c,d). These folds approximate the shape of Type 3 interference patterns as described by Ramsay (1967), where the axis of the later folds coincide, or nearly coincide, with the axial direction of the earlier folds.

Figure 28. Photographs of shear discontinuities in folds.

28a,b. HIghly contorted sedimentary material at the norht end of the Roxmark trenches. Folds have been disrupted and dislocated along narrow zones approximately parallel to cleavage.

28c,d. Highly folded magnetite laminae in greywacke at the Mosher East hydroline exposure. These folds resemble Ramsay's (1967) Class 3 refolded folds, in which both fold axes are parallel, suggesting at least two periods of deformation in a similar stress field.

3.1.5 Shear zones and faults

A common feature of the deformation in the Geraldton area is its inhomogeneity. Well-preserved packages of rock are often juxtaposed against strongly disrupted and transposed lithologies. Discrete shear zones are present in many outcrops within the Geraldton area. They are most easily recognized at the contacts of differing rock types where the less competent lithology has been extensively deformed, and as chlorite schist within relatively massive hornblende gabbro intrusive rocks. The change from relatively massive, undeformed gabbro, through to shear zones of chlorite and quartz schist is accomplished by the progressive development of a penetrative foliation and reduction in grain size and alignment of minerals, (especially obvious in the flattening and destruction of hornblende crystals). (Figure 19 a,b,c,and d, Chapter 2).

3.1.5.1 Fabrics within the shear zones

Within the chlorite schist zones, three distinct foliations are recognized; 1) The first are represented by through-going chloritic seams, labelled (a) in Figure 29. This fabric is subvertical and is consistent in orientation throughout the outcrop, striking 270° to 280°; 2) Oblique to the (a) surfaces is another subvertical foliation, labelled (b). These surfaces define the plane of preferred mineral orientation and correspond to a schistosity, and strike approximately 260°; and 3) A

Figure 29. Fabrics in chlorite schist shear zones. Three main fabrics are observed within the chlorite schist shear zones. Those labelled "a" are subvertical, through-going chloritic seams, consistent in orientation throughout the outcrop, striking 270 to 280°. The fabrics labelled "b" are also subvertical and are oriented obliquely to the "a" surfaces. These surfaces are defined by the preferred mineral orientation, and therefore correspond to a schistosity, and strike approximately 260°. The "c" surfaces make an angle of approximately 30 to 40° to the "b" planes. The photograph was taken at the Fault Rock Outcrop on Highway 11 (see Figure 3).
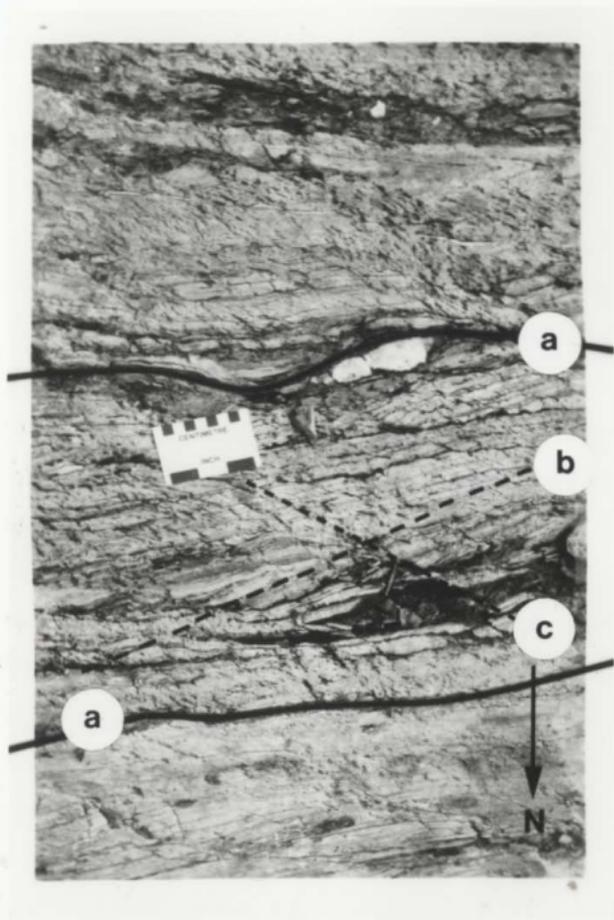
third foliation is sometimes present which makes an angle
of approximately 30° to the (b) planes, striking 130° to
140°, labelled (c).

3.1.5.2 Faults

The Bankfield-Tombill Fault is the largest and best-
defined strike fault in the area. It has been traced by
diamond drill holes and outcrops from the property of
Tombill Gold Mines in Lindsley Tp (just west of the
Bankfield Property) eastward through outcrops of chlorite
schist material south of Mosher Lake, to a strongly
sheared and brecciated zone in mafic rocks south of the
Hard Rock Mine, a distance of over 10 km (Pye, 1952;
Horwood and Pye,1955) (Figure 3). In addition, outcrops
of extremely sheared volcanic material were observed by
this author on the Ashmore Property further to the east
along strike from the Hard rock property and it is
postulated here that this zone represents the further
continuation of the fault zone.

The zone strikes 100-110° and dips steeply south at
60-70° for its entire length. The width and nature of the
fault zone is very variable and seems at least partly to
be determined by the type of rock the fault is
transgressing. In some places, where the fault zone
intersects massive hornblende gabbro, it consists of
discrete zones of ductile shear up to 3 metres in width
within relatively undeformed gabbro (described above).

These zones contain quartz veins, which are boudinaged and rotated. Carbonatization of the matrix is another feature of these zones.

In other places, as on the property of Roxmark Mines Ltd (formerly the McLellan property), the fault zone intersects a dominantly sedimentary succession (Figure 30). Here the fault itself is represented by a "fault gouge" of brecciated fragments in a clay-rich mud, which is surrounded by a zone up to 60 metres wide of highly silicified and carbonatized material with small amounts of chalcopyrite and pyrite. As the actual fault plane is approached the rock becomes increasingly fragmented and shows evidence of multiple brecciation. The "gouge" material may be up to ten centimetres in width. On either side of the fault the rocks are intensely deformed. To the south of the fault outcrops of chlorite schist are intensely stockworked with narrow quartz veinlets. To the north of the fault, outcrops of medium to fine grained greywacke and siltstone are intensely cleaved and fractured. Further to the north in the sedimentary rocks the penetrative cleavage and fracturing gives way to intense asymmetric folding (Figures 26a,c,d,e,f and 28a,b).

Numerous small east-west faults and shear zones occur within the area. Outcrops of highly schistose material are commonly observed at the contacts between rocks of differing ductilities. This indicates that within the
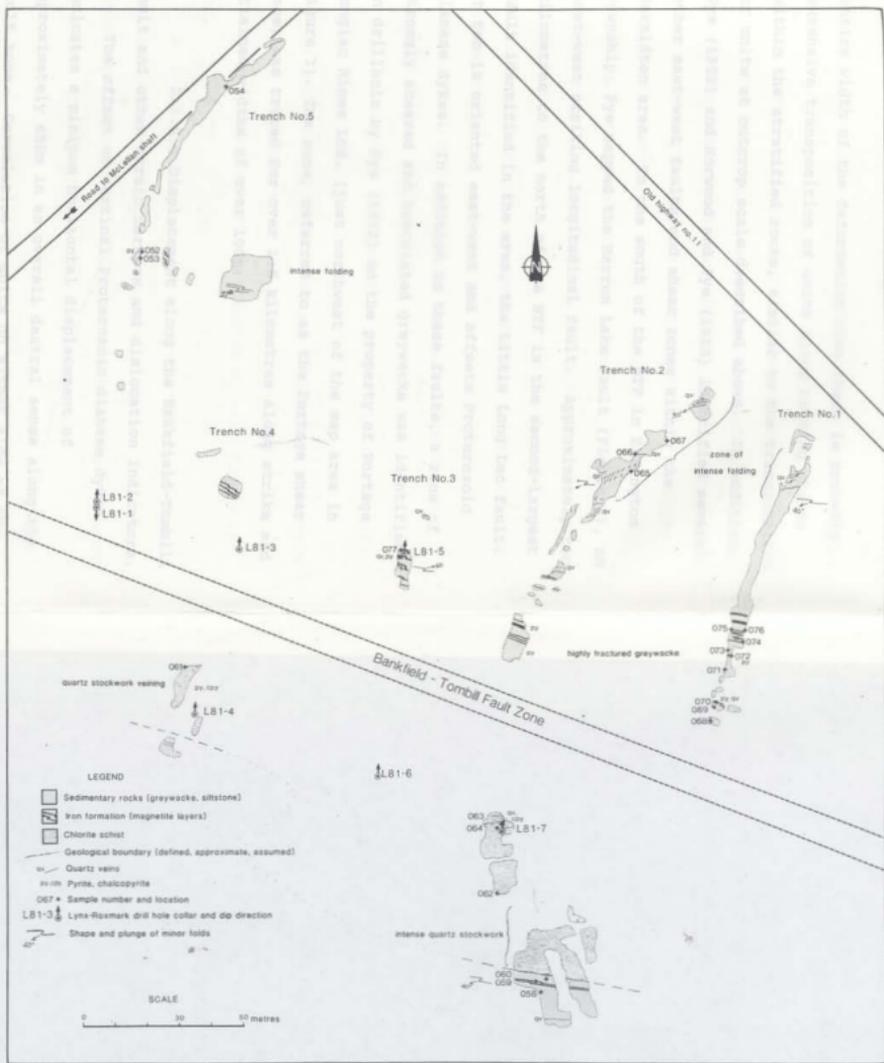
Figure 30. Geologic map of the Roxmark (McLellan) Property. The location of the Bankfield-Tombill Fault Zone is inferred from diamond drill hole information and outlined by dashed lines.

entire width of the deformation zone there is probably
extensive transposition of units along bedding planes
within the stratified rocks, similar to the transposition
of units at outcrop scale described above. In addition,
Pye (1952) and Horwood and Pye (1955) identified several
other east-west faults and shear zones within the
Geraldton area. To the south of the BTF in Errington
Township, Pye mapped the Marron Lake Fault (Figure 3), an
east-west striking longitudinal fault. Approximately two
kilometres to the north of the BTF is the second-largest
fault identified in the area, the Little Long Lac fault.
It too is oriented east-west and offsets Proterozoic
diabase dykes. In addition to these faults, a zone of
strongly sheared and brecciated greywacke was identified
in drillhole by Pye (1952) on the property of Portage
Longlac Mines Ltd. (just northwest of the map area in
Figure 3). The zone, referred to as the Portage shear
zone, was traced for over 1.5 kilometres along strike and
attained widths of over 100m.

3.1.5.3 Displacement along the Bankfield-Tombill
Fault and other strain markers and dislocation indicators.

The offset of vertical Proterozoic diabase dykes
indicates a minimum horizontal displacement of
approximately 650m in an overall dextral sense along the
fault zone. Correlation of units on either side of the
fault other than these dykes is very difficult due to the

subparallel orientation of the fault and lithological boundaries. Because of this, it is very difficult to determine the sense and amount of displacement along the fault. For this reason, a combination of strain markers and dislocative features were documented to determine sense of movement along the fault zone. Most of these features if taken alone would be suspect as indicators, but the fact that they all give a consistent sense of movement suggests that they are reliable. The features observed include:

1. fractured and transposed pebbles in conglomerate, (Figure 31a);

2. offset of layers along brittle fractures, and cleavage (Figure 28a,b);

3. shear bands and foliation fish in gabbro (Figure 31b);

4. sense of asymmetric folds - predominantly Z-style asymmetry (Figures 26, 28 and 31c);

5. offset of Proterozoic diabase dykes, (Figure 3); and,

6. boudinage and rotation of quartz veins and other competent layers, (Figure 31d);

These strain markers all indicate a dextral sense of shear movement.

Figure 31. Photographs of structural dislocation features.

31a. A fractured and offset pebble in conglomerate south of the Roxmark Property. The offset of the pebble fragment is in a dextral sense. Photograph was taken looking south.

31b. "Foliation fish" in sheared gabbro at the Fault Rock Outcrop on Highway 11. These features are described by Hanmer (1984) as asymmetric pull-apart features. They occur as elliptical packets whose internal foliation is oblique to the general foliation of the enveloping rocks. The internal foliation of these features commonly undergo back rotation during shearing thus indicating a dextral sense of shear in this case. (See Hanmer, 1984, Figures 15.8 E and F, p.140).

31c. Z-asymmetry of minor folds indicates a dextral sense of displacement of the limbs of the folds.

31d. Z-asymmetry of folding, boudinage and offset of quartz veinlet crosscutting finely laminated (stripey cleavage) sedimentary material.

3.1.5.4 Timing of faulting

Faulting must at least in part follow folding because the fault zone itself is not folded. Proterozoic diabase dykes have been offset along the fault, and all lithologies have been cut by the fault, therefore it is at least partly syn- to post-Proterozoic in age (Figure 3). However, the strong spatial coincidence between the fault zone and rocks of intrusive origin (Figure 3) suggests that the fault, or some related structural break, may have served as a locus for emplacement of late Archean magmas.

The fault may be a long-lived feature. Note on Figure 3 the very close spatial association between the fault zone and the long narrow conglomerate horizons. Throughout the Beardmore-Geraldton belt these conglomerate horizons are commonly found in association with faulted contacts (Chapter 1). This may indicate a long-lived instability along his zone that was active at the time of sedimentation (Figure 3).

3.1.6 Timing of quartz veining

Veins may be hosted in a variety of settings. No underground exposures were available in this study, but surface exposures clearly reveal the timing and setting of quartz veins.

At the Bankfield property veins are hosted in sheared rock at the contact of quartz feldspar porphyry dykes with hornblende gabbro and with sediments; and quartz

stringers, with associated disseminated pyrite, cut massive sheared quartz feldspar porphyry, (see Figure 16, map of Bankfield property, and Figure 32a,b).

At the Roxmark property (see Figure 30, map of the Roxmark property) different styles of veining include; (a) contorted veins in highly folded and sheared sedimentary rocks north of the BTF (Figure 32c); (b) stockwork veining in the fault zone with later, open space filling quartz, associated with chalcopyrite; (c) veins in fractures cross-cutting small folds, parallel to the axial planar cleavage of the small folds; and, (d) veins occupying cleavage in sedimentary rocks.

On Mosher property, west of Mosher Lake, veins are hosted in very sheared sedimentary rock; (a) parallel to the latest cleavage; (b) at a high angle to this later cleavage, occupying an earlier, folded, cleavage (Figure 32d); and deformed veinlets with tourmaline are hosted in very sheared quartz feldspar porphyry.

On the Hard Rock property, at the open stope exposure, veins occur; (a) as parallel sets of veins occupying fractures parallel to both earlier and later cleavage (Figure 33a); (b) along very sheared and brecciated contacts of iron formation and intrusive rock or sedimentary rock (Figure 33b); (c) crosscutting small asymmetric folds in orientations roughly parallel to axial planar cleavage (Figure 33b, and Figure 15, Chapter 2);

Figure 32. Photographs of quartz veining.

32a,b. Quartz veining in sheared quartz feldspar porphyry on the Bankfield Property. The veins are hosted in fractures that parallel the schistosity in the rock. The wallrock is mineralized with abundant pyrite and arsenopyrite.

32c. Contorted veins in highly folded and sheared sedimentary rocks at the north end of the Roxmark trenches.

32d. Quartz veinlets occupying two cleavages in highly deformed greywacke at the Mosher West hydroline exposure.
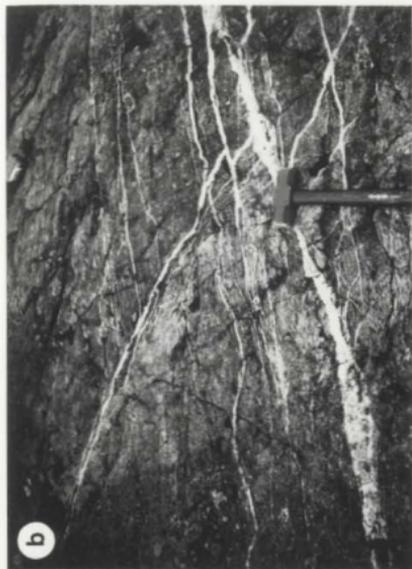
Figure 33a.
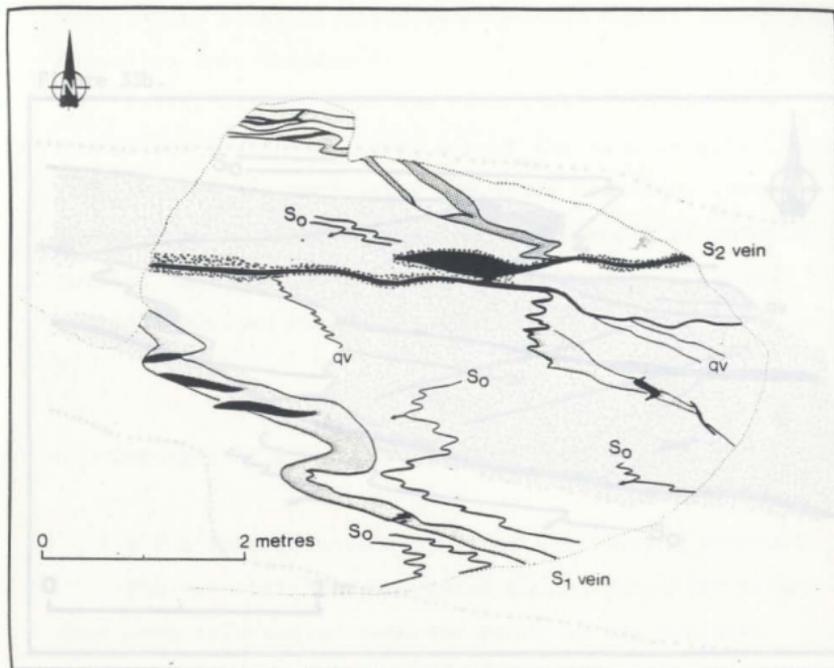
Figure 33. Detailed sketch maps of selected outcrops at the Open Stope exposure of the Hard Rock North Ore Zone.

   33a. Outcrop map from the east end of the Open Stope (see Fig. 57, Chapter 5). Early S_1 carbonate veins, which in this location crosscut bedding at a low angle, are folded into Z-asymmetric minor folds and are cut by later, S_2, quartz and quartz-carbonate veins. The S_2 veins are hosted in fractures parallel to the axial planes of the minor folds. Auriferous pyrite-arsenopyrite replacement haloes are developed along the borders of these veins where they crosscut iron formation. The host rock lithology is finely laminated magnetite-hematite-siltstone. (See next page for legend).

   33b. Outcrop map from the north edge of the Open Stope. Auriferous pyrite-arsenopyrite replacement lenses are developed at the margins of the late quartz and quartz-carbonate veins, which are localized at the contact between finely laminated oxide iron formation and highly carbonatized intrusive rock. These veins crosscut asymmetric Z-folds in the iron formation.

Figure 33b.
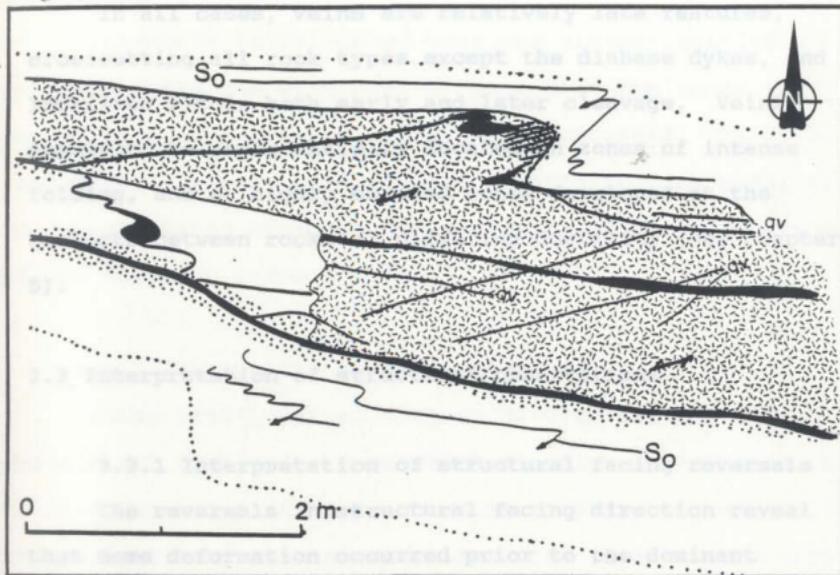
LEGEND

⬛ Quartz-sulphide (-carbonate) veins which occupy S_2 cleavage, parallel to axial planes of asymmetric z-folds.

▦ Pyrite-arsenopyrite replacement halo.

▨ Carbonate-quartz veins which occupy S_1 cleavage, which crosscuts bedding at a low angle.

☐ Magnetite-hematite iron formation with siltstone interlaminae.

▨ Carbonatized, sericitized, and pyritized intrusive.

S_0⤢ Trace of bedding, and sense and plunge of minor folds.

qv⤳ Quartz veinlet.

⤳ Schistosity.

and, (d) in zones of brecciation within highly folded iron formation (see Chapter 5).

In all cases, veins are relatively late features, crosscutting all rock types except the diabase dykes, and localized within both early and later cleavage. Veins appear to be preferentially located in zones of intense folding, and or highly sheared zones developed at the contacts between rocks of differing ductility (see Chapter 5).

3.2 Interpretation of structural observations

3.2.1 Interpretation of structural facing reversals

The reversals in structural facing direction reveal that some deformation occurred prior to the dominant period of folding. This prior deformation may represent an early folding episode, i.e. recumbent or nappe-style, and/or an early faulting of the stratigraphy, that juxtaposed back-to-back and front-to-front facing lithostratigraphic packages. This interpretation, combined with the observation of the prevalence of transposition and shearing of lithologies at the outcrop scale, implies that the belt may be composed of numerous narrow "slices" or panels of strata in which the structural facing, and therefore the overall younging direction, of each sequence is different from that in the adjacent panel. The Beardmore-Geraldton belt therefore

appears to be composed of a disrupted and discontinuous
stratigraphy.

Kehlenbeck (1984) noted that the discontinuities
which separate the distinctive "packages" are zones in
which evidence for shearing is very pronounced. He also
stated that in most outcrops the shear direction parallels
the axial planar cleavage and therefore the axial surface
of the dominant folds.

3.2.2 Interpretation of minor folds

Ramsay (1967, p.421) stated that folds with similar fold
geometrical form, or a form which closely approximates it
"...are generally found in the central parts of belts of
regional folding and metamorphism. The zones in the crust
where these folds are most common were probably in a very
ductile state during fold formation.", i.e. they were
probably high temperature and/or high pressure. He
suggested that all folds, whatever their initial class,
may come to resemble shear folds with increased
compression and deformation. These folds probably formed
from an initial compressive stress acting along the
layers, with subsequent flattening of the folds by
continued compression, acting across the layers.

Formation of minor folds in the Geraldton area is
consistent with an approximately north-south maximum
compression and a later component of shear acting
northwest-southeast. From the fold features observed it

is reasonable to postulate that the rocks were in a fairly ductile state during deformation.

3.2.3 Interpretation of shear zones and faults

Studies of shear zones by Berthe et al (1979), Platt (1984), and Ponce de Leon and Choukroune (1980) have described foliations that are very similar to those described above. These foliations are thought by the above authors to be characteristic of zones of simple shear.

The through-going chlorite seams, (a) surfaces (Figure 29) correspond to Berthe et al's (1979) C surfaces. They found that these were surfaces along which essentially horizontal displacement had occurred and that they maintained a constant orientation within each defined shear band. They also found that these fabrics parallel the "cartographic trace of the major shears, and are specific to zones of simple shear".

The (b) fabric (Figure 29) is similar to the S surfaces of Berthe et al (1979). They stated that these surfaces define the plane of preferred mineral orientation and contain the maximum extension direction of the deformed minerals.

According to Platt (1984), S and C surfaces develop together at the start of deformation and do not overprint each other. The angle between these two sets of surfaces is originally 45°, but diminishes progressively with

continued deformation by rotation of the S surfaces toward the C surfaces while the latter maintain a relatively constant orientation (Berthe et al, 1979). Associated with the rotation of the S surfaces, Ponce de Leon and Choukroune (1980) identified a concomitant decrease in grain sizes and an increase in the frequency of C planes. Both of these features are recognized in the sheared gabbro outcrops. At a given stage in the evolution of zones of simple shear, the C' planes appear, making an angle of 30° to the C planes (Ponce de Leon and Choukroune, 1980).

Weijermars and Rondeel (1984) showed that shear band foliation may be used as an indicator of the sense of shear. Shear bands show a consistent angular relationship to the shear zone boundaries and the rotated early foliation, such that the acute angle between the shear zone boundary and the shear band cleavage point in the opposite direction to the relative movement of the country rock outside of the shear zone. Using this criteria, the sense of shear indicated by the shear zones within the hornblende gabbros is dextral (Figure 29). This observation is consistent with other dislocation features observed within the belt.

The faulting in the Geraldton area appears to be a later, more brittle expression of the same dextral stress that was responsible for the minor folds and the shear zones. Note that the extension of the BTF eastward from

the Roxmark property passes through the gabbro outcrops where the shear zones are developed. Buck and Williams (1984) suggest that the late brittle stage of deformation may be the result of strain hardening or an increased strain rate producing a lower apparent rock ductility.

3.3 Summary

1. An early deformation is postulated which produced opposing facing directions within the sequence but was not accompanied by the development of a cleavage.

2. A later deformation event took place with the development of a pervasive regional cleavage, possibly in conjunction with the development of mesoscopic isoclinal folds;

3. Asymmetric folding and dextral shearing, with the development of a later cleavage in the most intensely deformed areas, overprinted the isoclinal folds and the earlier cleavage;

4. Several generations of quartz veins were introduced during deformation, both prior to and subsequent to the later episode of cleavage formation.

5. Deformation was probably progressive over a long period of time, evidenced by cleavage overprints and sets of deformed and undeformed quartz veins.

6. Dextral strike slip faulting continued at least into the Proterozoic. The fault may be a very long-lived

feature, as is suggested by its spatial coincidence with both the mafic and felsic intrusions, and also with long linear conglomerate horizons.

7. Veins are hosted within highly fractured and/or sheared zones which are later than intrusions, cleavage, and asymmetric folds which overprint both of the former. As outlined above, the structures which are crosscut by gold-bearing veins include relatively late features, and therefore the veins are themselves a later feature.

3.4 Structural model

The discontinuity in facing direction coincides with a major zone of intensely deformed rocks within the Geraldton area and this zone shows pronounced evidence of shearing. The discontinuity also parallels the major strike fault in the area, the Bankfield - Tombill Fault (BTF), and several lesser faulted and sheared zones. As noted in the introduction to this chapter, most of the mines in the area are also found in spatial association with this zone.

The structural facing reversal may be related to some early, large-scale deformation. This deformation may have resulted in the juxtaposition of at least two unrelated terrains (group A and group B) along a major break or suture by faulting or some other large-scale tectonic mechanism. This feature has very little expression other

than the structural facing reversal and the apparent facies change that coincides with this reversal. The BTF may merely be a later structure that is superimposed on this long-lived zone of weakness. It is interesting to note the proximity of the Beardmore-Geraldton belt and this structural discontinuity to the subprovince boundary between the Wabigoon and Quetico Belts, presently located at the southern boundary of the southernmost volcanic belt. This long-lived zone of structural weakness may represent a major tectonic suture, similar to that envisioned for accreted "suspect terranes" in the Cordillera and Appalachians (Williams and Hatcher, 1983).

North-south compressive stress caused the sequence to be isoclinally folded along east-west hinges, and this was followed by compression with a component of dextral shear. Continued deformation resulted in more brittle failure, with the development of the BTF and other east-west faults in the area.

The transposition of bedding which is observed in outcrop throughout much of the Geraldton area may be envisioned to be occurring on a much larger scale. This may involve transposition of major lithological units along cleavage parallel fault and shear zones, and may in fact be the process responsible for juxtaposing the different facies of sedimentary rock observed in group A and group B, as well as the alternating panels of mafic volcanic and sedimentary rocks.

Gold-bearing quartz and quartz-carbonate veins occupy a later cleavage and crosscut folds. They therefore are relatively late in the tectonic development of the belt. Many quartz veins are folded, indicating that deformation may have continued over a significant period of time.

CHAPTER 4

GEOCHEMISTRY

4.0 Introduction

The major and trace element composition of the
various rock units in the study area, the rare earth
element (REE) composition of the intrusive rocks, a U/Pb
zircon age of the felsic intrusions and the Pb isotope
composition of pyrite in felsic intrusions and iron
formation are discussed in this chapter. Gold analyses
were obtained for the sedimentary rocks in the Geraldton
area, and also for iron formation from both within the
Geraldton area and from several locations along the
Beardmore-Geraldton belt, to determine the distribution of
gold in these rocks.

The objectives of this geochemical study are;

A. Sedimentary rocks
   I) clastic sedimentary rocks:
        i) to determine if the Geraldton sedimentary
rocks are distinctive in any way compared to other Archean
sedimentary rocks
        ii) to determine if there is any geochemical
difference between the two groups of sedimentary rocks -
group A which hosts gold deposits versus group B which
does not
        iii) to determine if there is any primary
enrichment of gold in these rocks.

   II) iron formation;
        i) to establish the background gold content of
these rocks throughout the area and assess the hypothesis
that these rocks served as a source for the gold in the
area

ii) to ascertain which elements are introduced along with gold into these rocks, and that therefore may be used as a geochemical indicator of gold

B. Intrusive rocks:
    I) mafic intrusions and chlorite schists;
        i) to establish the composition of these rocks and compare them with other Archean mafic rocks
        ii) to geochemically test the hypothesis that the chlorite schist in the fault zone south to southeast of Mosher Lake is derived from the deformation of the hornblende gabbro

    II) felsic intrusions
        i) to compare the eastern and western porphyries
        ii) to outline the changes in these rocks due to alteration associated with gold mineralization, and
        iii) to comment on a possible association of these rocks with gold mineralization.

C. Isotope studies:
    I) U/Pb zircon
        i) to constrain the age of gold mineralization
    II) Pb isotopes
        i) to constrain age of gold mineralization and to investigate the possible source of fluids responsible for the mineralization.

4.1 Sedimentary rocks

    4.1.1 Clastic sedimentary rocks

    50 samples of greywacke and siltstone, 41 from group A and 9 from group B, were analyzed for major and trace elements, and 39 samples from both groups were analyzed for Au. All data are listed in Appendix A. Analytical methods are discussed in Appendix B. Samples were analysed for gold by delayed neutron activation analysis at X-Ray Assay Laboratories, Ltd. (Toronto) and Chemex Laboratories Ltd. (Vancouver). A suite of representative analyses of sedimentary rocks from each group is presented

in Table 5. When sampled, these rocks were not separated
into greywacke and siltstone as commonly a sample consists
of both rock types finely interbedded. To better compare
these samples with reported averages for Archean clastic
sedimentary rocks, the samples were classified according
to a geochemical criteria. Samples with greater than
61.0% SiO_2 were arbitrarily classified as greywacke, and
those with less than 61.0% SiO_2 as siltstone. In
addition, altered samples and those with quartz vein
material were deleted. Using these criteria, 26 samples
were classified as greywacke, 19 as siltstone and 5 cases
were deleted (all from group A). To test the validity of
this assumption, frequency distributions (histograms) were
plotted for the entire sample population of sedimentary
rocks for SiO_2, Al_2O_3, MgO and Fe_2O_3T, and probability
curves were plotted for SiO_2 and Al_2O_3 (Sinclair, 1976),
(Figures 34 and 35). The SiO_2 and Al_2O_3 probability plots
clearly show the existence of two distinct sample
populations with the change in slope occurring at 62-63%
SiO_2. Therefore the original estimate of 61% SiO_2 is
considered valid. In addition the Al_2O_3 probability plot
breaks in slope at 15% Al_2O_3. The average of the
Geraldton greywacke samples is <15% (Table 6), and that of
the siltstone samples is >15% based on the original 61%
SiO_2 distinction.

Table 5: Selected major and trace element analyses of clastic sedimentary rocks representative of group A and group B

	Roxmark Property Trenches					Grants Camp outcrops			
	058 "sand"	067 "mud"	068 "sand"	071 "mud"	076 "mud"	001 "mud"	002 "sand"	037 "mix"	038 "mud"
SiO_2	64.9	59.1	62.0	60.9	55.6	58.6	62.7	54.7	55.1
TiO_2	.60	.76	.64	.69	.62	.66	.54	.79	.66
Al_2O_3	15.0	17.1	16.2	17.2	15.9	18.0	14.7	19.0	19.3
Fe_2O_3	1.5	2.2	2.4	1.8	3.0	1.4	2.3	1.4	.9
FeO	4.5	5.6	6.2	5.6	8.9	5.3	4.2	6.7	5.3
MnO	.06	.08	.05	.11	.09	.08	.06	.09	.12
MgO	2.63	3.15	3.05	3.52	3.45	4.04	2.97	4.17	3.41
CaO	1.23	.44	.28	.83	1.98	1.25	1.81	.64	.99
Na_2O	2.8	1.8	2.8	.8	1.1	1.9	3.9	5.2	6.5
K_2O	2.30	3.18	2.52	3.42	2.54	4.41	1.93	3.48	3.09
P_2O_5	.13	.14	.14	.13	.13	.17	.17	.16	.19
H_2O_T	2.8	4.8	3.7	4.2	4.4	3.7	2.8	3.3	2.8
CO_2T	1.5	1.3	.1	1.0	2.6	1.1	1.9	.9	1.9
S	.07	.13	.95	0.00	0.00	.03	.20	0.00	0.00
Total	100.2	100.0	100.3	100.4	100.5	100.9	100.4	100.8	100.5
Au	1	10	10	< 1	16	< 1	-	2	2
As	20	267	6	25	0	54	25	20	15
Rb	82	113	102	130	86	133	56	101	93
Sr	151	75	73	62	73	256	242	173	336
Zr	130	136	139	125	101	146	159	146	165

Note: major elements are reported in wt %, Au in ppb, and As, Rb, Sr and Zr in ppm.
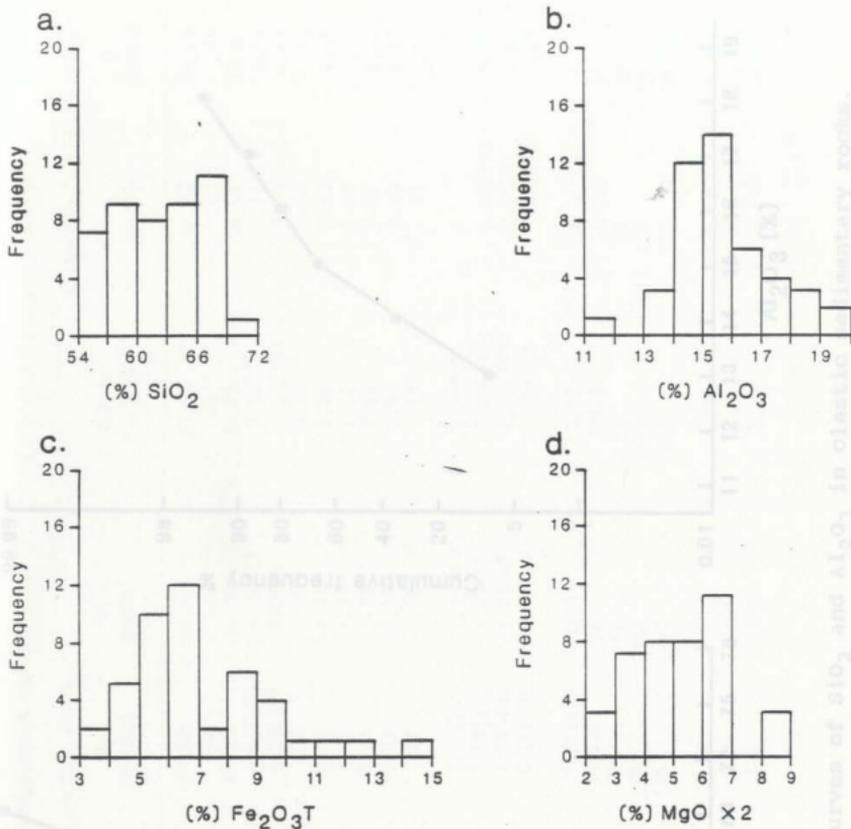
Figure 34. Frequency distributions of; a) SiO_2, b) Al_2O_3, c) Fe_2O_3T, and d) MgO (in weight per cent); in clastic sedimentary rocks.

Figure 35. Probability curves of SiO_2 and Al_2O_3 in clastic sedimentary rocks.

TABLE 6: Average of whole rock analyses for Geraldton greywacke and siltstone from group A and group B. (Weight percent)

	Geraldton Greywacke (groups A and B) $73.0 > SiO_2 > 61.0$			Geraldton Siltstone (groups A and B) $61.0 > SiO_2 \geq 51.0$		
	A & B N=26(n)	A N=21(n)	B N=5(n)	A & B N=19(n)	A N=15(n)	B N=4(n)
SiO_2	65.72	65.99	64.6	57.68	57.93	56.73
TiO_2	.56	.56	.53	.67	.66	.69
Al_2O_3	14.79	14.85	14.56	16.71	16.41	17.8
Fe_2O_3	1.4(23)	1.41(19)	1.35(4)	2.70(18)	3.14(14)	1.15
FeO	4.07(23)	4.07(19)	4.08(4)	5.59(18)	5.58(14)	5.63
MnO	.06	.06	.07	0.10	.10	.10
MgO	2.20	2.08	2.74	3.36	3.19	4.01
CaO	1.17	1.07	1.59	1.61	1.63	1.52
Na_2O	3.16	3.13	3.28	2.48	2.02	4.18
K_2O	2.11	2.13	2.04	2.97	2.89	3.37
P_2O_5	.12	.12	.15	.15	.15	.17
LOI	3.44(3)	3.56(2)	3.2(1)	3.74(1)		
H_2O_T	3.18(23)	3.13(19)	3.45(4)	3.94(18)	4.07(14)	3.48
CO_2T	1.58(23)	1.55(19)	1.73(4)	2.38(18)	2.6(14)	1.6
S	0.11(23)	0.11(19)	0.10(4)	.06(18)	.07(14)	.02
Au	8.6(19)	9.0(18)	1(1)	8.7(15)	10.4(12)	1.7(3)
As	67(23)	76(19)	21	65(18)	76(14)	26
Rb	72	72	71	93	92	97
Sr	209	189	292	182	157	276
Zr	153	156	140	125	118	149
Na_2O/K_2O	1.5	1.5	1.6	0.84	0.70	1.24
Al_2O_3/Na_2O	4.7	4.7	4.4	6.7	8.1	4.3
FeO/Fe_2O_3	2.9	2.9	3.0	2.1	1.8	4.9

4.1.1.1 Comparison of Geraldton sedimentary rocks with average Archean sedimentary rocks

The averages for all greywacke and all siltstone samples are listed in Table 6 along with the averages for these rocks subdivided into group A and group B samples. Comparison of these samples with Condie's data (1981, p.140, Tables 4.4 and 4.5) (reproduced here as Table 7) reveals that, for most elements and ratios reported, the Geraldton sedimentary rocks are very similar to average Archean sedimentary rocks. The Geraldton greywacke has a slightly lower FeO/Fe_2O_3 than Condie's average as does the group A siltstone. This may be due to a greater magnetite content in these rocks. The average Geraldton siltstone has only slightly lower SiO_2, Al_2O_3/Na_2O and FeO/Fe_2O_3 than Condie's averages; however, group B samples have a slightly higher Na_2O and therefore also higher Na_2O/K_2O and lower Al_2O_3/Na_2O than Condie's averages, while group A samples have similar values to Condie's. Therefore, it appears that there is no significant geochemical difference between Geraldton and average Archean clastic sedimentary rocks.

4.1.1.2 Comparison of group A versus group B sedimentary rocks

A series of student's t statistical tests were conducted on the geochemical analyses of the group A and group B sedimentary rocks to test for any significant

ABLE 7: Average compositions of Archean greywackes and argillites

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	63.7	66.2	63.3	64.4	69.2	66.9	70.5	65.2	57.8	59.2	60.6	63.0
TiO_2	0.57	0.52	0.56	0.62	0.53	0.57	0.3	0.57	0.70	0.69	0.67	0.8
Al_2O_3	14.9	10.2	13.3	15.5	13.7	15.7	14.6	15.8	18.4	20.2	12.6	18.2
Fe_2O_3	1.01	1.63	1.0	1.05	1.14	1.33	0.77	1.2	1.67	1.15	2.35	1.3
FeO	4.67	5.38	4.9	4.94	3.05	2.59	1.50	3.4	6.21	4.85	8.24	4.5
MgO	2.99	4.50	3.7	3.12	1.6	1.57	1.44	2.2	3.93	3.34	4.71	2.5
CaO	2.63	1.97	3.4	2.22	1.8	3.56	3.55	3.3	1.89	1.38	0.68	1.0
Na_2O	3.14	1.80	2.9	3.74	3.1	3.84	4.45	3.7	2.19	2.67	0.84	1.3
K_2O	2.30	1.58	2.1	2.44	2.0	3.07	1.32	3.23	3.26	2.49	2.28	3.5
H_2O	2.17	2.76	2.0		2.4	0.65	0.75	0.8	3.11	3.60	4.0	4.0
CO_2	1.49	2.59	1.0		0.3			0.2	0.17	0.05	2.6	0.2
P_2O_5	0.14	0.08	0.15		0.12	0.21	0.12	0.17	0.19	0.15	0.10	0.2
MnO	0.11	0.10	0.1		0.10	0.07	0.05	0.08	0.09	0.06	0.08	0.1
Na_2O/K_2O	1.4	1.1	1.4	1.5	1.6	1.3	3.4	1.1	0.67	1.1	0.37	0.37
Al_2O_3/Na_2O	4.8	5.7	4.6	4.2	4.4	4.1	3.3	4.3	8.4	7.6	15	14
FeO/Fe_2O_3	4.6	3.3	4.9	4.7	2.7	2.0	2.0	2.8	3.7	4.2	3.5	3.5

Note: Analyses are reported in weight percent.   (from Condie, 1981 p. 140-141)*

1 = average of 20 Archean graywackes
2 = average of 17 Archean greywackes from the Sheba Formation, South Africa
3 = composite Archean greywacke
4 = average of 23 Archean greywackes, South Pass greenstone belt, Wyoming
5 = average Phanerozoic greywacke
6 = average granodiorite
7 = average Archean tonalite
8 = average Precambrian continental crust

9 = average of 20 Archean slates
10 = average Archean slate from greywacke - argillite couplet
11 = average pelite from the Sheba Formation, South Africa
12 = average Phanerozoic argillite from greywacke - argillite couplet

difference in the major and trace element content between these two groups. The results of F-tests and pooled variance estimate t-test are presented in Tables 8 a and b. The tests were done to evaluate the hypothesis that the means of the two sample populations are the same, assuming a 5% (0.05) level of significance. F-tests to determine the equality of variances of the samples are evaluated to determine the validity of the t-test statistic. The results indicate that for all those comparisons for which the test is statistically valid, only MgO and P_2O_5 show any significant difference in the greywacke groups and Na_2O in the siltstone groups. Thus the two groups are essentially identical in major element composition.

4.1.1.3 Background gold content of Geraldton clastic sedimentary rocks

Most of the sampling of these rocks was done away from mineralization. For example, a detailed sampling cross-section was completed over a 330m across-strike section of greywacke-siltstone and iron formation east of Mosher Lake (Figures 3 and 6). The average gold contents for all 39 sedimentary rocks analyzed, subdivided by rock type and area, are presented in Table 9. The average gold contents of these rocks are all very low, ranging from 10.4 ppb for the group A siltstone to 1 ppb for the group B greywacke (only one analysis). The averages of all

Table 8. Results of F-tests and pooled variance estimate t-tests on whole rock geochemical analyses of group A versus group B sedimentary rocks: a) "sands" SiO₂ > 61.0% b) "muds" SiO₂ ≤ 61.0%

a) "sands" A vs B.

	N of A	N of B	F-value	NUM/DENOM	T-value	Pooled Variance Estimate deg of freedom	2-tail probability
SiO_2	21	5	1.31	A/B	1.22	24	.235
TiO_2	21	5	2.53	A/B	.48	24	.639
Al_2O_3	21	5	3.78	B/A	.52	24	.606
FeO	19	4	22.35	A/B	.01	21	.992
Fe_2O_3	21	5	2.04	A/B	-.12	24	.909
MnO	21	5	1.44	B/A	-1.47	24	.155
MgO	21	5	1.65	A/B	-1.89	24	.070
CaO	21	5	2.29	B/A	-.40	24	.176
Na_2O	21	5	1.44	A/B	-.45	24	.657
K_2O	21	5	1.12	A/B	.33	24	.748
P_2O_5	21	5	2.86	A/B	3.08	24	.005
Fe_2O_3T	21	5	12.07	B/A	-3.37	24	.718
H_2O	19	4	1.74	B/A	-1.35	23	.190
CO_2	19	4	1.59	A/B	-.35	21	.729
S	19	4	1.58	A/B	-.23	21	.824

b) "muds" A vs B.

	N of A	N of B	F-value	NUM/DENOM	T-value	Pooled Variance Estimate deg of freedom	2-tail probability
SiO_2	15	4	1.01	B/A	1.02	17	.323
TiO_2	15	4	5.31	B/A	-.29	17	.774
Al_2O_3	14	4	2.67	B/A	-.76	17	.097
FeO	14	4	5.63	A/B	.05	16	.958
Fe_2O_3	15	4	50.14	A/B	1.90	16	.075
MnO	15	4	10.75	B/A	-.15	17	.582
MgO	15	4	6.85	B/A	-1.41	17	.177
CaO	15	4	1.05	A/B	.18	17	.857
Na_2O	15	4	1.89	A/B	-2.36	17	.030
K_2O	15	4	1.30	B/A	-.26	17	.223
P_2O_5	15	4	5.82	A/B	-1.47	17	.160
H_2O	15	4	2.11	A/B	1.37	17	.189
CO_2	14	4	9.55	A/B	.85	16	.410
S	14	4	11.47	A/B	.92	16	.372

TABLE 9: Average gold content of Geraldton clastic sedimentary rocks

	Mean Au(ppb)	Standard Deviation	No. of Samples
Group A			
greywacke	9.0	21.4	18
siltstone	10.4	15.7	12
Group B			
greywacke	1.0	–	1
siltstone	1.7	0.6	3
Groups A & B			
greywacke	8.6		19
siltstone	8.7		15

greywacke and all siltstone are both less than 9 ppb gold
(greywacke, 8.6 ppb; siltstone, 8.7 ppb).

4.1.2 Iron formation

92 samples of iron formation were collected and
analyzed for major and trace elements and gold. The
complete results are listed in Appendix A. For purposes
of sampling, iron formation refers to a sedimentary rock
with visible magnetite laminae. In some cases the laminae
are very narrow, in others they are up to a centimetre in
width but make up less than 10% of the sample, and in
others a sample of iron formation may be greater than 80%
magnetite-hematite, therefore there is a great variation
in the composition of these rocks.

The average major and trace element composition of
all 92 samples, and the average compositions of these
rocks subdivided by sulphur content are presented in Table
10. Plots of Fe_2O_3T against SiO_2, Al_2O_3, TiO_2, Ni, Cr,
and Co, and SiO_2 against TiO_2 are presented in Figure 36.
All of these plots show negative correlations except the
SiO_2-TiO_2 plot which shows a weak positive correlation.
Plots of Al_2O_3 against TiO_2, Cr, Ni, and Co are presented
in Figure 36. These plots show good positive correlation.
The consistency of these plots suggest that although there
is a great variation in the composition of these rocks as
outlined above, the variation is due to a binary mixing of
a clastic sedimentary and a chemical sedimentary

TABLE 10: Average major and selected trace element analyses of Geraldton iron formation; total sample population and population subdivided by sulphur content

	Total Iron Formation N=92				Iron Formation; S <0.5% N=80				Iron Formation S >0.5% N=12			
	mean	min.	max.	S.Dev.	mean	min.	max.	S.Dev.	mean	min.	max.	S.Dev.
SiO_2	41.79	20.7	60.6	8.13	42.98	27.9	60.6	7.22	33.86	20.7	56.3	9.67
TiO_2	0.23	0.03	0.60	0.13	0.23	0.03	0.60	0.13	0.22	0.09	0.38	0.10
Al_2O_3	6.08	0.90	16.6	3.36	6.12	0.90	16.6	3.42	5.83	2.60	13.5	3.09
Fe_2O_3	33.25(82)	2.7	59.2	12.16	33.75	2.70	59.2	12.08	29.9	3.4	45.9	12.71
FeO	9.59(82)	0.30	28.8	5.74	9.17	0.30	18.4	5.14	26.25	23.70	28.8	3.61
MnO	0.08	0.02	0.2	0.04	0.08	0.02	0.17	.04	0.08	0.02	.20	.05
MgO	1.3	0.02	3.27	0.83	1.30	0.02	3.27	.84	1.34	0.30	3.04	.79
CaO	0.94	0.12	4.14	0.87	0.89	0.12	3.59	.78	1.33	0.22	4.14	1.34
Na_2O	0.66	0	3.2	0.79	0.64	0.0	3.20	.75	0.74	0.0	2.50	1.09
K_2O	0.83	0	3.29	1.14	0.85	0.0	3.11	.83	0.73	0.05	3.29	0.91
P_2O_5	0.21	0.07	0.44	0.07	0.21	0.07	0.44	.06	0.19	0.09	.39	0.07
H_2O_T	2.29	0.2	8.4	1.40	2.16	0.20	4.90	1.24	3.19	1.4	8.4	2.05
CO_2T	2.02	0.1	17.2	3.28	1.40	0.10	8.00	1.51	6.14	.20	17.20	6.57
S	1.50	0.0	27.2	4.95	.04	0	0.43	0.07	11.19	.57	27.2	9.18
Au	593.7	1.0	10001	20934	27.2(79)	1.0	1700	190.8	4323(11)	1.0	10001	4257
Ni	19	0	69	16.6	19			17.0	17			14.6
Cr	60	5	183	36.8	61			4.2	53			7.2
Co	10	0	27	6.5	8			0.7	11			1.8
Cu	25	0	260	31.0	22			18.8	51			68.2
Zn	49	16	130	20.5	50			19.0	47			30.2
Pb	15	0	41	9.5	16			1.1	13			3.0
As	859	0	70000	7296	24			46.0	6432			5783

Note: major elements are reported in wt%, Au in ppb, and other trace elements in ppm.
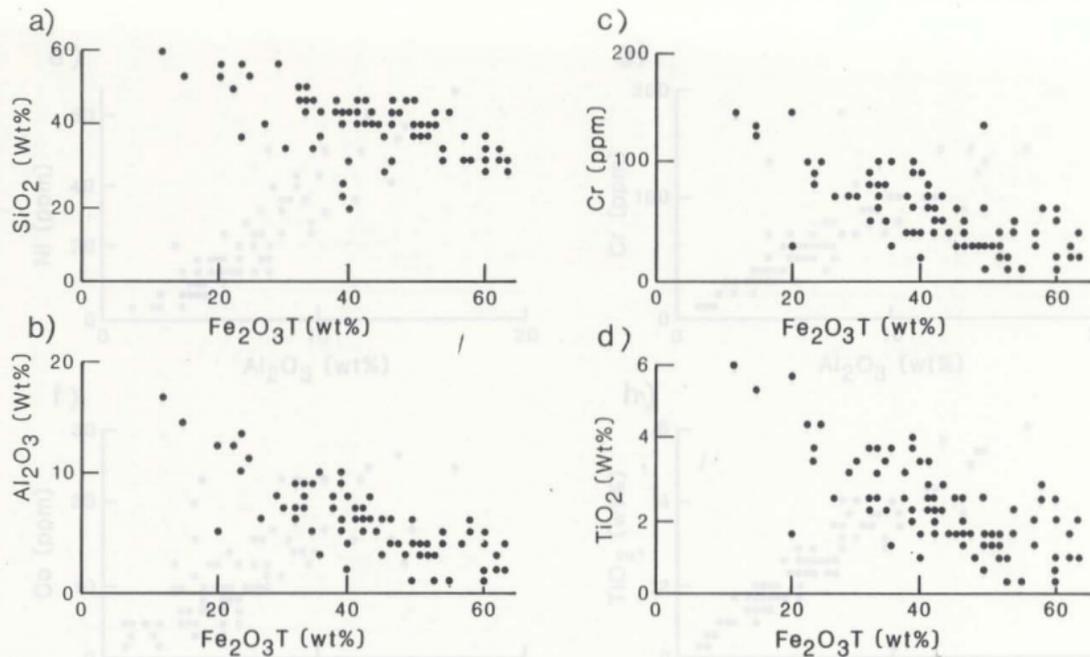
Figure 36. X-Y plots of iron formation geochemical analyses; a) SiO_2 vs Fe_2O_3T, b) Al_2O_3 vs Fe_2O_3T, c) Cr vs Fe_2O_3T, d) TiO_2 vs Fe_2O_3T, e) Ni vs Al_2O_3, f) Co vs Al_2O_3, g) Cr vs Al_2O_3, h) TiO_2 vs Al_2O_3, i) Ni vs Fe_2O_3T, j) Co vs Fe_2O_3T, k) TiO_2 vs SiO_2.
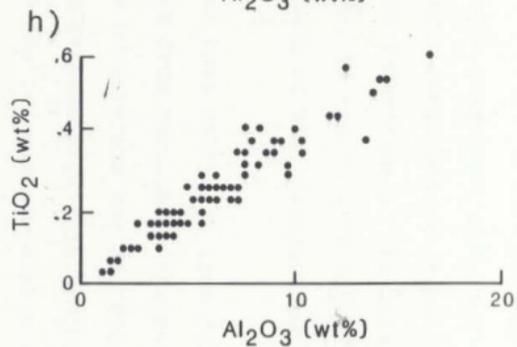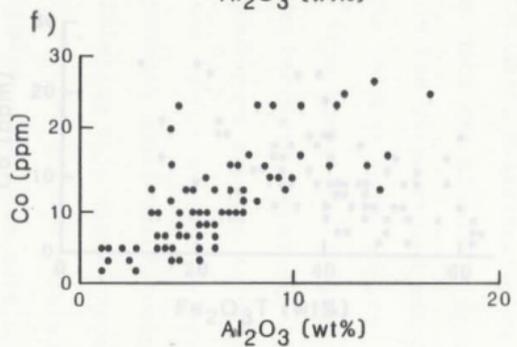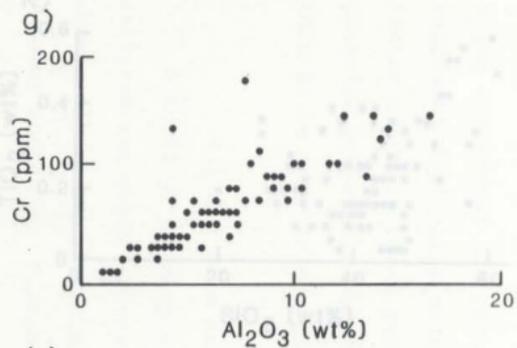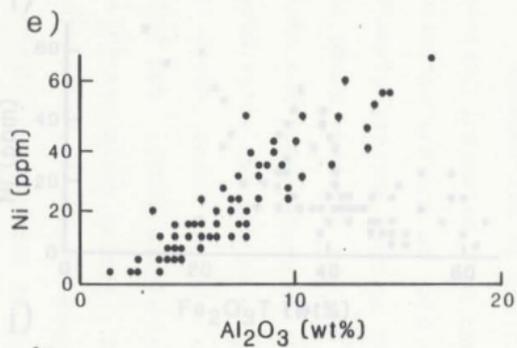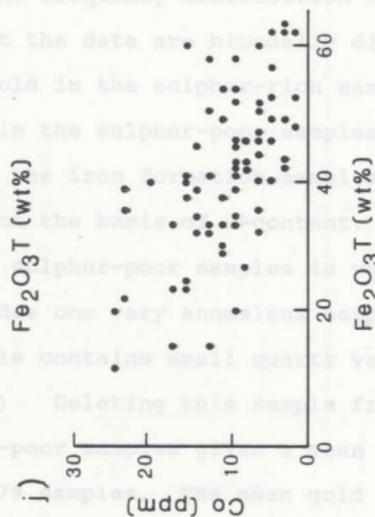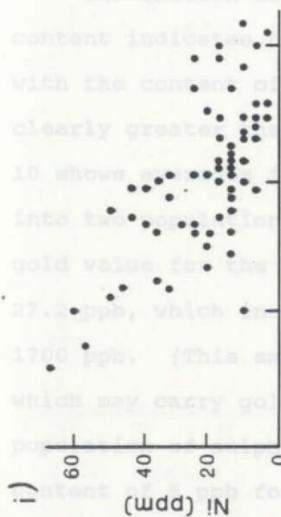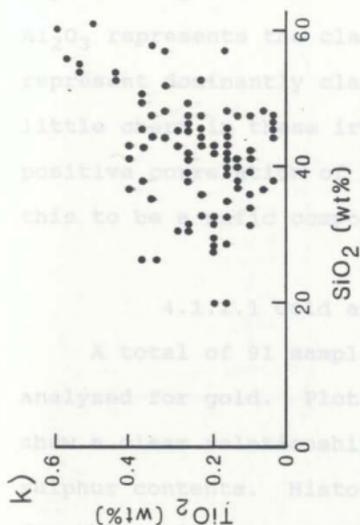
144

component. Fe_2O_3T probably dominantly represents the input of magnetite-hematite chemical precipitate, while Al_2O_3 represents the clastic component (SiO_2 may also represent dominantly clastic component as there is very little chert in these iron formations). The strong positive correlation of Cr, Ni and Co with Al_2O_3 suggest this to be a major component of the clastic input.

4.?.?.1 Gold and base metals in iron formation

A total of 91 samples from throughout the belt were analyzed for gold. Plots of S versus log Au (Figure 37) show a positive relationship between high gold and high sulphur contents. Histograms for samples with S >0.5% and for those with S <= 0.5% are given in Figure 38a.

Examination of the frequency distribution of gold content indicates that the data are bimodally distributed, with the content of gold in the sulphur-rich samples clearly greater than in the sulphur-poor samples. Table 10 shows ... the iron formation samples, divided into two groups on the basis ... content. The mean gold value for the 80 sulphur-poor samples is very low, 27.?ppb, which ... one very anomalous sample with 1700 ppb. (This sample contains small quartz veinlets which may carry gold.) Deleting this sample from the population of sulphur-poor samples ... a mean gold content for 79 samples. The mean gold value for the 12 sulphur-rich samples is 432ppb.

i) Ni (ppm)   j) Co (ppm) Fe_2O_3T (wt%)

k) TiO_2 (wt%) SiO_2 (wt%)

component. Fe_2O_3T probably dominantly represents the
input of magnetite-hematite chemical precipitate, while
Al_2O_3 represents the clastic component (SiO_2 may also
represent dominantly clastic component as there is very
little chert in these iron formations). The strong
positive correlation of Cr, Ni and Co with Al_2O_3 suggest
this to be a mafic component of the clastic input.

4.1.2.1 Gold and base metals in iron formation

A total of 91 samples from throughout the belt were
analyzed for gold. Plots of S versus log Au (Figure 37)
show a clear relationship between high gold and high
sulphur contents. Histograms for samples with S >0.5% and
for those with S <= 0.5% are given in Figure 38a.

Examination of the frequency distribution of gold
content indicates that the data are bimodally distributed,
with the content of gold in the sulphur-rich samples
clearly greater than in the sulphur-poor samples. Table
10 shows averages for the iron formation samples, divided
into two populations on the basis of S-content. The mean
gold value for the 80 sulphur-poor samples is very low,
27.2 ppb, which includes one very anomalous sample with
1700 ppb. (This sample contains small quartz veinlets
which may carry gold.) Deleting this sample from the
population of sulphur-poor samples gives a mean gold
content of 6 ppb for 79 samples. The mean gold value for
the 12 sulphur-rich samples is 432ppb.
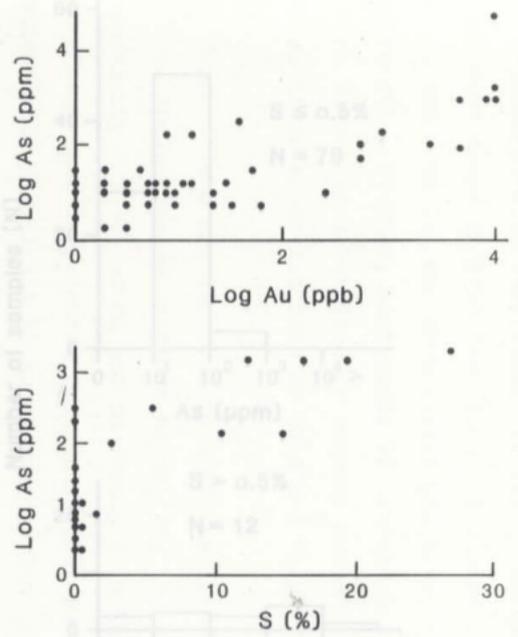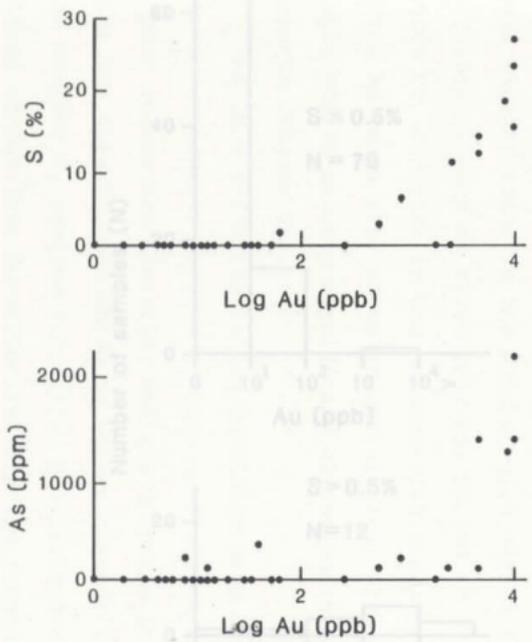
Figure 37. X-Y plots of sulphur, gold and arsenic in iron formation; a) S versus log Au, b) As versus log Au, c) log As versus log Au, and d) log As versus S.
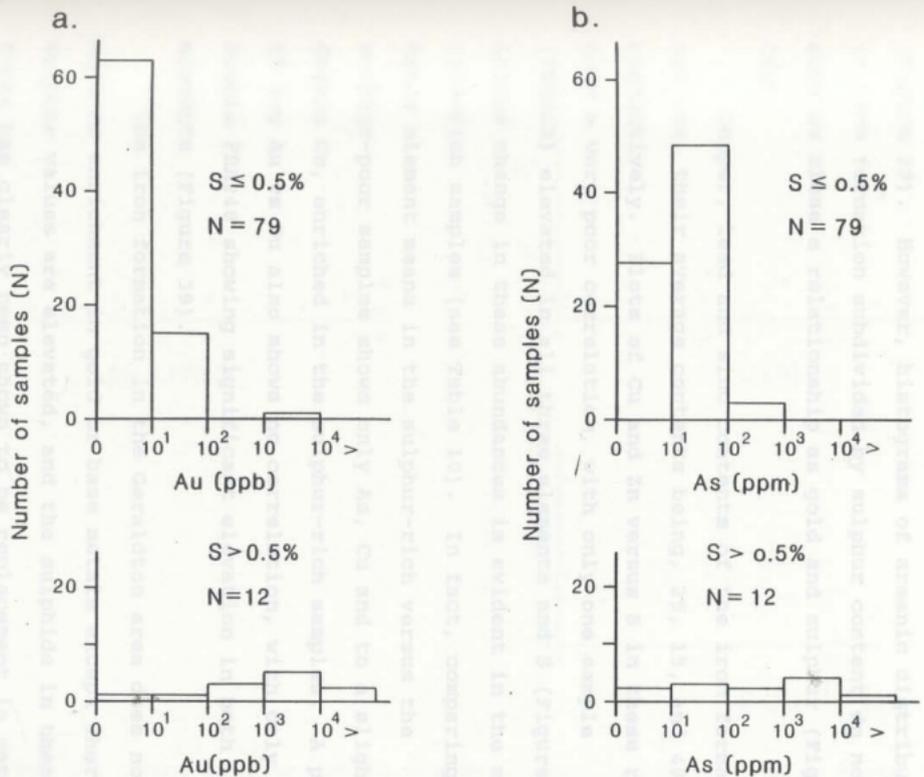
Figure 38. Histograms of gold and arsenic content of iron formation, subdivided by sulphur content; a) gold , b) arsenic.

Arsenopyrite is very common in the sulphide replacement zones in iron formation. Plots of log Au vs log As, and S vs log As, show a weak positive correlation (Figure 37). However, histograms of arsenic distribution in iron formation subdivided by sulphur content do not show as close a relationship as gold and sulphur (Figure 38b).

Copper, lead and zinc contents of the iron formation are low, their average contents being, 25, 15, and 49 ppm, respectively. Plots of Cu and Zn versus S in these rocks show a very poor correlation, with only one sample (FRA248) elevated in all three elements and S (Figure 39). Little change in these abundances is evident in the more gold-rich samples (see Table 10). In fact, comparing the trace element means in the sulphur-rich versus the sulphur-poor samples shows only As, Cu and to a slight degree Co, enriched in the sulphur-rich samples. A plot of log Au vs Cu also shows no correlation, with only sample FRA248 showing significant elevation in both elements (Figure 39).

The iron formation in the Geraldton area does not show an enrichment in gold or base metals except where sulphur values are elevated, and the sulphide in these rocks has clearly been shown to be replacement in nature (see Chapter 2, section 2.2.2.3). The background gold content of the iron formation is very low (compare with Crockett, 1974) and therefore this rock is probably not a
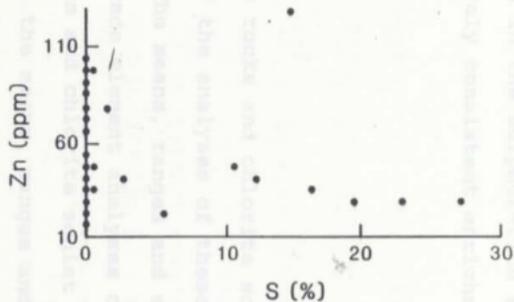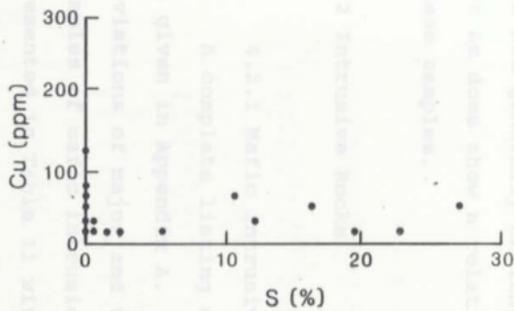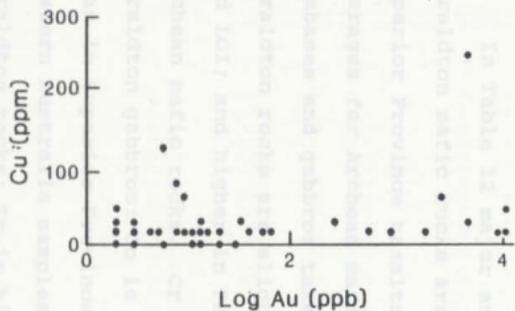
Figure 39. X-Y plots of base metals versus sulphur and gold in iron formation; a) Cu versus log Au, b) Cu versus S, and c) Zn versus S.

primary source for the gold in the veins. Cu, Pb and Zn are not generally enriched in the sulphur-rich samples, but As does show a relatively consistent enrichment in these samples.

4.2 Intrusive Rocks

4.2.1 Mafic intrusive rocks and chlorite schists

A complete listing of the analyses of these samples is given in Appendix A. The means, ranges and standard deviations of major and trace element analyses of 40 samples of mafic intrusions and chlorite schist are presented in Table 11 with the means, ranges and standard deviations for hornblende gabbro and chlorite schist as separate groups.

In Table 12 major and trace element averages for the Geraldton mafic rocks are given with averages for Archean Superior Province basalts taken from Goodwin (1977) and averages for Archean mafic flows and Western Australia diabases and gabbros taken from Condie (1981). The Geraldton rocks are slightly lower in TiO_2, Al_2O_3, CaO, and LOI; and higher in Fe_2O_3, MgO and K_2O than the other Archean mafic rocks. Cr and Sr are higher in the Geraldton gabbros; Co is higher in the Geraldton rocks than in Superior Province basalts, but lower than the Western Australia samples; Zn, Cu, and V are lower in the Geraldton rocks; Zr is higher in the Superior Province

Table 11. Means, ranges and standard deviation of major and trace element analyses of mafic intrusions and chlorite schist, Geraldton.

	Hornblende Gabbro N = 23					Chlorite Schist N = 16					Total Mafics N = 38				
	mean	min.	max.	S.D.	(n)	mean	min.	max.	S.D.	(n)	mean	min.	max.	S.D.	(n)
SiO₂	49.52	43.5	65.4	4.52		50.72	44.6	65.3	6.10		49.99	43.5	65.4	5.16	(15)
TiO₂	.89	.33	1.98	.27		.89	.2	1.24	.32		.89	.2	1.98	.29	
Al₂O₃	13.63	10.0	20.3	2.45	(11)	13.71	6.4	16.4	1.93		13.68	6.3	20.3	2.23	
Fe₂O₃	3.44	.3	9.9	2.44	(10)	4.45	2.40	9.0	3.51		3.97	.28	9.9	2.78	
FeO	7.43	3.4	11.0	2.33		7.07	5.8	10.0	1.70		7.35	3.4	11.0	2.66	
MnO	.19	.07	.46	.74		.17	.09	0.28	.05		.18	.07	.46	.06	
MgO	8.44	3.35	14.6	3.40		6.00	2.76	10.44	2.13		7.48	2.74	14.6	3.17	
CaO	8.44	.66	13.5	3.19		6.74	.68	7.95	2.31		6.38	.66	13.5	3.14	
Na₂O	2.33	0	5.56	1.46		2.50	.37	5.2	1.24		2.64	0	5.56	1.37	
K₂O	.67	.02	2.90	.59		1.20	.18	2.71	.84		.83	.02	2.90	.73	
P₂O₅	.139	.03	0.27	.06		.13	.07	.23	.04		.13	.03	.27	.05	
LOI	3.911	1.20	9.24	1.93	(23)	7.18	4.63	10.04	1.89	(11)	3.48	1.2	10.04	2.50	(23)
Total Fe (as Fe₂O₃)	12.09	5.3	19.6	2.22	(35)	11.95	5.88	14.31	1.93	(15)	12.03	5.3	19.6	2.08	(35)
TOTAL															
H₂O+	4.235	2.9	5.2	.71	(13)	3.73	3.0	4.2	.31	(4)	4.11	2.90	5.20	.69	(13)
CO₂+	1.791	.2	5.6	1.53	(13)	4.83	1.2	7.6	3.05	(4)	2.60	.20	7.00	2.37	(13)
S	.04	.0	0.3	0.09	(13)	.32	.03	1.15	.55	(4)	.114	0.0	1.115	.29	(15)
Au (ppb)	1.3	1.0	3.0	.7	(12)	29	1	180	66	(7)	12	1.0	190	40	(19)
Ni (ppm)	136	35	920	(24)		85	14	210	40	(16)	115	14	420	92	(15)
Cr	643	19	1900	(24)		225	0	917	178	(16)	155	0	1900	421	
Co	67	19	67	(24)		67	9	63	13	(16)	47	9	129	34	
Cu	55	2	110	(24)		45	31	129	63	(16)	51	9	314	35	
Zn	36	6	130	(24)		41	28	314	42	(16)	37	28	21	4	(15)
As	19	0	33	(11)		7	6	46	17	(16)	22	4	52	12	(15)
Rb	21	4	73	(26)		35	9	85	23	(16)	36	4	83	20	
Sr	331	88	1381	(26)		140	90	402	100		255	30	1381	289	(39)
Y	21	6	42			23	7	35	8		22	6	42	8	
Zr	70.5	26	140	2±	(14)	73	17	149	31		71	17	147	30	
Nb	3	0	6	(14)		3.5	3.5	7	1		3	0	6		
V	304	186	407			374	151	496	91	(2)	336	151	496	85	
Ba	134	16	400	(14)		300	40	817	246	(12)	211	16	817.0	204	(26)

Note: N = number of samples except where otherwise indicated by number in parentheses.
S.D. = standard deviation

TABLE 12: Average major and trace element analyses for Geraldton mafic rocks, Archean Superior Province basalts (Goodwin, 1977) and Archean mafic flows and Western Australian gabbro and diabase (Condie, 1981)

| | Geraldton | | Goodwin (1977) | | | Condie (1981) | |
	hornblende gabbro	chlorite schist	Timmins-Kirkland Lake	Wabigoon	Uchi	Archean flows	Western Australia gabbro and diabase
SiO_2	49.5	50.72	49.1	49.5	49.1	51.4	50.8
TiO_2	.89	.89	1.15	1.02	0.95	0.02	1.16
Al_2O_3	13.65	13.71	14.6	14.6	15.2	14.8	14.5
Fe_2O_3	3.44(11)	5.45(4)	2.69	2.70	2.69		
FeO	7.43(10)	7.07(3)	8.51	9.20	8.78		
MnO	.19	.17	0.21	0.21	0.19		
MgO	8.44	6.00	6.18	6.33	6.02	6.7	6.9
CaO	7.44	4.74	8.95	8.90	8.55	10.7	9.9
Na_2O	2.53	2.80	2.62	2.26	2.22	2.7	2.7
K_2O	.67	1.20	0.51	0.40	0.38	0.18	0.25
P_2O_5	.14	.13	0.14	0.27	0.12		
LOI	3.91	7.18	-	-	5.29		
Fe_2O_{3t}	12.09	11.95	-	-		10.4	11.7
H_2O	4.26	3.73	3.3	2.33			
CO_2	1.79	1.2	1.17	2.23			
S	0.4	.03					
Ni	136	85	170(484)	160	105(58)	161	145
Cr	443	225	245(487)	257	250(57)	395	314
Co	47(11)	47	36(483)	37	41	59	57
Cu	55	45	106	90	111	98	111
Zn	84	91	81	110	139	112	107
Pb	5	7	3.9	6.0	7.9		
Rb	21	35				9	9
Sr	331	140	172	174	219	105	91
Y	21	23				22	22
Zr	71	73	84	121	153	60	54
Nb	3	4					
V	304(14)	374(12)	372(488)	337	387	320	307
Ba	134(14)	300(12)	152	136	107		
	23	15	503	171	62	123	84

(except where noted in parentheses)

basalts and lower in the Western Australian rocks than in the Geraldton samples; and Ni, Pb and Ba are the approximately the same.

REE plots of four Geraldton gabbro samples are shown in Figure 40. (A listinf of REE data is given in Appendix D.) Sample 254A is a basalt from the Sturgeon Lake area (sampled by J.M. Franklin) and was analyzed for comparison. The gabbro patterns are essentially flat with a very slight light rare earth element (LREE) enrichment, with values 10-30X chondrite, and heavy rare earth element (HREE) 6-15X chondrite. Condie (1981) presented average compositions and REE plots for Archean basaltic komatiites (BK) (Condie, 1981, p.93), and Archean tholeiites which he subdivided into two groups (TH1 and TH2) (Condie, 1981, p.98) (Figure 41). TH1 is characterized by flat REE patterns (approximately 10X chondrite) with or without small Eu anomalies and TH2 is characterized by enriched LREE and a sloping REE pattern (Figure 41). Both TH1 and TH2 differ from BK by their higher TiO_2, Al_2O_3, Na_2O, K_2O, Ba, Sr, Zr, Y, Zr/Y, and Ti/V and by their lower MgO/FeO (<1), Cr, Ni, Co and Ni/Co. TH1 and TH2 have slightly higher REE abundances than BK. BK range from slight LREE enrichment to extreme LREE depletion. TH1 differs from TH2 by its higher TiO_2, K_2O, P_2O_5, V, Zr, Sr, Y and Zr/Y and by its lower CaO, Cr, FeO/Fe_2O_3, and Ti/Zr.

Based on the above criteria, the Geraldton mafic intrusive rocks best approximate Condie's TH group and not
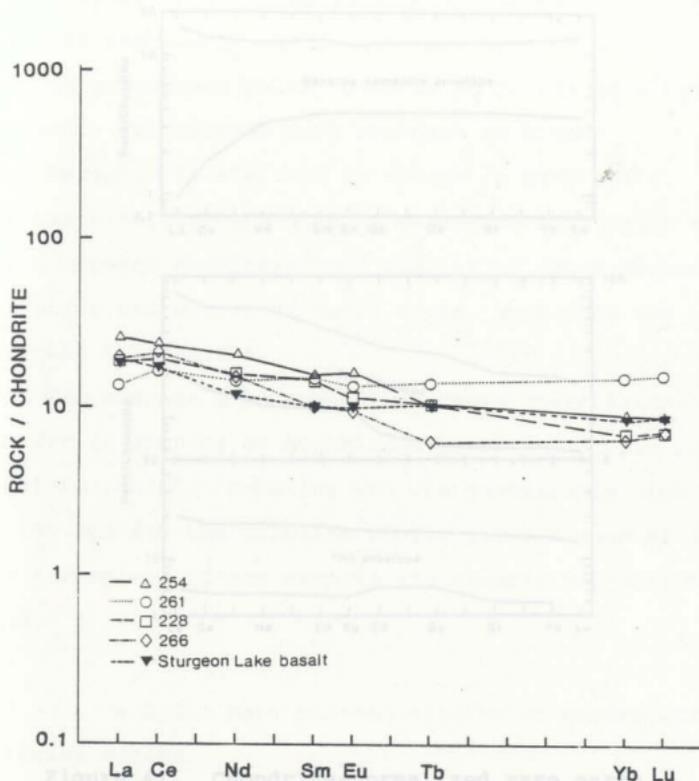
Figure 40. Chondrite-normalized rare earth
element plots of mafic intrusive rocks. One
sample of Sturgeon Lake basalt (sample collected
by J.M. Franklin) is plotted for comparison.
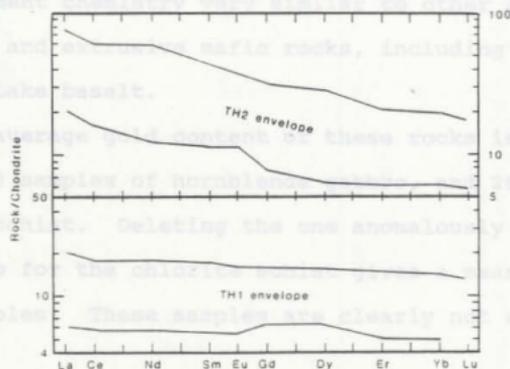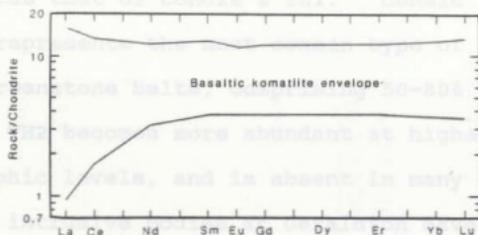
Figure 41. Chondrite-normalized rare earth
element plots of a) Archean basaltic komatiites,
and b) Archean tholeiites (after Condie,(1981)
pages 93 and 98).

BK. The REE pattern of the Geraldton intrusive rocks best approximates that of Condie's TH1. Condie (1981) states that TH1 represents the most common type of volcanic rock in most greenstone belts, comprising 50-80% of a typical section. TH2 becomes more abundant at higher stratigraphic levels, and is absent in many belts. Thus, the mafic intrusive bodies at Geraldton have major and trace element chemistry very similar to other Archean intrusive and extrusive mafic rocks, including the Sturgeon Lake basalt.

The average gold content of these rocks is only 1.5 ppb for 12 samples of hornblende gabbro, and 29.0 ppb for chlorite schist. Deleting the one anomalously high value of 180 ppb for the chlorite schist gives a mean of 3.8 ppb for 6 samples. These samples are clearly not enriched in gold.

4.2.1.1 Mass balance studies of gabbro and chlorite schist

Table 11 illustrates that there are some obvious geochemical differences between the Geraldton hornblende gabbro and chlorite schist samples. However, the similarity in trace element composition between the gabbro and chlorite schist samples is very clear (a plot of Cr versus MgO and Zr versus TiO_2 is given in Figure 42 for 5 samples of gabbro and 3 of chlorite schist from the Highway 11 Fault Rock outcrops).
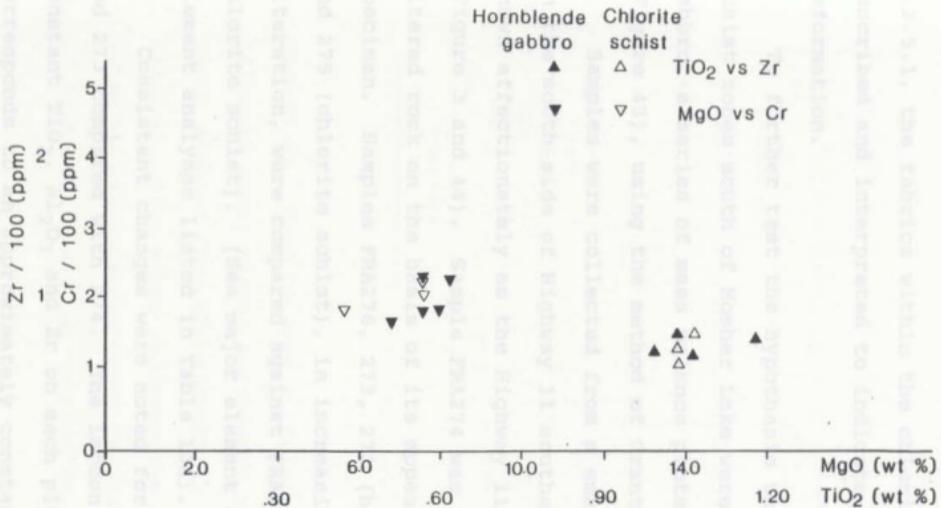
Figure 42. Zr versus TiO_2 and Cr versus MgO in hornblende gabbro and chlorite schist samples from the Highway 11 Fault Rock Outcrop.

In chapter two the relationships of these rocks in outcrop were described, and it was postulated that the chlorite schists were derived from hornblende gabbro by deformation and alteration. In Chapter 3, section 3.2.5.1, the fabrics within the chlorite schist zones were described and interpreted to indicate dextral shear deformation.

To further test the hypothesis that the chlorite schist zones south of Mosher Lake were derived from the gabbro, a series of mass balance plots were produced (Figure 43), using the method of Grant (1986).

Samples were collected from a small area of outcrop on the south side of Highway 11 southeast of Mosher Lake, known affectionately as the Highway 11 Fault Rock outcrop (Figure 3 and 44). Sample FRA274 was chosen as the most altered rock on the basis of its appearance in hand specimen. Samples FRA276, 273, 272 (hornblende gabbro) and 275 (chlorite schist), in increasing order of apparent alteration, were compared against FRA274 (most altered chlorite schist). (See major element and selected trace element analyses listed in Table 13a).

Consistent changes were noted for samples 276, 272, and 273 compared with 274. The isocon is chosen for constant TiO_2, Al_2O_3 and Zr on each plot. This corresponds to an approximately constant Fe_2O_3T, MnO, MgO, CaO (except 273 vs 274), Ni and V. A slight loss in SiO_2 and Na_2O, a slight gain in Ba and K_2O, a large loss of Sr
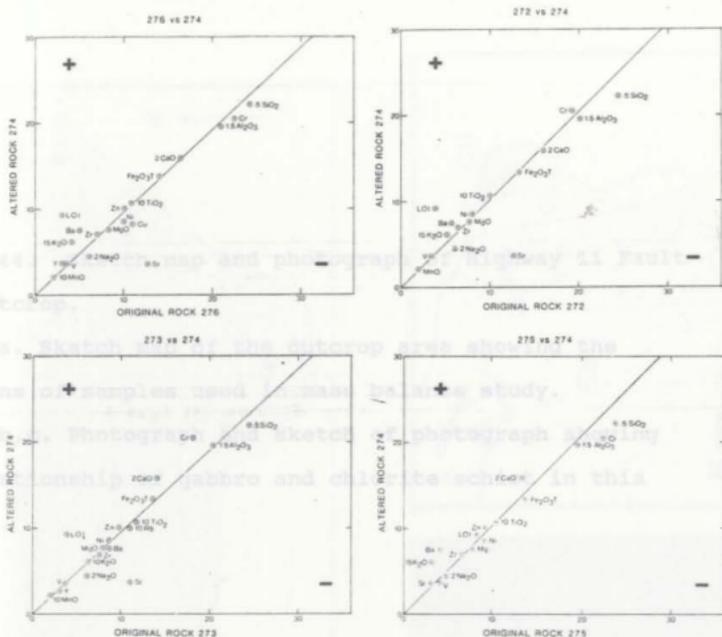
Figure 43. Mass balance plots of chlorite schist
(altered rock) versus hornblende gabbro (unaltered
rock) samples from the Highway 11 Fault Rock
Outcrop. Plus signs indicate the direction of
relative gains, minus signs indicate the direction
of relative losses, of components.

Figure 44. Sketch map and photograph of Highway 11 Fault
Rock Outcrop.

44a. Sketch map of the outcrop area showing the
locations of samples used in mass balance study.

44b,c. Photograph and sketch of photograph showing
the relationship of gabbro and chlorite schist in this
outcrop.
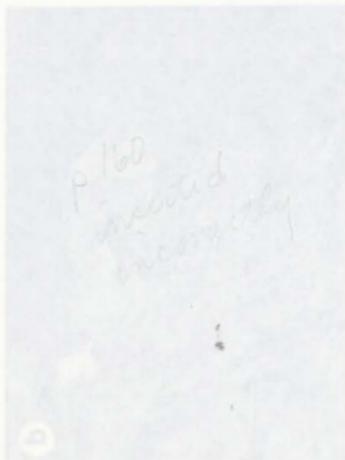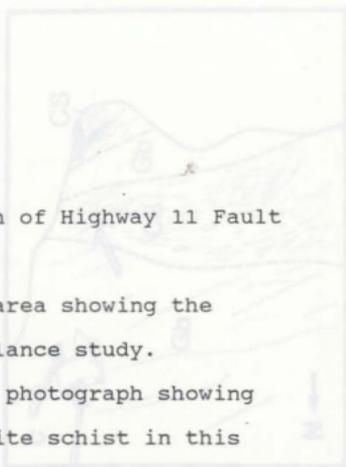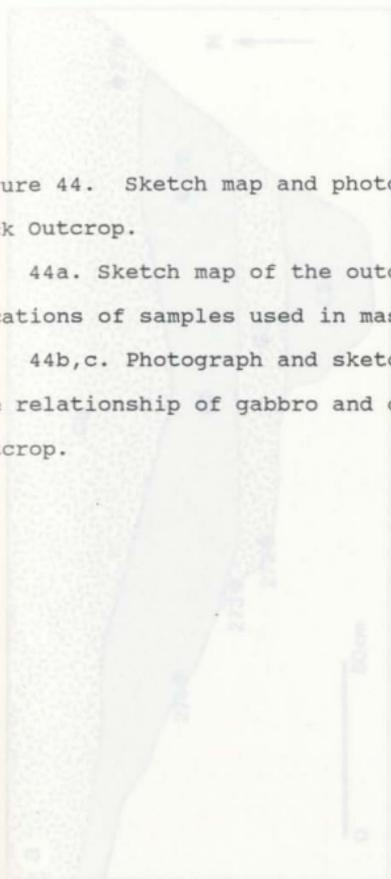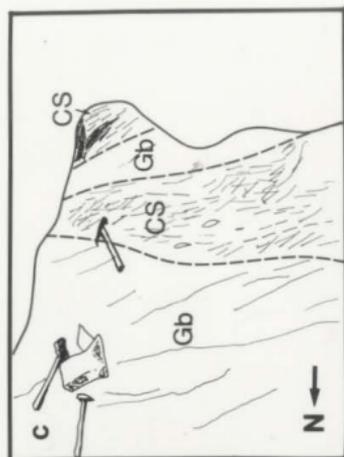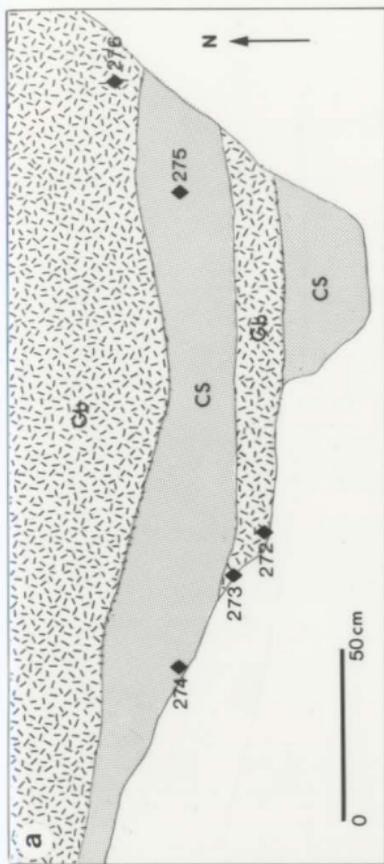
TABLE 13. a) Major element and selected trace element analyses and densities of samples illustrated in mass balance plots (Figure 43). b) Equation of the isocons based on constant TiO_2 and Al_2O_3.

a)

Sample	272	273	274	275	276
SiO_2	48.7	48.9	44.4	47.4	48.3
TiO_2	0.99	1.18	1.07	1.03	1.09
Al_2O_3	13.40	13.6	13.1	13.0	14.0
Fe_2O_3	-	-			
FeO	-	-			
MnO	0.19	0.20	0.21	0.21	0.20
MgO	7.59	8.03	7.70	7.70	8.30
CaO	8.02	7.06	7.95	6.59	8.24
Na_2O	3.03	3.12	2.24	2.37	3.04
K_2O	0.34	0.42	0.41	0.21	0.27
P_2O_5	0.09	0.10	0.09	0.09	0.10
LOI	3.94	3.91	9.25	8.10	2.98
Total Fe (as Fe_2O_3)	13.29	13.60	13.38	13.60	14.00
TOTAL	99.58	100.12	99.80	100.30	100.52
Density (ρ)	2.917	2.922	2.795	2.790	2.973
Cu	86	84	82	80	110
Zn	91	98	101	101	101
Ni	80	87	86	90	100
Cr	192	181	205	224	225
Rb	9	11	10	7	10
Sr	127	110	37	30	127
Zr	64	76	70	65	71

272 = slightly sheared gabbro
273 = slightly sheared gabbro
274 = chlorite shist
275 = chlorite schist
276 = massive hornblende gabbro

b)

Equation of the isocon through points of equal geochemical concentration:

$$C^A = (M^O/M^A) \, C^O$$

$\dfrac{M^O}{M^A}$ = Slope of the isocon (from plots).

if constant volume is assumed:

$$C^A = (\rho^O/\rho^A) \, C^O$$

$$\frac{V^A}{V^O} = \frac{1}{slope} \times \frac{\rho^O}{\rho^A}$$

I.   276 vs 274 $\dfrac{M^O}{M^A} = 0.946$ $\rho^O = 2.973$ $\rho^A = 2.795$

$$\frac{V^A}{V^O} = 1.057 \times \frac{2.973}{2.795} = 1.124$$

II.   272 vs 274 $\dfrac{M^O}{M^A} = 1.03$ $\rho^O = 2.917$ $\rho^A = 2.795$ $\dfrac{V^A}{V^O} = 1.013$

III.   273 vs 274 $\dfrac{M^O}{M^A} = 0.95$ $\rho^O = 2.922$ $\rho^A = 2.795$ $\dfrac{V^A}{V^O} = 1.100$

IV.   275 vs 274 $\dfrac{M^O}{M^A} = 1.047$ $\rho^O = 2.790$ $\rho^A = 2.795$ $\dfrac{V^A}{V^O} = 0.953$

Note: o = unaltered sample
A = altered sample
ρ = specific gravity
V = volume of sample
M = mass of sample

and a large gain in volatiles (LOI) were also noted in all three comparisons of unaltered against the altered sample.

Comparing the two chlorite schist samples, 274 versus 275, almost all components fall on the constant TiO_2, Al_2O_3, Zr isocon (which is very close to the constant mass line) including Sr and volatiles. A slight gain is recorded in CaO, Ba and K_2O.

In each case of 276, 273 and 272 versus 274, TiO_2, Al_2O_3, MgO, Fe_2O_3T, Zr, V, and Y all lie on or very close to a line through the origin and therefore probably represent a consistent isocon. In each case the isocon closely approximates the constant mass line, whose slope is 1.00. This is good evidence for the chlorite schist in this outcrop being derived from the gabbro. The order of alteration for these samples from least altered to most altered as indicated by the mass balance studies is; 276 < 273 <= 272 < 275 <= 274. The volume factors for these four comparisons are 1.124, 1.100, 1.013, and 0.953 respectively (Table 13b). Thus the most altered samples show a volume decrease compared to the least altered samples. Chemically the most altered samples show an increase in volatiles and loss in Sr. This probably represents a hydration of the rocks during deformation which led to the volume increase, and destruction of the feldspars with resulting loss in Sr.

In comparing the two most altered samples, 275 versus 274 (both chlorite schist), volatiles and Sr both lie on

the isocon, small gains are shown in K_2O, Ba and CaO. This may reflect the inhomogeneity that these rocks develop when they are most intensely deformed, i.e. chlorite-rich laminae versus quartz-carbonate-feldspar laminae. Sample 275 has lost volume compared to 274 indicating that samples which are most intensely deformed suffer a volume decrease.

4.2.2 Felsic intrusive rocks

The compositions of the felsic intrusive rocks in the Geraldton area were studied; 1) to compare the eastern and the western porphyritic intrusions, 2) to document the changes in these rocks due to alteration, and 3) to comment on the possible association between these rocks and gold mineralization.

The results of analyses of 17 samples of felsic rocks, 12 of the western porphyry (WP) and 5 of the eastern porphyry (EP) are given in Table 14. These rocks were analyzed for major, minor and trace elements, and 5 WP and 2 EP were analyzed for REE (Figure 45). In addition, one sample of the Croll Lake Stock, a large granodioritic pluton to the east of the thesis area (Figure 2) was similarly analyzed.

Table 14. Major and trace element analyses of selected quartz-feldspar and feldspar porphyritic intrusions, Geraldton.

| | WESTERN PORPHYRIES | | | | | | | | | | | | | EASTERN PORPHYRIES | | | | |
| | PORPHYRY HILL | | MOSHER-EAST | | MOSHER-WEST | | BANKFIELD | | | | | | WOODS-MAC | ROCHE LONGE LAC | | | |
Sample No.	82FRA011	214	156	221	215	146	220	222	226	259	264	268	209	202	205	207	208
wt % oxides																	
SiO_2	62.3	63.8	64.1	66.0	64.30	66.90	64.30	63.8	65.0	65.80	64.90	68.50	64.80	65.60	63.70	65.90	65.50
TiO_2	.35	.33	.32	.31	.32	.27	.33	.34	.30	.40	.38	.31	.34	.36	.39	.33	.35
Al_2O_3	17.0	15.2	16.90	16.40	15.50	16.00	16.40	15.80	15.10	16.30	14.80	15.10	15.10	15.30	15.00	16.20	15.30
Fe_2O_3	1.70		1.70			.80											
FeO	2.3		.70		2.00	2.00											
MnO	.04	.03	.04	.03	.03	.03	.02	.03	.03	.03	.04	.03	.05	.05	.06	.05	.07
MgO	.86	1.14	.58	.39	.92	.98	.72	1.15	.75	1.12	1.11	.84	2.10	2.17	2.41	2.00	2.07
CaO	3.07	4.37	3.34	2.07	3.02	1.81	2.55	3.24	3.79	1.53	2.28	2.30	3.90	3.83	4.38	2.41	4.64
Na_2O	5.2	3.19	4.40	6.14	4.77	6.60	5.96	5.00	4.68	5.09	5.60	6.96	4.90	4.58	4.41	5.00	5.63
K_2O	2.21	2.11	2.67	2.16	2.80	1.56	3.89	2.51	2.27	2.94	0.00	1.50	1.47	2.10	1.60	1.53	.83
P_2O_5	.14	.09	.12	.03	.03	.09	.17	.11	.14	.09	.10	.10	.16	.18	.16	.15	.16
L.O.I.	–	5.71	–	3.08	4.13	3.00	2.92	4.01	4.35	2.74	2.93	2.46	3.00	1.91	2.05	.81	1.48
Total Fe (as Fe_2O_3)	5.71	1.77	2.50	2.41	1.75	3.00	1.74	3.83	1.95	3.69	4.55	1.96	4.04	3.95	5.34	4.24	6.38
H_2O+	2.0	1.7	1.40		1.4	1.60							2.1				1.5
CO_2+	3.4	4.8	3.90		2.4	1.30							1.6				.9
S	0.25	0.51	0.00		1.23	0.40							0.10				0.13
Au(ppb)	8	214	1	1	4	270	140	172	4	4	–	–	1	10	1	20	12
Ni(ppm)	6	4	12	–	–	11	3	–	–	3	23	23	64	18	13	16	16
Cr	16	63	14	27	29	26	7	2	1	12	81	16	5	45	56	31	51
Co	64	–	9	–	–	7	2	–	–	–	8	–	48	35	55	221	245
Cu	20	16	33	12	14	17	30	33	3	11	13	2	20	38	25	40	37
Zn	22	37	55	28	5	19	10	11	31	12	14	–	2	0	10	8	20
Pb	66	0	13	3	5	88	–	3	7	6	4	–	–	–	–	–	–
As		72	–	–	–												
Rb	64	50	71	35	79	38	96	80	71	81	36	36	52	81	79	68	31
Sr	242	330	355	341	242	384	319	421	419	260	122	517	812	493	528	93	621
Y	5	5	8	6	6	6	6	6	6	6	12	8	13	13	21	9	9
Zr	124	110	127	101	94	96	58	92	58	98	82	85	135	138	121	133	130
Nb	–	–	–	–	–	–	5	7	5	5	8	5	6	9	7	6	9
V	4	50	48	33	53	–	93	70	55	68	113	59	36	36	64	37	57
Ba	890	1052	947	919	643	–	728	583	705	661	464	692	868	481	638	906	373

Figure 45. Chondrite-normalized rare earth
element plots of felsic porphyritic intrusive
rocks, including Eastern Poprhyries, Western
Porphyries and one sample of the Croll Lake Stock
(see Figure 2).

4.2.2.1 Comparison of eastern and western felsic porphyritic rocks

Based on field evidence and spatial distribution the felsic porphyritic rocks are divided into two distinct groups; the western porphyries and the eastern porphyries, (west and east of Lake Kenogamisis respectively, (Figures 3 and 4)). It is important to recall that both porphyry groups are cut by gold mineralization.

There are four possible associations between the two porphyry types; 1) they represent different fractionation products of the same melt; 2) the western porphyries are an altered version of the eastern porphyries; 3) a combination of 1) and 2); or, 4) they are completely unrelated rocks.

The major and trace element analyses indicate a similarity of these two porphyry types. The eastern porphyries have slightly higher TiO_2, MnO, MgO, Fe_2O_3T, Ni, Cr, and Zr contents, and lower LOI, Na_2O, K_2O, Au, and Ba contents than the western porphyries. The REE patterns are essentially identical in shape for both groups, but the eastern porphyry has higher abundances.

The similarity of REE patterns suggests that the two porphyry types were generated by a similar petrogenetic process and were probably derived from a similar magmatic source. The similar spatial and timing relationships (similar structural history) of the two porphyry groups also implies that they are probably genetically related,

and therefore that the slight differences in their
composition are due to fractionation and/or alteration.
The western porphyries are in every location more strongly
deformed and altered (based on a greater sericite,
carbonate and sulphide content) than the eastern
porphyries. The differences in plagioclase phenocryst
composition (see probe data, Chapter 2, Figure 23) also
suggests an alteration process, either a sodium addition
or a calcium loss in the phenocrysts in the western
porphyries. The higher K_2O, Na_2O, LOI and Ba contents of
the western porphyries also may have resulted from an
alteration process. However, the relatively higher
ferromagnesian contents of the eastern porphyries, the
consistent change in the abundances of the REEs,
decreasing from the eastern to the western porphyries, and
the presence of quartz phenocrysts only in the western
porphyry, are more easily explained as the result of a
fractionation process.

A plot of Al_2O_3 versus SiO_2 (Figure 46, not corrected
for volatiles) does not show a separation of the two
porphyry groups, consistent with the similarity in quartz-
feldspar dominant mineralogy of these rocks. On the plot
of Cr versus Al_2O_3 (Fig 46f), Cr is negatively correlated
with Al_2O_3 and the two populations overlap. In contrast,
plots of Fe_2O_3T, and FeOT + MgO versus SiO_2 (Figs 46a and
c) show two distinct populations, the latter plot showing
a distinct separation of the two groups, the EP being more
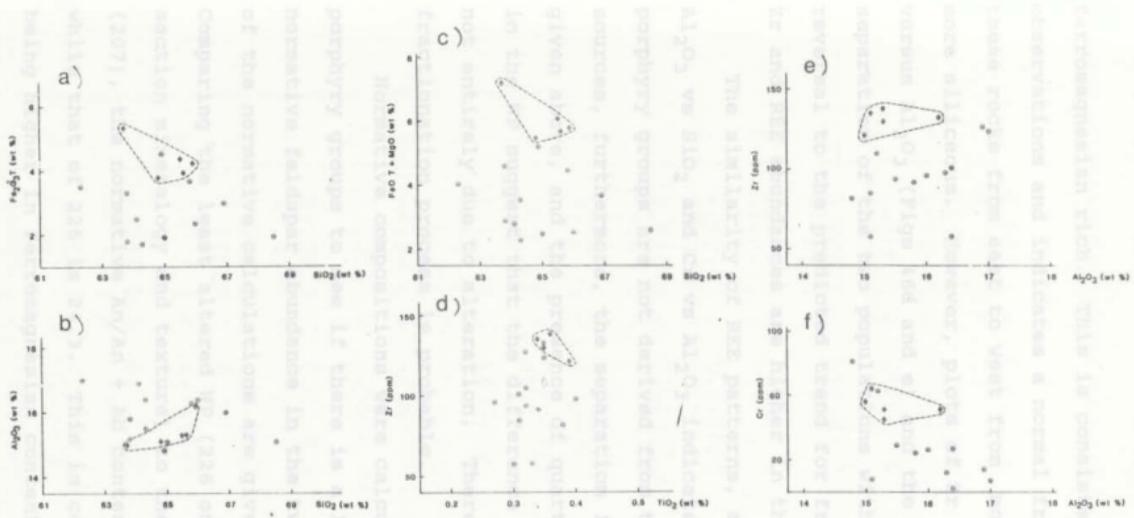
Figure 46. X-Y plots of selected element analyses for comparison of Eastern versus Western porphyries; a) Fe_2O_3T vs SiO_2, b) Al_2O_3 vs SiO_2, c) FeOT + MgO vs SiO_2, d) Zr vs TiO_2, e) Zr vs Al_2O_3 and f) Cr vs Al_2O_3. The Eastern Pophyries are represented by the diamond-shaped symbol and are outlined by the dashed line. The Western Poprhyries are plotted with circles.

ferromagnesian rich. This is consistent with petrographic observations and indicates a normal fractionation trend in these rocks from east to west from more ferromagnesian to more siliceous. However, plots of Zr versus TiO_2 and Zr versus Al_2O_3 (Figs 46d and e) and the REE patterns show a separation of the two populations with an apparent reversal to the predicted trend for fractionation in that Zr and REE abundances are higher in the EP.

The similarity of REE patterns, and relationships of Al_2O_3 vs SiO_2 and Cr vs Al_2O_3 indicates that the two porphyry groups are not derived from two different sources, furthermore, the separation in the other plots given above, and the presence of quartz phenocrysts only in the WP suggest that the difference in the two groups is not entirely due to alteration. Therefore some type of fractionation process is probable.

Normative compositions were calculated for the two porphyry groups to see if there is a large difference in normative feldspar abundance in the two groups. Results of the normative calculations are given in Table 15. Comparing the least altered WP (226 on the basis of thin section mineralogy and texture) to the least altered EP (207), the normative An/An + Ab content of 207 is 27.5 while that of 226 is 24.3. This is consistent with the EP being higher in ferromagnesian content. Total normative feldspar content is greater in the WP than the EP, but the difference is only 5-10%. This is consistent with

Table 15. Calculated normative mineralogy of Geraldton felsic porphyritic intrusive rocks.

Sample Number	011	214	136	221	215	146	220	222	226	239	264	268	209	202	205	207	208
Q	15.331	17.791	21.214	18.049	19.908	14.679	10.187	17.420	22.592	20.283	17.723	17.967	20.842	20.248	18.958	20.003	18.928
C	0.00	0.00	0.654	0.457	0.00	0.00	0.00	0.00	0.00	2.253	0.00	0.00	0.00	0.00	0.879	0.879	0.879
OR	13.503	13.299	16.612	13.346	17.715	9.613	26.010	15.531	10.316	17.999	13.440	9.10	8.969	12.702	9.733	9.161	4.989
AB	46.496	46.790	39.158	59.265	53.168	60.536	52.618	46.255	52.216	44.574	49.611	60.448	42.762	39.626	38.372	42.823	46.685
AN	15.115	12.728	17.647	10.044	13.486	7.708	6.783	6.783	14.380	7.287	9.252	5.678	15.333	15.223	16.874	17.236	15.166
Total Fspr	75.374	72.817	72.417	77.655	74.369	77.857	83.411	73.649	70.912	69.82	72.303	75.234	67.064	67.651	64.979	69.22	66.30
AN/AN + AB norm ratio	23.47	20.41	29.51	14.85	22.25	10.72	10.83	22.80	29.30	13.29	14.95	8.13	25.26	26.71	29.30	27.50	23.44
DI	0.0	6.525	0.0	0.0	1.373	0.0	4.036	1.291	3.651	0.0	1.219	4.175	7.617	1.813	2.878	2.878	4.152
HE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.422	0.0	0.0	2.329	0.163	0.163	4.686	4.333	4.333	1.631
EN	2.48	0.0	1.519	1.015	1.911	1.679	0.0	2.397	0.299	2.887	2.005	0.212	4.181	4.686	4.333	5.042	3.314
FS	2.097	0.0	0.0	0.0	0.0	0.0	0.0	1.026	0.0	1.458	2.005	0.0	0.298	1.515	2.956	1.915	1.493
MT	1.531	2.105	1.535	2.105	1.186	1.186	.185	.178	.743	2.611	.809	.508	3.20	2.624	2.773	2.715	2.667
IL	.702	.289	.639	.238	.238	.524	.185	.676	.243	.472	.696	.312	1.394	.524	.703	.703	.598
HM	0.0	0.0	.730	.240	.069	0.0	1.547	1.215	.312	0.0	0.0	1.334	0.0	0.0	0.0	0.0	0.0
AP	.343	.769	.242	.242	1.872	.934	.195	.267	.360	.216	.233	.233	.383	.427	.382	.352	.377
PY	.543	.222	.293		.199	.861											

Key to Symbols:

Q = quartz   AB = albite   DI = diopside   FS = ferrosilite   AP = apatite
C = corundum   AN = anorthite   HE = hedenbergite   MT = magnetite   PY = pyrite
OR = orthoclase   Fspr = feldspar   EN = enstatite   HM = hematite

petrographic observations that the amount of phenocryst
feldspar is not greatly different between the two groups.

On a triangular plot of normative quartz-K-feldspar-
plagioclase, the Geraldton feldspar and quartz feldspar
porphyries plot in the granodiorite-quartz monzodiorite
field of the IUGS (1973) modal mineral classification plot
(Figure 47). The normative quartz and plagioclase
mineralogy of these rocks appears to be close to their
modal composition except in K-feldspar content, which is
too high in the normative calculations. The composition
of the Geraldton porphyrites would probably be better
described as tonalite to quartz diorite.

The REE patterns have no significant Eu anomaly in
either EP or WP despite the large amount of modal feldspar
in these rocks. The shape of the REE patterns are very
similar for each group with a slightly smaller difference
in the middle REEs between the EP and the WP than between
the heavy REE and the light REE of the two groups (Figure
45). The patterns are typical of those interpreted to be
the result of melts formed in the presence of residual
garnet (Drury, 1979). The EP are probably the result of
slightly higher temperature melting which fused slightly
more of each of the residual phases (zircon, biotite and
possibly hornblende) without changing the shape of the REE
patterns, but only increasing REE, Zr and ferromagnesian
abundances. Therefore, the EP and the WP are thought to
be derived from varying degrees of partial melting of the

GERALDTON NORMPLOT - QFP'S
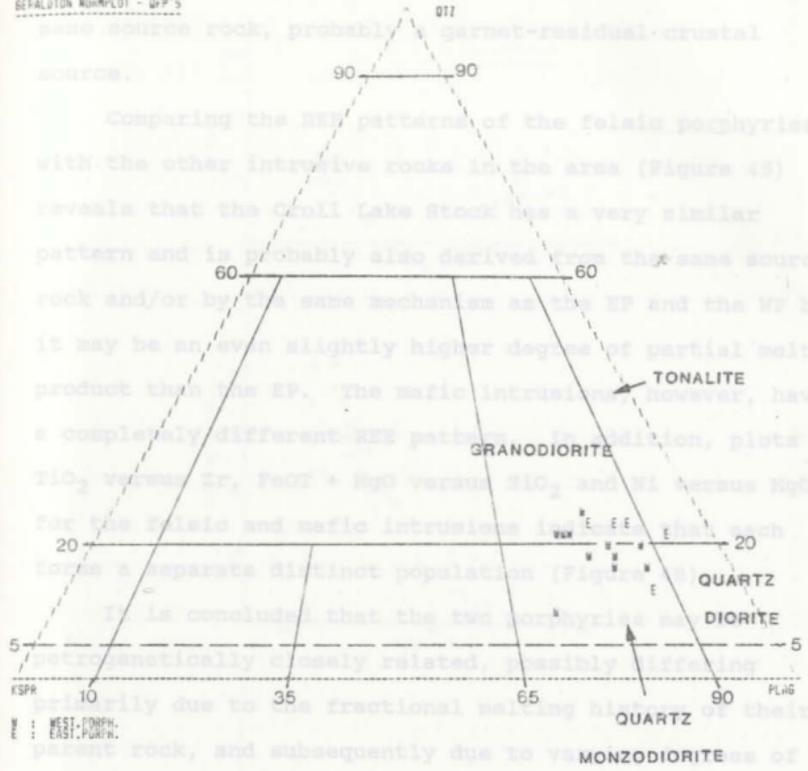
Figure 47. Plot of calculated normative quartz-plagioclase-K-feldspar on an IUGS modal mineral ternary classification plot for plutonic rocks. The normative quartz and plagioclase of the felsic intrusive rocks is close to their modal composition, but the normative K-feldspar is too high. Therefore, these rocks are probably better classified as tonalite and quartz diorite.

same source rock, probably a garnet-residual crustal source.

Comparing the REE patterns of the felsic porphyries with the other intrusive rocks in the area (Figure 45) reveals that the Croll Lake Stock has a very similar pattern and is probably also derived from the same source rock and/or by the same mechanism as the EP and the WP but it may be an even slightly higher degree of partial melt product than the EP. The mafic intrusions, however, have a completely different REE pattern. In addition, plots of TiO_2 versus Zr, FeOT + MgO versus SiO_2 and Ni versus MgO for the felsic and mafic intrusions indicate that each forms a separate distinct population (Figure 48).

It is concluded that the two porphyries may be petrogenetically closely related, possibly differing primarily due to the fractional melting history of their parent rock, and subsequently due to varying degrees of alteration.

4.2.2.2 Alteration of the felsic porphyritic rocks

The WP are all variably altered, even within single outcrops. The alteration consists of feldspar phenocrysts being altered to almost pure albite, with variable development of sericite, carbonate and quartz. The matrix is variably altered to sericite, carbonate and quartz with some chlorite. These changes imply that the alteration
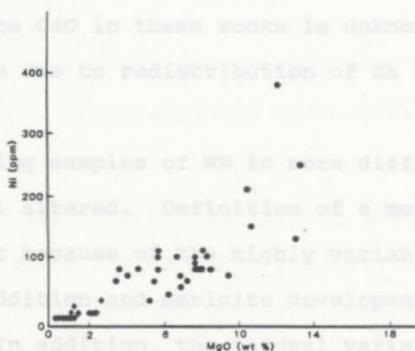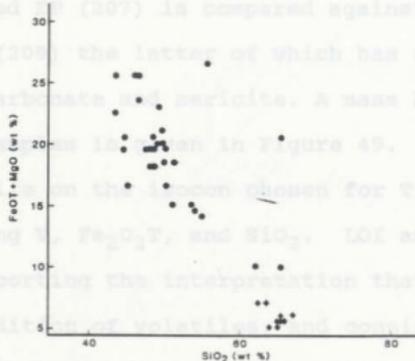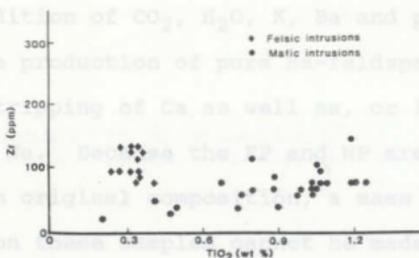
Figure 48. Plots of a) Zr versus TiO$_2$, b) FeOT + MgO versus SiO$_2$, and c) Ni versus MgO for comparison of felsic and mafic intrusive rocks.

involved addition of CO_2, H_2O, K, Ba and possibly Na, although the production of pure Na-feldspar may be the result of stripping of Ca as well as, or instead of, addition of Na. Because the EP and WP are slightly different in original composition, a mass balance comparison on these samples cannot be made. Instead, the least altered EP (207) is compared against the most altered EP (209) the latter of which has a small amount of secondary carbonate and sericite. A mass balance plot of these two samples is given in Figure 49. Most of the components lie on the isocon chosen for TiO_2, Al_2O_3 and Zr, including V, Fe_2O_3T, and SiO_2. LOI and CaO were gained, supporting the interpretation that alteration involved addition of volatiles, and consistent with the petrographic observations for these two samples. The source of the CaO in these rocks is unknown. Losses and gains may be due to redistribution of Ca with CO_2 alteration.

Comparing samples of WP is more difficult because they are all altered. Definition of a most-altered sample is difficult because of the highly variable amount of carbonate addition and sericite development between outcrops. In addition, the natural variation in the composition of these rocks makes comparing samples from two different outcrop areas somewhat unreliable. For this reason, mass balance comparisons were done on pairs of samples from the same outcrop area (except for one

Wods-Mac (209) vs. Roche Long Lac (207)
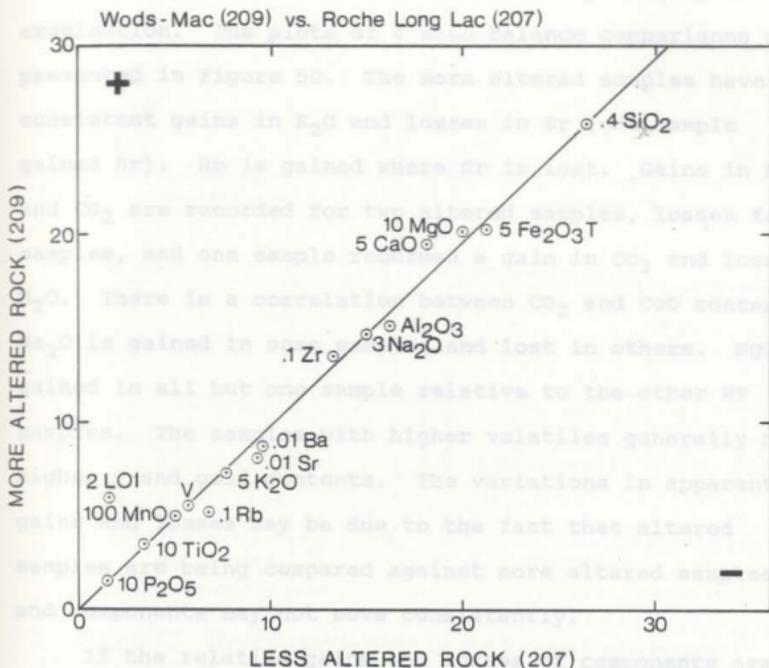
Figure 49. Mass balance plot of two Eastern porphyritic intrusive rocks; the Wods Mac porphyry (sample FRA209), the most altered Eastern porphyry, versus the Roche Long Lac porphyry (sample FRA207) the least altered Eastern porphyry.

comparison, which probably included samples from the same porphyry body), and categorizing less altered versus more altered samples was done on the basis of petrographic examination. The plots of 4 mass balance comparisons are presented in Figure 50. The more altered samples have consistent gains in K_2O and losses in Sr (one sample gained Sr). Rb is gained where Sr is lost. Gains in H_2O and CO_2 are recorded for two altered samples, losses for 2 samples, and one sample recorded a gain in CO_2 and loss of H_2O. There is a correlation between CO_2 and CaO content. Na_2O is gained in some samples and lost in others. MgO is gained in all but one sample relative to the other WP samples. The samples with higher volatiles generally have higher S and gold contents. The variations in apparent gains and losses may be due to the fact that altered samples are being compared against more altered samples, and components may not move consistently.

If the relative gains and losses of components are compared with the normative An/An+Ab values for each of these samples (Table 15), there is a consistent correlation between the relative addition of Na_2O to the rock and its normative albite content. An increase of Na_2O corresponds to a decrease in the normative An/An+Ab. There does not seem to be the same correlation with addition of CaO and normative feldspar composition. The behaviour of CaO may be due to variable carbonate composition. The four anomalously high gold samples

Figure 50. Mass balance plots of the Western porphyries.

(>100ppb) also have lower An/An+Ab normative feldspars (<21).

In summary, the fluids that altered the western porphyritic rocks consistently introduced K and Mg, removed Sr, and generally introduced volatiles, including S, thus hydrating, carbonatizing and pyritizing the WP relative to the EP. CaO increases with CO_2 and Na_2O is variably lost or gained. The normative feldspar content reflects the Na_2O gains and losses. Generally Rb is gained and Sr is lost in the more altered samples. Plots of K_2O versus Al_2O_3 for the two porphyry groups overlap in Al_2O_3, but the WP have higher K_2O and Sr versus Al_2O_3 shows the EP to be higher in Sr (Figure 51), supporting the above conclusions.

The presence of abundant sericite alteration indicates that the fluid responsible for the alteration was probably moderately acidic, since both sericite and albite are stable and K-feldspar is not. The albite and oligoclase phenocrysts show alteration to sericite, suggesting that sericitization continued after albite formation. The fluid was also CO_2, K^+, Mg^{++} and S - bearing, and mobilized Na_2O. The loss of Sr and gain in Rb reflect the destruction of feldspar and development of mica as observed petrographically. A very significant indicator of alteration in the WP is the presence of unzoned, almost pure albitic feldspar, with sericite and carbonate. Evidently the alteration process involved
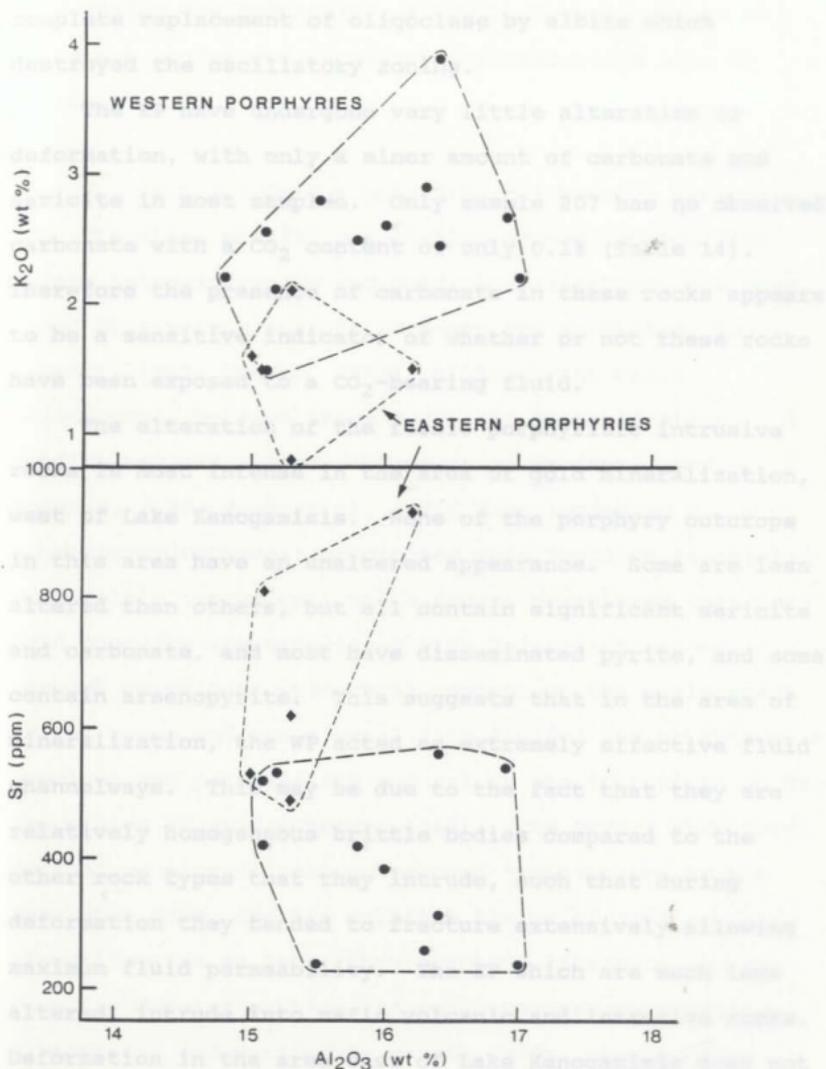
Figure 51. Plots of K$_2$O and Sr versus Al$_2$O$_3$ for Eastern versus Western felsic porphyritic intrusive rocks. Data for the Eastern porphyries are plotted as diamonds and outlined with short dashes. Data for the Western porphyries are plotted with circles and outlined with long dashes.

complete replacement of oligoclase by albite which destroyed the oscillatory zoning.

The EP have undergone very little alteration or deformation, with only a minor amount of carbonate and sericite in most samples. Only sample 207 has no observed carbonate with a CO_2 content of only 0.1% (Table 14). Therefore the presence of carbonate in these rocks appears to be a sensitive indicator of whether or not these rocks have been exposed to a CO_2-bearing fluid.

The alteration of the felsic porphyritic intrusive rocks is most intense in the area of gold mineralization, west of Lake Kenogamisis. None of the porphyry outcrops in this area have an unaltered appearance. Some are less altered than others, but all contain significant sericite and carbonate, and most have disseminated pyrite, and some contain arsenopyrite. This suggests that in the area of mineralization, the WP acted as extremely effective fluid channelways. This may be due to the fact that they are relatively homogeneous brittle bodies compared to the other rock types that they intrude, such that during deformation they tended to fracture extensively allowing maximum fluid permeability. The EP which are much less altered, intrude into mafic volcanic and intrusive rocks. Deformation in the area east of Lake Kenogamisis does not appear to have been as intense as in the west, and in addition, much of the deformation in this area may have been taken up by the less competent mafic rocks

surrounding the porphyries, allowing them to remain as
competent bodies and therefore not allowing access to
fluids.

4.2.2.3 Gold - porphyritic intrusion association

The close spatial association between porphyritic
felsic intrusive rocks and gold mineralization, has been
noted by numerous authors (Hodgson and MacGeehan, 1982;
Marmont, 1983; Cherry, 1983), although the exact
relationship between these rocks and mineralization
remains unclear. Some authors (e.g. Macdonald and
Hodgson, 1986; Wood et al, 1986) have suggested a
magmatic-hydrothermal origin for gold deposits associated
with felsic intrusions, while others postulated that some
gold deposits are associated with felsic intrusions
through coincident structural control on the emplacement
of the magma and the mineralizing fluids, and/or through a
chemical and permeability control by the intrusions on the
deposition of gold (Cherry, 1983). The strong structural
control on mineralization has been demonstrated in the
Geraldton area, and the relative timing of gold
mineralization as later than porphyry intrusion is obvious
from field relationships, as sericite-carbonate-pyrite
alteration, and auriferous quartz veins, crosscut the
felsic porphyritic intrusions. However, the absolute
timing of magma emplacement and gold mineralization must
be known before the exact relationship of these rocks may

be determined. For this reason, isotopic studies
including U/Pb zircon dating of the felsic intrusions, and
Pb isotope analyses of pyrite from mineralized areas, were
undertaken to try to resolve the absolute timing of
magmatism and mineralization and therefore to determine
the relationship between gold mineralization and the
felsic intrusive rocks in the Geraldton area.

4.3 Isotopic studies

4.3.1 Uranium-lead zircon dating of a felsic porphyritic intrusion

The Wods Mac porphyry (sample 209, see Figure 2) was
chosen for U/Pb zircon dating as it is close to the main
area of mineralization, but it appears to be only slightly
altered, and good euhedral zircons were observed in thin
section. Approximately 20 kilograms of this rock were
collected and submitted to the Geochronology Laboratory of
the Geological Survey of Canada. Procedures used for the
concentration of zircon and preparation of zircon
fractions, chemical extraction of U and Pb from zircon and
isotopic analyses of U and Pb are described in van Breemen
et al (1986). The uranium decay constants and isotopic
composition recommended by Steiger and Jaeger (1977) were
used to calculate the U/Pb ages.

The zircon concentrate from sample 209 consisted of
relatively uniform purple, translucent, euhedral finely

zoned crystals. Some crystals have small overgrowths of a
clearer, lighter colour on their terminations, while a few
have multiple terminations. Some crystals have darker,
purplish inner zones, but most are uniform. Polished
sections of grain mounts were etched with HF fumes to
determine if these zircons contained inherited cores.
Zoning is continuous from the central area into the clear
overgrowths and therefore the central darker areas
represent a U-rich zone and not an inherited core. The
length to width ratios generally fall into the 3:1 to 4:1
range but many of the crystals are broken, especially in
the larger fractions. Clear bubble inclusions and
fractures are common.

The zircons were seived and hand-picked into three
fractions. Five fractions were then analyzed, two abraded
(Krogh, 1982) and three not abraded; all compositions lie
below concordia. The analytical results are presented in
Table 16 and the concordia diagram is given in Figure 52.
Regression analysis yields upper and lower intercept ages
of 2691 +3/-2 Ma and 328 +79/-74 Ma. The continuous
growth zoning, euhedral habit and absence of inherited
cores in these zircons indicate crystallization from a
cooling silicate melt. Therefore the upper intercept age
is interpreted as the age of intrusion of the Wods Mac
feldspar porphyry.

For comparison, a U/Pb zircon age was determined for
a porphyritic rhyolite from northwest of the the Onaman

TABLE 16: U/Pb zircon analytical results; G = Wods Mac Porphyry, sample 209; OL = Onaman Lake Rhyolite

Label	Size Fraction		Wt (mg)	U (ppm)	Pb (ppm)	Measured $^{206}Pb/^{204}Pb$	Isotopic Abundances			Isotopic ratios		Age $^{207}Pb/^{206}Pb$ (Ma)
							^{204}Pb	^{207}Pb	^{208}Pb	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	
G-1	-105,74	A	0.019	301.5	167.0	2528	0.0107	18.526	8.961	0.50685	12.856	2689
G-2	-105,74	A	1.54	228.8	123.6	1842	0.0435	18.853	11.160	0.49041	12.390	2682
G-3	-105,74		0.68	733.6	390.1	3234	0.0220	18.557	10.843	0.48129	12.136	2679
G-4	-74,62		3.15	297.0	157.8	6531	0.0120	18.459	11.133	0.47837	12.078	2681
G-5	-62,35		3.17	245.3	129.1	5380	0.0174	18.503	12.040	0.47127	11.885	2679
OL-1	-105,74	A	0.38	105.0	69.40	1362	0.0166	19.429	18.797	0.51799	13.734	2762
OL-2	-74,62	A	0.69	179.5	110.07	1172	0.0651	19.961	22.366	0.51054	13.501	2758
OL-3	-105,74		1.21	260.4	147.6	767	0.1213	20.398	23.809	0.47360	12.366	2737
OL-4	-74,62		1.11	2239	124.7	634	0.1356	20.572	25.078	0.46247	12.073	2736

Note: A = abraded fraction

Figure 52. Concordia diagram for U/Pb zircon analyses of the Wods-Mac porphyry (sample FRA209) and the Onaman Lake rhyolitic volcanic (sample FRA602). The analytical results are presented in Table 16.

Lake area, north of the Beardmore-Geraldton belt (Figure
1a). This gave an age of 2769 +6/-5 for the metavolcanic
rocks in this area. Zircon dating of felsic volcanism at
Sturgeon Lake in the western Wabigoon subprovince gives an
average age of 2735 +/- 1.2 Ma for the lower cycles, and
an age of approximately 2718 +/- 2 Ma for the uppermost
cycle (Davis, et al, 1985). This latter age is one of the
youngest ages yet obtained on volcanic rocks in the
Wabigoon subprovince. These U/Pb zircon ages give a
difference of approximately 80 Ma between the age of
extrusion of the metavolcanics in the Onaman Lake area,
and a difference of approximately 30 Ma between the age of
youngest volcanism in the Wabigoon subprovince, and the
age of intrusion of the Geraldton porphyries. In
addition, the Onaman Lake volcanics are relatively old
compared to other Wabigoon subprovince volcanic sequences.

4.3.2 Lead isotopes

In order to examine some additional age and genetic
aspects of gold mineralization in the Geraldton area, 14
samples of pyrite and two of galena, were analyzed for
their lead isotopic composition. Thorpe (1982) and
Franklin and Thorpe (1982) have pointed out the
dissimilarity of lead isotopic compositions between gold
and volcanogenic massive sulphide deposits (VMS). Galena
from gold deposits is generally more radiogenic than
galena from VMS deposits. Franklin et al (1983) noted

that the lead isotopic composition of pyrite in most
massive sulphide deposits is close to that for galena from
the same deposits, but in gold deposits, pyrite samples
have comparatively radiogenic compositions; in some
deposits these latter samples yield a linear array of
isotopic compositions that is amenable to interpretation
by conventional two-stage techniques.

Samples were selected to examine several types of
gold mineralization including:

1) Three samples of disseminated pyrite from gold zones
within the albite porphyry bodies; one of these bodies
(sample 202) is similar to the porphyry body that is the
source of the zircons for the age determination discussed
above;

2) One sample of pyrite from an intermediate intrusion
mineralized with pyrite and arsenopyrite.

3) Five samples (including one replicate) from a zone of
sulphidized iron formation from the North Ore Zone of the
Hard Rock Mine;

4) Five samples from the Solomons Pillar's deposit, a
small gold occurrence which is a fracture-controlled
pyrite-arsenopyrite replacement zone totally within iron
formation, similar to but much smaller than (3);

5) Galena from two deposits within the Geraldton district
(the Bankfield Mine and the Bema Property at Watson Lake).

4.3.2.1 Lead isotope methods

The samples of galena and pyrite were mechanically separated from the silicate portions of the rock by a combination of magnetic and super-panner methods. The samples were analyzed by Geospec Consultants Ltd., Edmonton, Alberta. They were prepared by dissolving a small amount in 10 ml of high purity 2N HNO_3, and evaporating the solution slowly until $Pb(NO_3)_2$ crystallized. The crystals were extracted from the solution, washed in 4N HCl, dried and dissolved in water. An aliquot of 1 to 2 micrograms was loaded onto a rhenium filament in a silica gel-phosphoric acid mixture and analyzed on a Micromass MM-30 mass spectrometer. The data are presented in Table 17. A discussion of the errors associated with the lead isotope analyses is included as Appendix C.

Data sets which form distinctive linear arrays were subjected to linear regression using the method of York (1969). Upon inspection of the data, linear arrays were subjected to two-stage calculations following the method of Russell and Farquhar (1960). Model ages were calculated using the Stacey-Kramers (1975) model and models developed by Thorpe (pers. comm., 1986) using a set of galena analyses from massive sulphide deposits from the Abitibi belt and the western Superior subprovince for which the ages are well constrained by U-Pb (zircon) age determinations.

TABLE 17: Lead isotope analyses

Sample No.		Deposit	Mineral	Pb isotope ratios 206/204	207/204	208/204
83FRA	-235	Bema, Watson L.	gn	16.122	15.383	35.364
	-202	Roche Long Lac	py	17.306	15.514	36.818
	-212A	Hard Rock Mine	py	15.749	15.196	35.289
	-212B	Hard Rock Mine	py	16.250	15.238	35.921
	-212C	Hard Rock Mine	py	15.362	15.041	34.977
	-212D	Hard Rock Mine	py	16.345	15.297	36.008
	-214	Porphyry Hill	py	21.050	16.150	39.214
	-215	Mosher Hydroline	py	19.168	15.833	38.002
	-327	Ashmore	py	18.189	15.688	37.927
	-366	Solomons Pillars	py	15.026	15.051	34.731
	-369	Solomons Pillars	py	14.947	15.005	34.541
	-370	Solomons Pillars	py	14.929	14.980	34.459
	-380	Solomons Pillars	py	15.683	15.068	35.275
	-382	Solomons Pillars	py	15.608	15.283	35.315
TQ82	-130	Bankfield Mine	gn	13.910	14.793	33.755

4.3.2.2. Theory of lead isotopes

The theory of lead isotopes has been discussed by Franklin et al (1983) and is treated in detail by Russell and Farquhar (1960) and Faure (1977) and will only briefly be discussed here.

Lead in any mineral is a mixture of isotopes; ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb, the latter three of which are the radiogenic isotope end products of radioactive decay of ^{238}U, ^{235}U and ^{232}Th respectively. ^{204}Pb has no known parent isotope. The abundances of the radiogenic isotopes have increased with time and therefore so have the ratios $^{206}Pb/^{204}Pb$ (6/4), $^{207}Pb/^{204}Pb$ (7/4), and $^{208}Pb/^{204}Pb$ (8/4). Very old lead-bearing minerals that have remained isolated from U and Th since they were formed will have the smallest ratios.

In a single-stage model, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ grow along curved paths from a starting point (a_0, b_0, c_0) representing primeval lead. The growth curve that the sample follows depends on the initial starting composition, and the U/Pb and Th/Pb ratios of the host environment. If a Pb-bearing mineral (eg galena), evolved from primeval material, was separated from its parent U and Th at a given time, t, and remained a closed chemical system with no subsequent addition of radiogenic lead, this galena will have a unique 7/4 vs 6/4 set of ratios and from this the age of separation may be

calculated assuming a t_o, or age of formation of the
Earth, and a primeval lead starting composition (a_o, b_o,
c_o).

However, a simple single-stage model in which all the
lead is derived from the mantle does not account for
complex crustal and mantle interactions, remelting of
crustal material, or geophysical evidence of considerable
inhomogeneity in the upper mantle (Franklin et al, 1983).
Three models have recently been proposed which attempt to
reconcile geological considerations, and yield reasonable
agreement between model lead ages and independently
determined wallrock ages; a) Cumming and Richards (1975),
b) Stacey and Kramers (1975), which will be used in this
study and c) Doe and Zartman (1979). In addition, models
are being developed by Thorpe (1986, pers. comm.) for
specific areas in the Superior subprovince (see above).

Galena and pyrite were the minerals chosen for lead
isotopic analysis in this study. Galenas are high lead-
bearing minerals which are not strongly affected by
addition of radiogenic lead. Because of the amount of
lead in these minerals they are most likely to have formed
at the time of mineralization. Although model ages for
galenas from gold deposits may be difficult to determine,
the lead in the galena may be a relatively good indicator
of the composition of lead in the mineralizing fluid.
Model ages may be valid for these minerals, providing that
a model consistent with the composition of the source

rocks for the lead can be applied. However, most lead
isotope models have been generated for volcanogenic
massive sulphide deposits, where the processes of ore
formation and source of fluids and metals are better
constrained than models for gold deposits.

Lead in pyrite is a relatively minor component and
therefore the lead isotopic composition is more readily
subject to modification after crystallization of the
pyrite by radiogenic addition of Pb from included U and
Th. The problem of source of the common lead, U and Th is
much greater with pyrites because the source of these
components could include both the immediate wall rocks
and/or the mineralizing fluid.

Often, lead isotopic compositions form linear arrays
on plots of $^{207}Pb/^{206}Pb$ versus $^{206}Pb/^{204}Pb$ (7/4 vs 6/4),
and $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ (8/4 vs 6/4). Colinear
anomalous leads may be interpreted in several ways:
1. as a mixture of two (or more) ordinary leads, a mixing
line;
2. a two-stage, or secondary isochron, lead; and,
3. multistage leads, and repetition of the two-stage
process.

1. A mixture of two ordinary leads (a binary mixing
line) results from mixing two homogeneous leads, one
relatively non-radiogenic, the other more radiogenic.
Binary mixing lines are normally very short as it would
require one very radiogenic lead composition to get an

extensive binary mixing line. A long binary mixing line would only be formed in a uranium deposit, where there is a substantial amount of U to generate a large radiogenic component.

2. Two-stage and, 3. multistage leads; These result from radiogenic addition of Pb that formed in varying U/Pb environments, to a single common lead composition. The repetition of this process gives rise to multistage leads. To interpret a secondary isochron by conventional two-stage analysis requires that either t_1 (time of addition of U and Th to the common lead component) or t_2 be fixed based on independent age estimates or otherwise geologically reasonable criteria. In addition, two specialized limiting cases may be examined; t_{max}, when there has been continuous addition of radiogenic lead to the present and t_2 is therefore set to 0; and, t_{min} (or $t_{instantaneous}$) which indicates that U and Th were added to the mineral sometime before, and removed sometime after, this calculated time. This latter calculation is a limiting case only and has virtually no significance in the case of pyrite.

4.3.2.3 Discussion of the lead isotope data

I. Model ages

Galenas

Model lead ages were calculated using both the Stacey-Kramers model and the models of Thorpe (per comm,

1986) for all minerals analyzed. The results are presented in Table 18. As outlined above, model ages determined on galenas are much more reliable than those determined on pyrite because the former are very lead-rich minerals and therefore are not very susceptible to modification by radiogenic addition of lead.

The model ages on the Bankfield sample give a range of ages from 2474 Ma by Thorpe's Abitibi model, to 2563 Ma by the Stacey-Kramer's model. These are relatively young ages which may indicate time of emplacement of this galena (ie. time of removal of the lead from its parent U and Th). The Bema sample gives ages ranging form 1360 Ma to 1512 Ma which are interpreted to be too young to represent age of formation of the galena and are therefore anomalous. However, so little is known about the conditions under which the lead minerals in gold deposits were formed, for example the source of the fluids or the lead, that it makes the application of any model age system suspect.

The galena samples from the immediate Geraldton area have moderately to very radiogenic compositions. The sample from the Bema property has a composition close to the main cluster of pyrite samples from iron formation-hosted deposits (this sample comes from a small vein cutting chert oxide iron formation). The sample from the Bankfield Mine is much less radiogenic, and is at the top end of the main cluster of galena compositions for

TABLE 18. Model lead ages

Sample location & no.		Mineral	Model: Stacey-Kramers (1975)	Thorpe (pers. comm., 1986) Abitibi	Thorpe (pers. comm., 1986) Western Superior
Bankfield	TQ82-130	gn	2563	2474	2516
Bema	FRA83-235	gn	1512	1360	1402
Roche Long Lac	FRA83-202	py	827	645	690
Mosher	FRA83-215	py	0	-331	-282
Porphyry Hill	FRA83-214	py	-555	-1319	-1263
Ashmore	FRA83-327	py	500	0	254
Hard Rock	FRA83-212A	py	1497	1442	1486
	FRA83-212B	py	1150	1113	1158
	FRA83-212C	py	1555	1576	1620
	FRA83-212D	py	1184	1104	1149
Solomon's Pillars	FRA83-366	py	1884	1841	1884
	FRA83-369	py	1876	1857	1900
	FRA83-370	py	1848	1847	1890
	FRA83-380	py	1314	1359	1403

Superior Province gold deposits (Figures 53 and 54);
deposits in this cluster yield model ages in the 2700 to
2550 Ma range (Thorpe, 1982; Franklin and Thorpe, 1982).
The Bankfield is a relatively big deposit compared to Bema
which is a small occurrence, and therefore, more lead may
have been derived from the mineralizing fluid at the
Bankfield than at Bema where wallrock lead may be a more
significant component.

Pyrites

All of the model ages on the pyrites are anomalous,
particularly the pyrites in the felsic porphyritic rocks,
two of which give "future" model ages (Table 18).

II. Secondary isochrons on pyrite samples

On plots of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ and
$^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ the pyrite data clearly
fall into two distinct populations; a) the felsic and
intermediate intrusive rocks and, b) iron formation
(Figures 54 and 55).

a) Felsic and intermediate intrusive rocks:

The isotopic compositions of these samples are
clearly anomalous. They are far too radiogenic to be
interpreted as representing a primary isochron or a simple
single-stage lead isotopic evolution. Initial inspection
of the 7/4 vs 6/4 plot shows a general colinearity of the
four intrusive rocks, however, the intermediate, Ashmore,
intrusion (sample 327), is slightly different. The 8/4 vs
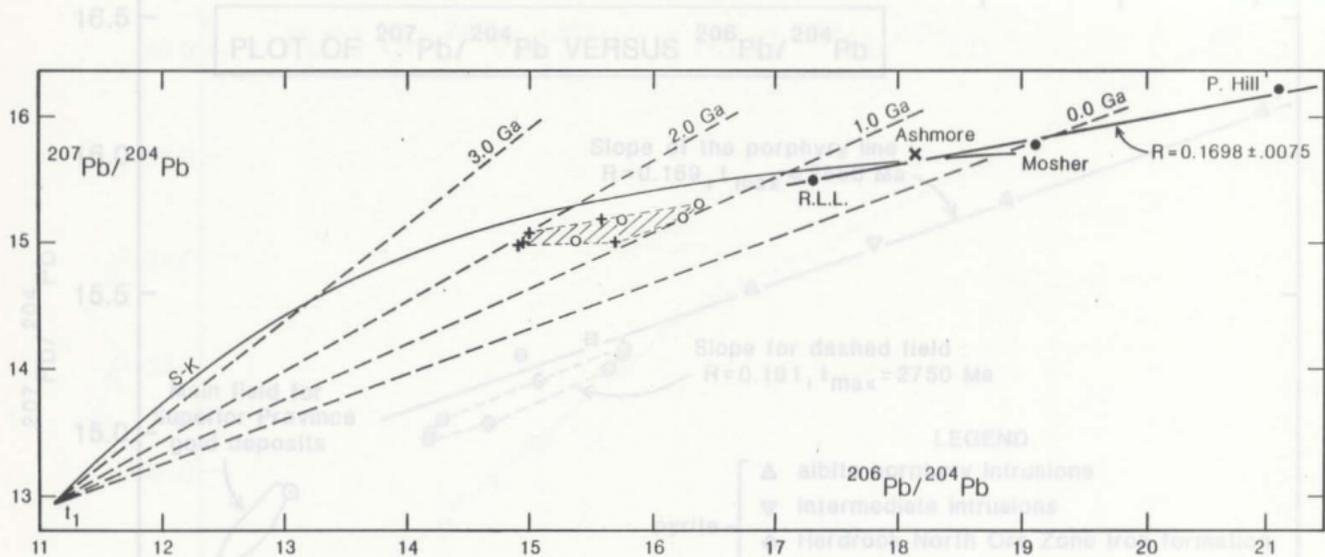
Figure 53. Geraldton lead isotope data superimposed on a Stacey-Kramers (1975) growth curve and selected isochrons. The iron formation data is plotted with crosses (Solomon's Pillars) and open circles (Hard Rock), the porphyry data is plotted with closed circles, and the one intermediate intrusive sample is plotted with an "x" (see Figures 54 and 55).

Figure 54. $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot of lead isotope analyses of pyrites and galena showing the main field for Superior Province massive sulphides and gold deposits (Franklin and Thorpe, 1982).
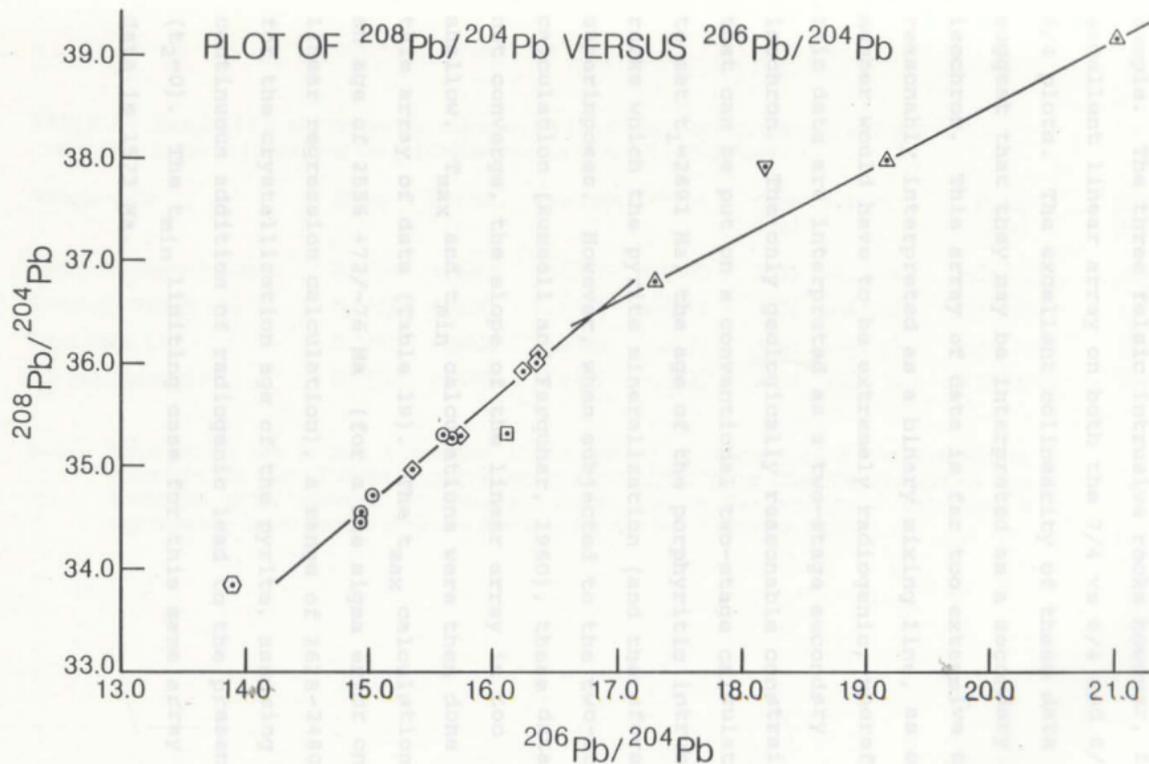
Figure 55. $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot of lead isotope analyses.

6/4 plot reveals an even greater difference for this sample. The three felsic intrusive rocks however, form an excellent linear array on both the 7/4 vs 6/4 and 8/4 vs 6/4 plots. The excellent colinearity of these data suggest that they may be interpreted as a secondary isochron. This array of data is far too extensive to be reasonably interpreted as a binary mixing line, as one end member would have to be extremely radiogenic, therefore, this data are interpreted as a two-stage secondary isochron. The only geologically reasonable constraint that can be put on a conventional two-stage calculation is to set t_1=2691 Ma, the age of the porphyritic intrusive rocks which the pyrite mineralization (and therefore gold) superimposes. However, when subjected to the two-stage calculation (Russell and Farquhar, 1960), these data do not converge, the slope of the linear array is too shallow. T_{max} and t_{min} calculations were then done one this array of data (Table 19). The t_{max} calculation gave an age of 2556 +72/-76 Ma (for a one sigma error on the linear regression calculation), a range of 2628-2480 Ma, for the crystallization age of the pyrite, assuming continuous addition of radiogenic lead to the present (t_2=0). The t_{min} limiting case for this same array of data is 1573 Ma.

TABLE 19. Results of linear regression calculations for a two-stage continuous addition secondary isochron (tmax) and for a t-instantaneous (tmin) limiting case

Sample suite	Slope	/ Error	Intercept	/ Error	tmax (Ma)	/ Error	Range (Ma)	tmin (Ma)
Felsic Porphyry-3 points	0.1699	±.0075	12.5751	±.0060	2556	+72/-76	2628-2480	1573
Solomon's Pillars I.F.	0.1718	±.0057	12.4575	±.0217	2576	+54/-57	2630-2519	1587
Hard Rock I.F.	0.2232	±.0060	11.6384	±.0191	3002	+44/-42	3046-2960	1931
All Iron Formation	0.1910	±.0040	12.1422	±.0102	2750	+28/-36	2778-2714	1713

Note: slope errors are in part a function of the number of points used in the calculation, therefore the line of three porphyry points has a higher error than the clusters of iron formation data, whereas the intercept error reflects the scatter of data and is significantly lower for the porphyry line than for the iron formation data.

b) Iron formation:

The iron formation pyrite samples are from sulphide replacement zones in oxide iron formation from a) the North ore zone of the Hard Rock Mine and b) from the Solomon's Pillars property, a small showing northwest of Jellicoe. The iron formation data are collectively less radiogenic than that of the porphyries, and the compositions are more scattered on the $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ plot. The calculated present-day $^{232}Th/^{238}U$ of the porphyries is 2.2 while that of the iron formation is 3.8 (calculated by method shown in Faure, 1977). However they still form a broad linear trend, (Figure 54) with a slope similar to that for the data for the pyrite samples from the porphyry-hosted mineralization. The data from Solomon's Pillars give a calculated t_{max} of 2576 Ma, very similar to that for the porphyry line (Table 19).

The scatter of data in the iron formation may represent a common lead component that originated by binary mixing of lead from the chemical and clastic components of these rocks. The samples from the Solomon's Pillars deposit include the least radiogenic pyrite of this study. On the $^{208}Pb/^{204}Pb-^{206}Pb/^{204}Pb$ plot (Figure 55), they define a linear trend which is broadly coincident with the data for the samples from the Hard Rock Mine. The Hard Rock deposit is substantially larger than the Solomon's Pillars occurrence, and the more radiogenic nature of the lead in the former may indicate

that more U and Th were introduced into the pyrite from the mineralizing fluid at the Hard Rock than at Solomon's Pillars.

Although the data for both the Hard Rock and Solomon's Pillars deposits cannot be collectively subjected to rigorous two-stage analysis, the similar slope of the Solomon's Pillars data to that of the porphyries indicates that radiogenic addition was produced from the same starting time as for the porphyry samples. The samples from the two iron formation deposits share a common $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ line which is very distinct from the line for the porphyries (Figure 55), indicating that the U/Th ratio of the iron formation pyrites was very different from the felsic porphyry pyrites. Therefore, the immediate host rocks appear to be the major controlling factor on the lead isotopic composition of the pyrite, as there is no reason to assume two entirely different mineralizing systems in the felsic porphyries and the iron formation samples from the district.

4.3.3 Implications of U/Pb zircon and Pb isotope results for genetic models of gold deposits

Taking the continuous addition model as being the most reasonable interpretation of the secondary isochron of the pyrite in the felsic porphyritic intrusive rocks, gives an age of crystallization of the pyrite of 2560 Ma.

Taking into account a one sigma error on the linear regression calculation gives a range of ages of 2628 to 2480 Ma, the oldest of which is significantly younger than the crystallization age of the felsic porphyritic intrusive rocks determined by U/Pb zircon dating to be 2691 +3/-2 Ma. This indicates a significant difference in time of magmatism and time of emplacement of gold of between 63 and 211 Ma with a best estimate around 130 Ma. Therefore, the mineralization is not a product of a magmatic-hydrothermal system associated with these porphyries.

The Stacey-Kramers (1975) model age of 2563 Ma on the Bankfield galena is consistent with the calculated continuous addition secondary isochron age of the pyrites in the porphyries, as is the calculated secondary isochron age of 2576 Ma of the pyrites from the Solomon's Pillars property.

The lead isotopic compositions of the pyrites and galenas from the Geraldton area are significantly more radiogenic than the main field of galenas from Superior Province gold deposits (Figure 54) (Franklin and Thorpe, 1982), possibly indicating that they devloped in a more uranium-rich environment than the latter, and therefore indicating a greater crustal component to the fluids in the Geraldton area than in other Superior Province gold camps. It is interesting to note that regionally the Geraldton area is characterized by a greater amount of

sedimentary rock than typical Superior province Archean
gold camps such as Timmins and Val d'Or which are
dominated by mafic volcanic rocks. The greater amount of
clastic (i.e. crustally-derived) material in the Geraldton
area may be giving the mineralizing fluids their more
radiogenic signature. This "local" control on the
composition of the mineralizing fluids provides some
support for a metamorphogenic origin for the fluids.
However, gold mineralization post-dates regional
metamorphism in the Geraldton area so the source of the
fluids is probably not related to a regional metamorphic
event.

If the mineralizing fluid were derived from a mantle-
related magmatic source, a more homogeneous, less
radiogenic, lead isotopic composition would be expected
for the fluids derived from this melt. In addition, a
single line or scatter should be developed on the 8/4 vs
6/4 plot for pyrite data from both the porphyry and the
iron formation if a single magmatic source is responsible
for the mineralization.

4.4 Summary

1. The Geraldton clastic sedimentary rocks are not
geochemically distinct from average Archean clastic
sedimentary rocks; there appears to be no significant
geochemical difference between the group A and group B
sedimentary sequences other than the presence of more

iron-rich rocks (iron formation) in the group A and not the group B; and there appears to be no primary enrichment of gold in these rocks away from zones of deformation and quartz veining, the average gold content of both greywacke and siltstone is less than 9 ppb.

2. The background gold content of oxide iron formation in the Beardmore-Geraldton belt is also very low, at 6 ppb, for samples with less than 0.5% sulphur. The mean gold value for iron formation samples with greater than 0.5% S is 432 ppb. Increases of S and As are closely associated with elevated gold values in iron formation, but the base metal Cu, Pb, Zn, Ni and Cr do not show any enrichment in the S- and Au-rich iron formation.

3. The hornblende gabbros in the Geraldton area have compositions very similar to other Archean mafic intrusive and extrusive rocks. The mean background gold content of these rocks is 1.5 ppb. Many of the chlorite schist outcrops in the Geraldton area were derived from deformation and hydration of original hornblende gabbro. Mass balance plots indicate addition of volatiles, K_2O, and Ba, and loss of Sr, Na_2O and SiO_2 in the chlorite schists compared with the hornblende gabbro. The mean background gold content of chlorite schist is 4 ppb.

4. The eastern and western felsic porphyritic intrusive rocks have very similar REE patterns, the eastern porphyries have slightly higher REE abundances, as well as being slightly higher in ferromagnesian components, and

the two groups are thought to represent slightly different amounts of partial melting from the same source. However, both porphyry groups are cut by gold mineralization.

The most distinctive difference between the two porphyry groups is the degree of alteration they have undergone. The western porphyry is everywhere more altered than the eastern porphyry, with extensive development of sericite, carbonate and pyrite and quartz veinlets in the former. In addition, the phenocryst composition of the western porphyries is albite, whereas that of the eastern porphyries is oligoclase, and this is thought to be a result of stripping of Ca from the feldspars in the western porphyries by CO_2-rich fluids to form carbonate.

The alteration of the porphyries is characterized by addition of CO_2, H_2O, S, K, Ba and possibly Na and Mg, as well as gold. The fluids must be moderately acidic as they stabilize albite + muscovite rather than K-feldspar + muscovite.

5. U/Pb zircon dating of the Wods Mac feldspar porphyry gives an age of crystallization of 2691 +3/-2 Ma. This is significantly younger than the age of 2769 +6/-5 Ma determined on a porphyritic rhyolite volcanic rock from the Onaman Lake area, approximately 60 km to the northwest of the Geraldton area. The age of the Geraldton felsic porphyritic intrusion is also significantly younger than the upper cycle rhyolite at Sturgeon Lake which at 2717 Ma

represents the youngest dated volcanics in the Wabigoon subprovince.

6. A continuous addition secondary isochron determined on pyrite from the Geraldton porphyritic felsic intrusions gives an age of crystallization of the pyrite, and therefore of gold emplacement, of 2556 +72/-76 Ma. This places the timing of gold emplacement approximately 130 Ma younger than the intrusion of the felsic porphyritic magmas, thus negating the hypothesis that there is a direct magmatic-hydrothermal association between the gold and these intrusions. This calculated secondary isochron age is in agreement with a Stacey-Kramers (1975) model age calculated on a galena from the Bankfield property which gives a model date of 2563 Ma.

7. The lead isotopic compositions of pyrites and galenas from the Geraldton area are all relatively radiogenic when compared to other Superior province Pb-isotopic data. This may possibly be reflecting a greater amount of clastic material in the Geraldton area than in other Superior province gold camps, which in turn implies a "local" control an some aspects of the mineralizing fluid chemistry.

CHAPTER 5

GOLD MINERALIZATION IN THE GERALDTON AREA: SELECTED

EXAMPLES

5.0 Introduction

Two gold deposit types, exposed at the time of this
study, are described in this chapter; 1) mineralization
hosted in iron formation, exposed in an open stope on the
North Ore Zone of the Hard Rock Mine, and 2) porphyry-
associated mineralization, observed at "Porphyry Hill" on
the Hard Rock and MacLeod-Cockshutt properties, and at the
Bankfield property. These two deposit types exhibit
several important structural, textural and geochemical
aspects of the mineralization at Geraldton. Descriptions
of several other deposits are summarized from the
literature for comparison.

5.1 Relationship of gold mineralization to iron formation;
North Ore Zone, Hard Rock Mine

The North Ore Zone, or No. 30 Vein System, of the
Hard Rock Mine is exposed in outcrop and pit faces where
the mine workings broke through to surface (Figure 56).
This open stope is located 200m south of highway 11
approximately 750m east of the intersection of highways 11

Figure 56. Aerial photograph of the Open Stope exposure
of the North Ore Zone on the Hard Rock property. Note the
Z-shape of the workings. The pit is approximately 80
metres long. The photograph is oriented with north toward
the top of the page. (Photograph courtesy of A.J.
Macdonald, Ontario Geological Survey, Toronto, Ontario,
1983).

and 584 (Figure 3). The pit is in the shape of a large Z (Figure 56) 80m long by 35m wide at its greatest width. This exposure was mapped in detail (Figure 57) to document the distribution of quartz veins and to examine the controls acting on the emplacement of the veins and the massive sulphide lenses. Rock types exposed at the pit include; interbedded thin banded oxide iron formation (magnetite, hematite, minor chert and jasper) and fine-grained siltstone laminae, medium-grained greywacke, and a quartz-carbonate-sericite(-chlorite)-pyrite rock (probably a highly altered intrusive rock). Gold-bearing quartz veins and irregular replacement lenses of sulphide and quartz crosscut the above rock types (Figure 58a). All of the rocks in the immediate vicinity of the pit are strongly deformed and carbonatized. Minor folding has been extensive, with a dominant z-asymmetry to the folds. Carbonate minerals are secondary, overgrowing all primary minerals, thus carbonate alteration post-dates the peak of metamorphism in the area.

The quartz veins exposed in the outcrops surrounding the pit and in the pit walls (Figure 57) are dominantly of approximately east-west strike and are fairly continuous along strike. In addition there are irregular veins which follow contacts or occupy fractured or brecciated zones at the contacts between iron formation and altered intrusive or iron formation and greywacke, and smaller, more irregular veinlets that may show "ladder" or sigmoidal

Figure 57. Detailed map of the Open Stope exposure of the
North Ore Zone, Hard Rock property.

LEGEND

Sedimentary rock

Iron formation

Carbonate-sericite-quartz schist (carbonatized intrusion?)

Quartz and quartz-carbonate veins

Sulphide replacement lenses

Sense and plunge of minor folds

Outline of pit

Outline of outcrop ledge (of overburden)

Sample location and number

Location and figure number of photograph or detailed sketch

Irregular sulphide replacement of brecciated iron formation

Outline of overburden

58,33b

Irregular sulphide replacement of brecciated iron formation

?

Edge of pit

33a

61

Disrupted and transposed bedding

Sheared zone

Scale

0   5   10

metres

Figure 58. Photographs and sketches of sulphide replacement lenses at the Open Stope exposure. (See Figure 57 for location of photographs and legend for sketches.)

58a. Sulphide replacement lens in banded oxide iron formation at the borders of a crosscutting quartz vein. Note: the lighter-coloured material immediately adjacent to the vein is fresh sulphide, exposed by chipping away weathered material. The dark rubbly surface next to it is oxidized sulphide. The dark, smooth surface is oxide iron formation. 58a'. Sketch of 58a.

58b. Photograph of quartz veins and sulphide replacement lenses localized at the contact between banded oxide iron formation and highly carbonatized intrusive (now a quartz-carbonate-sericite-(chlorite)-pyrite schist). Note the small cleavage-parallel veinlets in the intrusive that are not found in the more competent iron formation. Veins crosscut the iron formation where it has fractured, as in the hinge area of minor folds. Sulphide replacement lenses are formed at the margins of the quartz veins where they are in contact with the iron formation. Note also the different orientation of the veins in the intrusive as opposed to the iron formation. It appears that cleavage (schistosity) controls the site of veins in the intrusive, while ductility contrasts between different rock types and along layers of different composistion, and the tendency of the more competent rock to fracture, control the emplacement of veins in the iron formation. (See also Figure 61.) 58b' Sketch of 58b.
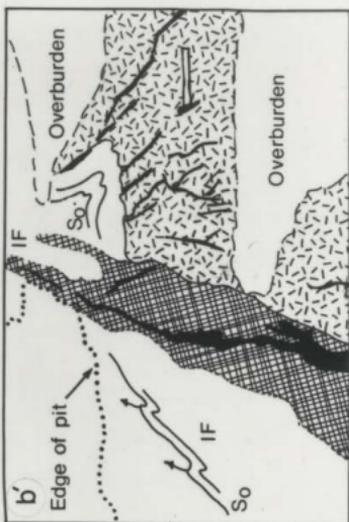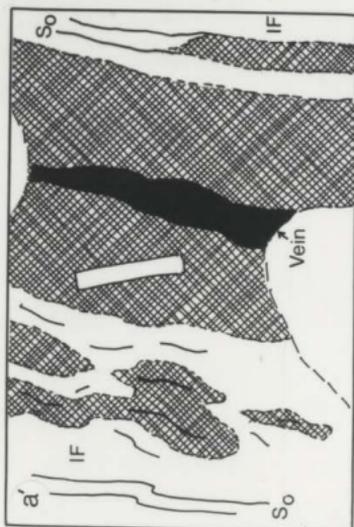
form and appear to be tension gashes off the main vein zones.

The quartz veins crosscut folds in the iron formation and greywacke, along fractures subparallel to the fold hinge lines (Figure 58b), and are often continuous into veins that follow bedding in the sedimentary rocks, or contacts with the altered intrusive. The quartz veins also cut earlier carbonate veins. The main quartz veins exposed at the open stope are variable in width, from less than a centimetre to 20 centimetres wide. Horwood and Pye (1955) report that the veins attain widths of up to two feet (70 cm) in underground exposures.

The veins are often bordered by irregular gold-bearing sulphide lenses which replace the sedimentary rocks outward from the vein walls where the veins crosscut iron formation or ferruginous greywacke (Figure 58a). The individual lenses generally strike approximately east-west, dip steeply, and are variable in size. The lenses are reported to attain lengths up to 100 metres and widths up to 10 metres (Horwood and Pye, 1955).

Collectively these lenses formed a strong ore-zone which was hosted along the north limb and in the trough of a large synformal fold in the greywacke and iron formation that plunges 30 degrees W (Figure 57 and 59, and 60). The ore zone persisted along strike and down dip (85 degrees S) to the eastern and lower limits of the fold in the iron formation (Horwood and Pye, 1955). The ore zone
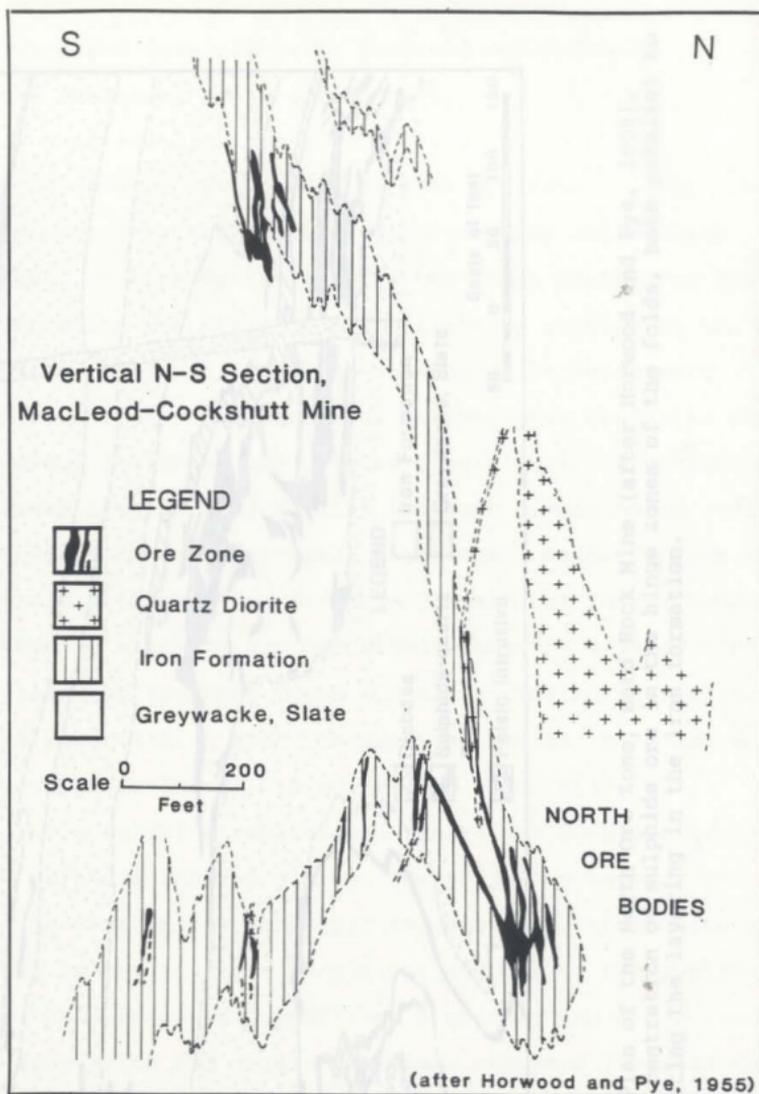
Figure 59. Vertical north-south cross-section of the North Ore
Zone, MacLeod-Cockshutt Mine (after Horwood and Pye, 1955).
Note the distribution of the sulphide lenses; a) in the hinge
zones of folds roughly parallel with the axial planes of the
folds, and b) along the contacts between the intrusive rocks
and the iron formation.
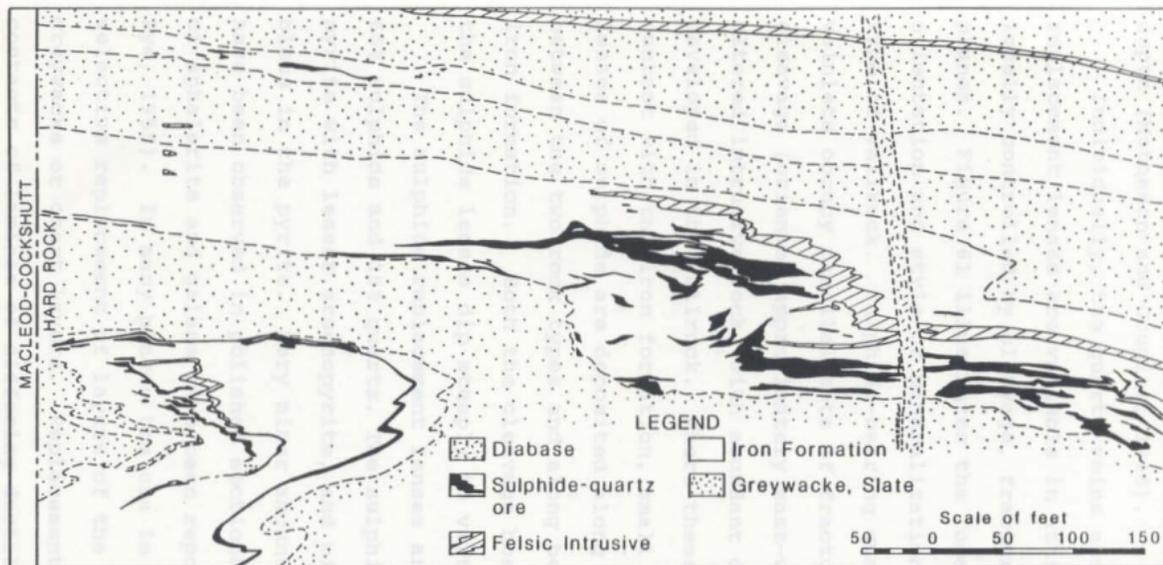
Figure 60. Plan of the North Ore Zone, Hard Rock Mine (after Horwood and Pye, 1955). Note the concentration of sulphide ore in the hinge zones of the folds, both parallel to and crosscutting the layering in the iron formation.

disappeared down plunge as the fold straightened out at depth (Matheson and Douglas, 1948).

Individually, the quartz veins and sulphide replacement lenses are variable in attitude as they are locally controlled by cleavage, fractures and bedding planes. Figure 61 illustrates the local control on the orientation and style of mineralization exerted by the type of wallrock. Sulphide-bearing quartz-carbonate veinlets occupy parallel sets of fractures hosted in the cleavage (oriented approximately east-west) in a highly altered intrusive rock, with abundant disseminated pyrite developed in the wallrock. Where these veinlets come into contact with the iron formation, small but fairly massive lenses of sulphide are deposited along the sheared contact between the two rock types and along bedding planes in the iron formation. Both the cleavage hosted veinlets and the sulphide lenses dip steeply to vertically.

The sulphide replacement lenses are composed of up to 65% sulphide and 35% quartz. The sulphides consist of pyrite with lesser arsenopyrite, and minor pyrrhotite as blebs in the pyrite. Very minor amounts of chalcopyrite have been observed in polished sections, and minor amounts of sphalerite and galena have been reported (Horwood and Pye, 1955). In many places the ore is banded due to the selective replacement of layers of the iron oxide between greywacke or chert layers. Replacement begins along contacts of laminae of differing ductility, in this case

Figure 61. Photograph illustrating the control exerted by
rock type on the form and emplacement of quartz veins and
sulphide replacement lenses, Open Stope exposure, Hard
Rock property.

p 222
inserted
incorrectly
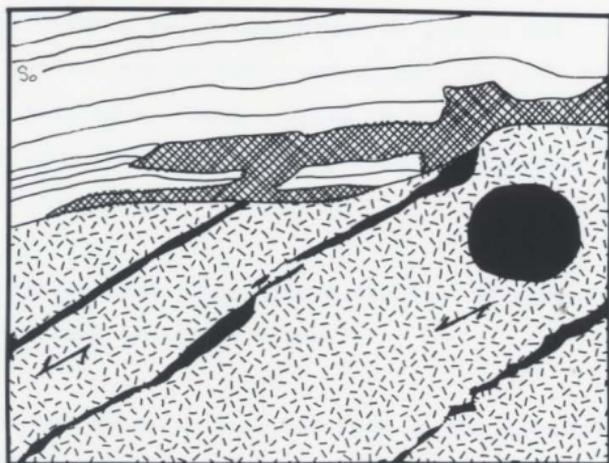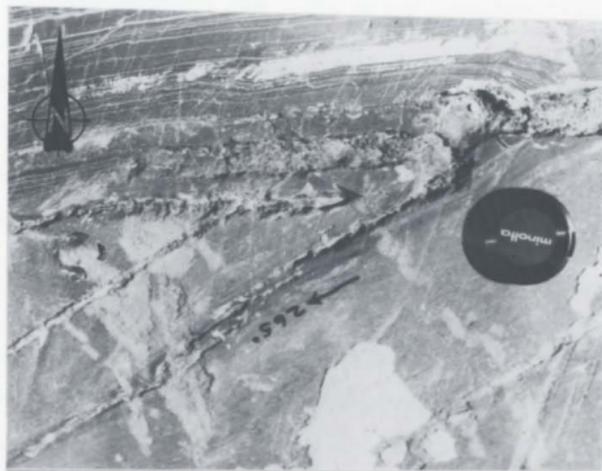
between iron oxide and siltstone laminae, and
progressively engulfs the iron oxide laminae (Figures 13
and 14, Chapter 2).

The pyrite varies from coarse to fine grained (less
than 2mm grain size). In many samples, arsenopyrite
appears to be earlier than the pyrite. It displays good
rhombohedral and lath-shaped forms which are often
fractured and surrounded by pyrite grains. The
arsenopyrite also ranges in grain size from laths 5 mm
long to very fine grained crystals less than 1 mm long.

Gold is intimately associated with the pyrite and
arsenopyrite in the replacement lenses (Figure 62). Gold
grains are found; 1) associated with, and at the edges of,
inclusions in inclusion-rich pyrite, (Figure 62a), 2) at
the contacts of grain boundaries of pyrite and
arsenopyrite (Figure 62b), and 3) filling tiny fractures
in the sulphides. Hand samples of sulphide replacement
lenses from the open stope exposure consistently assayed
over 10,000 ppb Au.

5.2 Porphyry-associated mineralization; MacLeod-Cockshutt,
Hard Rock and Bankfield Mines

At the Porphyry Hill outcrops on the Hard Rock and
MacLeod-Cockshutt properties, fractured and altered
massive quartz-feldspar porphyry (QFP) hosts numerous
parallel quartz veinlets associated with disseminated

Figure 62. Photomicrographs of gold in pyrite-arsenopyrite sulphide replacement lenses, Open Stope exposure.

62a. Gold grains scattered throughout an inclusion-rich pyrite grain, and along grain boundaries.

62b. Gold grains along grain boundaries between pyrite and arsenopyrite, and along margins of inclusions wihtin the pyrite.
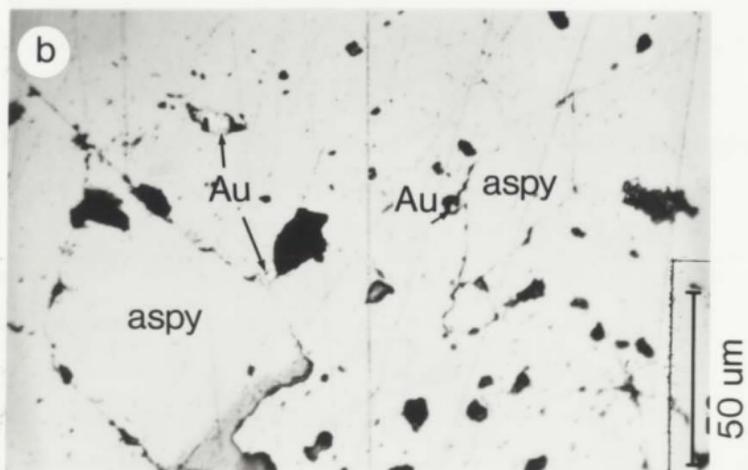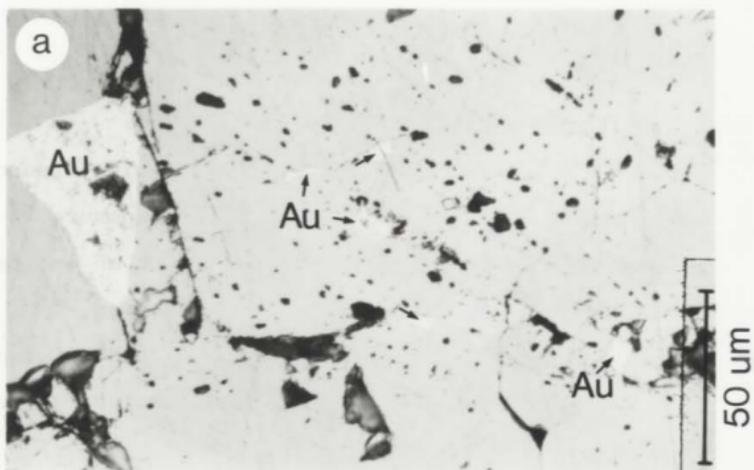
pyrite and arsenopyrite. The porphyry is strongly
sheared, and alteration consists of sericitization and
carbonatization as described in Chapters 2 and 4. The
quartz and quartz-carbonate veinlets occupy cleavage-
parallel fractures which strike approximately east-west
and dip vertically. Individual veinlets are seldom
greater than 2 cm wide and most are less then 1 cm.
Outcrops of QFP immediately to the north of the mill
building on the Bankfield property exhibit this style of
mineralization (Figure 32a and b, Chapter 3; and Figure
16, map of Bankfield property, Chapter 2).

In addition to these quartz stringer zones hosted
entirely in porphyry, mineralization is hosted in
fractured and deformed sedimentary rocks at the contacts
with the porphyry bodies. To the west of the main
Porphyry Hill outcrops, tongues of the porphyry intrude
into greywacke and lean, slaty iron formation beds. Near
the contacts, small replacement lenses of sulphide are
developed in the sedimentary rocks. Similarly, on the
Bankfield property, a favourable site for veins is at the
sheared contacts between the QFP sills and greywacke
(Figure 16, Chapter 2). Sulphides are hosted within veins
and where the strike of the contact changes slightly, the
veins may show an increase in width and amount of
sulphide.

At both the Hard Rock and MacLeod-Cockshutt mines
important orebodies were associated with the quartz

feldspar porphyry intrusive rocks. Horwood and Pye (1955) described several of the porphyry-associated orebodies to which they had underground access during their study. They identified two types of mineralization, similar to those observed in outcrop, associated with porphyries at these mines:

1) quartz veins and mineralized zones in greywacke and lean iron formation along the contacts of, and in, the porphyry. Examples of this type include:

   a) the No. 1 vein system at the Hard Rock mine: a 75 cm wide zone, striking N85E and dipping steeply S, of narrow parallel quartz stringers in fractured albite porphyry and, to the east, at the contact between porphyry and sedimentary rocks;

   b) the South Ore Zone on the MacLeod-Cockshutt property (Figure 63): a zone of shearing and fracturing striking N83°W dipping 75°S, along the main contact between sedimentary rocks and porphyry intrusive, characterized by numerous small lenses of almost massive sulphide in the sedimentary rocks, and disseminated gold-bearing sulphides in the porphyry;

   c) the No.210 vein and No.517 drift zone, MacLeod-Cockshutt Mine: gold-bearing quartz veins hosted within porphyry.

2) large, low grade bodies composed of auriferous quartz stringers in sheared and fractured greywacke and porphyry along the contacts of porphyry tongues. The stringers consistently strike approximately east-west and dip steeply to vertically. Where the strike of the contacts change, the stringers often coalesce to form large "replacement" lenses. Examples of this second type include;

   a) the A and D zones of the Hard Rock Mine: quartz stringer zones in sedimentary rocks at the contacts with the porphyry;

   b) the F-zone of the MacLeod-Cockshutt Mine (Figure 64): innumerable quartz veins and stringers localized in a wide zone of shearing and fracturing along the north contact of the main porphyry intrusive body. The stringers strike N80W and dip steeply S, are generally less than 10cm wide but persistent along strike, and collectively formed a very large, important orebody. The ore body plunged to the west following the contact of the porphyry.
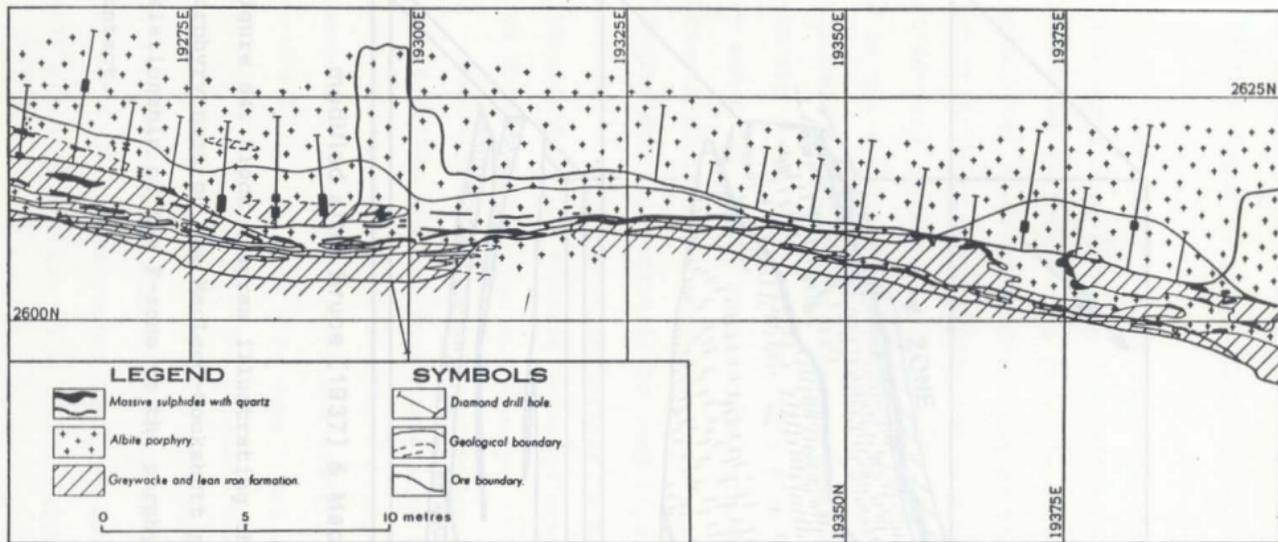
Figure 63. Plan of the South Ore Zone, 349-foot level, of the MacLeod-Cockshutt Mine, illustrating the nature of the sulphide lenses in relation to the porphyry-sediment contact (after Horwood and Pye, 1955).

modified after Bruce (1937) & Macdonald (1984).

Figure 64. Block diagram illustrating the shape of the
porphyry nose on the MacLeod-Cockshutt property and the
relationship of the F-zone to the porphyry-sediment
contact.

5.3 Other types of mineralization

The two types of deposits described above are 1) those associated with iron formation and 2) those associated with felsic porphyritic intrusive rocks. Horwood and Pye (1955) noted that at the Hard Rock Mine, a particularly favourable site for gold deposition was in sedimentary rocks along their contacts with the porphyry, as in the A and D zones. In addition, they noted that the stringers increase in number and grade toward the contact with the porphyry. However, they also noted that numerous ore zones are hosted in fractured greywacke, at its contacts with rocks other than porphyry, including, talc-chlorite schist, conglomerate, and iron formation. They concluded that the most favourable rock type for gold mineralization was brittle deformed greywacke at contacts with rocks of differing competency.

The Little Long Lac Mine provides an excellent example of the control rock competency has on fracturing and localization of veins. The following description is summarized from Bruce (1935 and 1937a), and Pye (1952). The ore bodies at this mine were lodes made up of narrow, continuous, closely-spaced, parallel quartz veins occupying shear planes striking approximately east-west and dipping steeply south in fractured quartz greywacke (Figure 65). The fractures approximately paralleled the axial plane of a large fold in the sedimentary rocks. The

a.
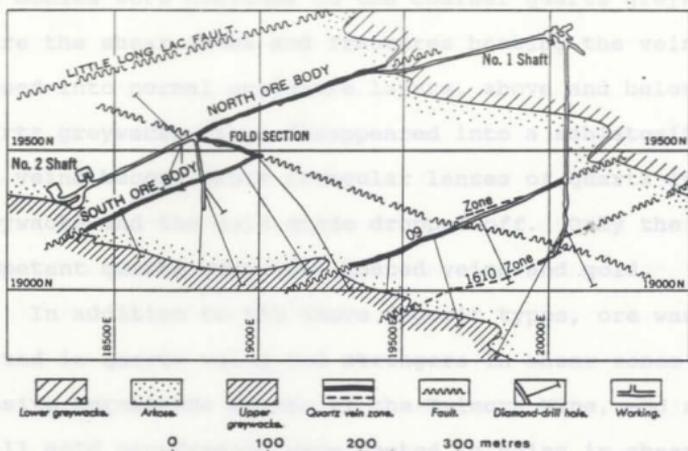
(after Pye, 1952)

b.
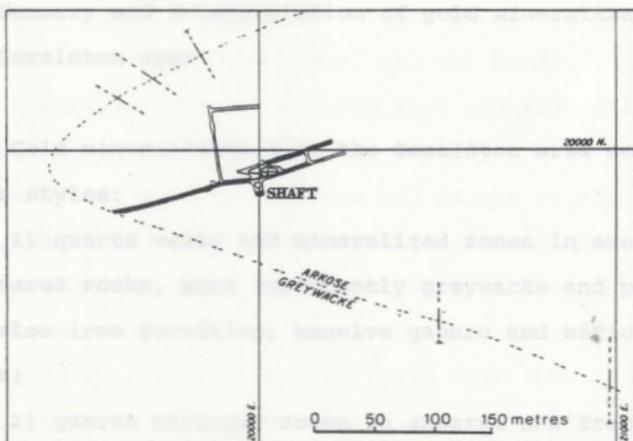
(after Bruce, 1937a)

Figure 65. Geological plans of the Little Long Lac Mine.
   65a. Plan of the second level of the Little Long Lac Mine (after Bruce, 1937a).
   65b. Plan of the 16th (2,214-foot) level of the Little Long Lac Mine (after Pye, 1952).

ore bodies were confined to the coarser quartz greywacke. Where the shear zones and fractures hosting the veins passed into normal greywacke layers, above and below the quartz greywacke, they disappeared into a schistosity. The veins become short irregular lenses of quartz in the greywacke and the gold grade dropped off. Only the more competent quartz greywacke hosted veins and gold.

In addition to the above deposit types, ore was hosted in quartz veins and stringers in shear zones in massive hornblende gabbro at the Talmora Mine, and several small gold occurrences were hosted in veins in sheared and carbonatized volcanic rocks (Pye, 1952).

5.4 Summary and interpretation of gold mineralization in the Geraldton area

Gold mineralization in the Geraldton area occurs in three styles:

1) quartz veins and mineralized zones in sheared and fractured rocks, most importantly greywacke and porphyry, but also iron formation, massive gabbro and mafic volcanic rocks;

2) quartz stringer zones in sheared and fractured greywacke and porphyry; and,

3) sulphide replacement lenses in oxide iron formation.

The most important control on the site of individual orebodies was the development of a zone of fracturing or shearing that allowed the mineralizing fluids access to the rocks. These zones may be developed in competent rocks where they have been folded and fractured, often parallel to the axial plane of folds, as at the Little Long Lac mine or the North Ore Zone of the Hard Rock Mine. Zones of shearing and brecciation are commonly developed at the contacts between rocks of differing ductilities, as between greywacke and porphyry, and greywacke and iron formation. These zones represented some of the largest and most important ore bodies in the Geraldton area, including the F-zone and South Ore Zone of the MacLeod-Cockshutt Mine, and the North Ore Zone of the MacLeod-Cockshutt and Hard Rock Mines, and the Bankfield Mine.

Generally, the zones which host mineralization strike approximately east-west and dip steeply. This orientation is consistent with shear zones and strike faults in the area, which reflect the compressive dextral shear deformation that acted on the rocks in a roughly NW-SE direction.

Iron formation is a favourable host for mineralization because it acts as a relatively competent rock during deformation and therefore is susceptible to fracturing. The strong structural control on mineralization in the iron formation is obvious from Figures 59 and 60, which illustrate the axial planar

orientation of many of the ore lenses in the North Ore
Zone of the Hard Rock Mine. The iron formation appears to
exert an additional control on mineralization in that it
acts as a chemical trap for the sulphur-arsenic-gold-
bearing solutions. The replacement character of the
sulphide lenses where quartz veins crosscut bands
containing iron oxide minerals has been clearly shown in
Chapter 2 and above.

Phillips et al (1984) suggest that the iron formation
acts as the source of iron for the formation of pyrite
during the interaction of these rocks with the
mineralizing fluid. Gold shows a strong spatial
association with pyrite in the mineralization and
therefore they suggest that the interaction of iron-rich
host rocks and sulphide-bearing solutions is an effective
mechanism for precipitating gold. They present the
equation;

$$Fe_3O_4 \; + \; 3HAu(HS_2) \; + \; 1/4O_2 \; = \; 3FeS_2 \; + \; 9/2H_2O \; + \; 3Au$$
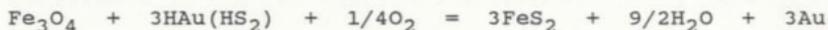
which represents the oxidation of sulphur (S^{2-}) to form
pyrite (S^-) as the mechanism by which aurous complexes are
reduced to native gold.

The close spatial association between ore zones and
intrusive quartz feldspar porphyry bodies appears to be
largely due to structural control. The porphyries

represent a rock type of different ductility to the
sedimentary rocks that they intrude, and provide zones of
weakness at their contacts where shearing and brecciation
are localized. The porphyry bodies in the vicinity of
mineralization are all moderately to strongly altered. As
discussed in chapter 4, none of the western porphyries
have any remnant oligoclase phenocrysts, and all have
abundant sericite and carbonate, indicating that the
alteration, although variable in degree, has affected this
entire suite of rocks. This suggests that these
porphyries were very susceptible to alteration, probably
by the mineralizing fluids. One explanation of this is
that the quartz feldspar porphyry, being a more competent
rock, tends to fracture more completely during deformation
than the surrounding rocks, and therefore is more
permeable to fluid penetration.

CHAPTER 6

SUMMARY AND DISCUSSION

6.1 Summary of observations

6.1.1 Sedimentary environment

The Geraldton area is characterized by turbiditic sedimentary rocks with associated oxide iron formation and polymict pebble conglomerate. The group A sedimentary rocks consist of graded greywacke-siltstone (mudstone) turbidites with minor coarse greywacke, polymict matrix-supported conglomerate and iron formation. To the south the group B sequence consists entirely of graded greywacke-siltstone and mudstone with no conglomerate or iron formation. The lack of iron formation in the group B assemblage indicates that there was either no source of iron to form a chemical precipitate in this area, or the clastic sedimentation rates were higher and/or more consistent so that no distinctive iron-sediments were produced.

No primary sulphide or carbonate facies of iron formation were observed anywhere in the Geraldton belt. All sulphide and carbonate in iron formation was clearly a later overprint on primary oxide minerals. Gold has a very distinctive association with sulphide, suggesting it is also introduced very late. That the sedimentary rocks in the area could be a primarily-enriched source of gold

is not likely as the background gold content of both clastic and chemical sedimentary rocks is less than 10 ppb throughout the Geraldton area.

Two of the most distinctive rock types in the Geraldton area are the extensive linear conglomerate horizons and the iron formation. There is a close spatial association of both these rocks with the major deformation zone, and specifically the Bankfield-Tombill Fault zone, in the Geraldton area. In addition, it has been observed by many of the earlier workers that similar conglomerate beds are commonly associated with faults and shear zones throughout the belt (Bruce, 1937a, b). These conglomerate horizons may have been generated due to uplift along a fault-scarp, and may be indicative of the deformation zone being a very long-lived feature. The added spatial coincidence of an anomalous accumulation of iron formation in the area also suggests the presence of some early syn-sedimentary structure(s) that focussed the exhalative activity necessary to form these chemical sediments. These syn-depositional structures may have been listric or basin-margin faults.

While the group A and the group B clastic sedimentary rocks are not distincive geochemically, there is no iron formation or conglomerate within the group B sequence. These rocks therefore must have been in a different sedimentary/tectonic environment than the group A when they were deposited.

The relationship of the sedimentary rocks to the mafic volcanic rocks in the Geraldton area is unknown as the contacts between the two are generally occupied by faults. The mafic volcanics are submarine in nature, and do not appear to host interbedded clastic sediment.

6.1.2 Intrusive rocks

The sedimentary and volcanic rocks in the Geraldton area were intruded by mafic magma, and then by felsic porphyritic bodies, the latter of which are largely confined to the group A sedimentary panel immediately south of Geraldton. Both intrusive rock types show an anomalous abundance in the Geraldton area.

The mafic intrusive rocks are dominantly gabbro and hornblende gabbro. Their composition is similar to typical Archean intrusive and extrusive mafic volcanic rocks. They do not show a background enrichment in gold. The outcrop pattern of these intrusive rocks suggests that they may be structurally controlled. They are emplaced into both the group A sedimentary rocks and the volcanic rocks to the north, but not into the group B sedimentary rocks.

The felsic intrusive rocks in the Geraldton area have an even more restricted spatial distribution than the mafic intrusive rocks in that they intrude only the group A rocks and the mafic volcanic rocks immediately adjacent to the group A sequence. They crosscut the gabbros and

they appear to post-date at least some deformation of these mafic intrusions. Chemically they are quite distinct from the mafic intrusions in the area and therefore they appear to have both a distinct source and time of emplacement from the mafic intrusions. Their REE patterns suggest that these rocks are derived form a garnet-residual partial melt of crustal material.

There is a strong spatial association of the felsic intrusive rocks and the Bankfield-Tombill Fault zone. The porphyries are distributed as long linear features, parallel and close to the fault zone. The fault may have acted as a conduit for these magmas.

6.1.3 Structural setting

The Geraldton area is characterized by a major zone of intense deformation, roughly centered on the Bankfield-Tombill Fault zone. Within the area, this zone is spatially coincident with a package of rocks that has an anomalous accumulation of chemical sediment, conglomerate, and intrusive rocks, all of which are distributed roughly parallel to the fault zone. The gold deposits also have a strong spatial association with the areas of most intense deformation.

The change in structural facing direction between the group A and group B sedimentary rock packages may be indicative of an early, large scale deformation. This deformation may have been a large fold or fault that

juxtaposed the two opposing facing packages. The structural discontinuity between the two packages also roughly coincides with the Bankfield-Tombill Fault zone.

At some time these rocks were subjected to an isoclinal folding event that generated upright folds with steep fold axes, possibly associated with the development of a pervasive regional cleavage, which probably postdated the intrusion of the mafic rocks, as they appear to be folded about the same axes. Subsequent to the isoclinal folding, a dextral shearing deformation flattened pre-existing folds, produced a dominant z-shaped asymmetry in minor folds, developed sheared and dilatant zones in massive gabbro and along contacts of rocks of differing ductility, and opened fractures in competent rocks.

The intense dextral shearing developed mylonitized chlorite schist zones in massive hornblende gabbro. Mass balance calculations on these chlorite schists indicate that a) the chlorite schists are derived from the gabbro and b) these rocks have undergone a volume increase (due to hydration) followed by a decrease during deformation. Chemically, the chlorite schists show an increase in volatiles and a loss in Sr, relative to the massive gabbro. This represents a hydration of the gabbro during deformation and the destruction of feldspar resulting in the loss of Sr. The volume decrease is associated with laminated zones in the chlorite schists that are the result of recrystallization into mineralogically

distinctive zones, chlorite alternating with quartz-
feldspar layers.

6.1.4 Structural controls on and relative timing of
quartz vein emplacement

Quartz veins are hosted in zones of dilatancy
localized a) in cleavage, b) in fracture zones parallel
to, and commonly occupying, the fold axes of asymmetric
folds, and c) in highly deformed areas localized at the
contact of rocks of differing ductility. Iron formation
was an especially competent lithology within the
sedimentary sequence and pervasive fractures within it
effectively allowed access of the mineralizing fluids.

The structures which host quartz veins crosscut all
Archean rock types in the area including the felsic
porphyritic intrusive rocks, and crosscut the later Z-
shaped asymmetric minor folds associated with the later
dextral shearing event which affected these rocks.
Therefore these veins are relatively late features in the
structural development of the belt. The lack of high
background contents of gold in any of the rock types in
the Geraldton area (relative to the common content of gold
in all rock types on a world-wide basis), particularly the
chemical sediments, and the relatively younger time of
emplacement of the quartz veins is strong evidence against
a syngenetic or exhalative origin for these deposits. In
addition, the lack of base metal enrichment associated

with the gold mineralization at Geraldton is a feature
that has been used by Kerrich (1983) as evidence that
these deposits are not formed by a process similar to
volcanogenic massive sulphides, as has been suggested by
Hutchinson and Burlington (1984), and Valliant and
Bradbrook (1986) for some Archean lode gold deposits.

6.1.5 The absolute timing of emplacement of gold
mineralization

The close spatial association between gold
mineralization and felsic intrusions in Superior Province
gold camps has been well-documented (Marmont, 1983;
Hodgson and MacGeehan, 1982). In most areas, however, the
relative timing of the intrusion and mineralization events
is not known precisely, although mineralization
consistently overprints felsic intrusions. A U/Pb zircon
date on a felsic porphyritic intrusion in the Geraldton
area gave an age of intrusion of 2691 +3/-2 Ma.

To determine the absolute age of mineralization, a
continuous addition Pb isochron age was determined on
pyrite from the mineralized felsic porphyries. The time
of formation of pyrite, and by inference, the time of gold
mineralization is calculated to be 2560 Ma. This age is
not model dependent as it is calculated as a two-stage
isochron with t_2 = zero. Even taking a one sigma error
into account on the slope of the linear regression
calculation, the range of ages obtained is 2628 to 2480

Ma, the oldest of which is significantly younger then the crystallization age of the porphyry. This indicates a difference of 63 to 211 Ma, and probably on the order of 130 Ma, in the time of magmatism and the time of gold emplacement. This long time interval suggests that the gold mineralization is probably not derived from a magmatic hydrothermal system directly associated with the felsic porphyries.

It is interesting to note that the time interval between magmatism and mineralization determined for the Geraldton gold deposits is consistent with recent high resolution step-heating $^{40}Ar/^{39}Ar$ studies done in the Val d'Or and Timmins Archean gold camps. At the Sigma Mine in Val d'Or Hanes et al (1986) obtained a $^{40}Ar/^{39}Ar$ age of 2578 +/- 4 Ma on coarse muscovite from gold-bearing veins. They also determined the timing of regional metamorphism with a metamorphic hornblende, which gave an age of 2687 +/- 18 Ma, thus bracketing gold mineralization to within 110 Ma. Similarly, Masliwec et al (1985) dated fuchsite alteration and the Dome and Hollinger Mines in the Timmins camp by the same $^{40}Ar/^{39}Ar$ step-heating method. They obtained ages of alteration of 2560 +/- 8 to 2633 +/- 6 Ma. A preliminary U/Pb zircon age of 2685 +/- 3 Ma has been reported for the Millerton porphyry in the Hollinger Mine (Masliwec et al, 1985). This also gives a difference in age of magmatism and mineralization on the order of 52 to 125 Ma.

These $^{40}Ar/^{39}Ar$ ages are cooling ages on alteration minerals and therefore may only be used as a minimum estimate of the time of mineralization, but their similarity to the calculated lead isotope age from Geraldton suggests that similar processes have operated in many Archean gold camps whereby mineralization is significantly (> 50 Ma !) younger than the porphyry emplacement, thus negating a magmatic-hydrothermal association with these intrusive rocks (but not ruling out the possibility of a magmatic association with some other, unexposed, magma at depth).

6.1.6 Alteration

Associated with the gold mineralization is an extensive development of carbonate, sericite, and pyrite alteration, with a variable amount of chlorite and arsenopyrite, in all rock types except the diabase dykes (which cross-cut mineralization). Mass balance studies have shown that addition of CO_2, S, As, K, Ba and H_2O, and loss of Sr are characteristic of the alteration in the Geraldton area. Mineralogically, massive pyrite-arsenopyrite-iron carbonate alteration is observed in the iron formation, whereas, sericite-carbonate-pyrite(-arsenopyrite) alteration is developed in the felsic porphyritic rocks, and chlorite-sericite-pyrite-(arsenopyrite)-carbonate alteration in clastic sedimentary rocks. In all cases, the degree and type of alteration

appears to be wall-rock controlled, with the host rock
contributing cations (ie Fe in the iron formation to make
the abundant pyrite and arsenopyrite) and the mineralizing
fluid contributing anions.

The thoroughness of alteration of the western
porphyries as compared to the eastern porphyries may be a
result of the amount of deformation, and therefore
fracturing, that affected the two different rocks. The
eastern porphyries are not as deformed, foliated or
fractured as the western porphyries, and therefore fluids
would not have as ready access to these rocks as they
would to the fractured western porphyries.

6.1.7 Source of the mineralization fluids

The lead isotopic compositions of pyrites and galenas
from the Geraldton area are significantly more radiogenic
than the main field of galenas from Superior Province gold
deposits (Franklin and Thorpe, 1982), possibly indicating
a greater crustal component to the fluids in the Geraldton
area than in other Superior Province gold camps. It is
interesting that regionally the Geraldton area is
characterized by a greater amount of sedimentary material
than typical Archean gold camps such as Timmins or Val
d'Or, which are dominated by mafic volcanic rocks. This
greater amount of clastic material may be giving the
fluids in the Geraldton area a more radiogenic signature.
This "local" influence on the chemical composition of the

fluids might be invoked to support a metamorphic origin
for these fluids, but gold mineralization post-dates
regional metamorphism in the Geraldton area and therefore
mineralization is probably not related to this metamorphic
event. The long time interval between felsic porphyritic
magmatism and gold emplacement discussed above precludes a
direct magmatic-hydrothermal association between the two,
but it does not rule out the possibility of some magmatic
source at depth.

6.2 Discussion

The principal problems facing geologists in
attempting to understand the formation of Archean lode
gold deposits are; timing of emplacement of the
mineralization; the source of the fluids; and, the cause
and mechanism of focussing of the fluids. A comprehensive
model of Archean gold deposits has been proposed by the
Ontario Geological Survey (Colvine et al, 1984). Many of
their general observations apply to the Geraldton area,
including the strong structural control on the deposits,
the characteristic alteration associated with this style
of mineralization, and the close spatial association of
gold with feldspar pophyritic intrusive rocks. However,
the ultimate source of the gold, and the absolute timing
of its emplacement is still unclear.

In the Geraldton area, as in many other Archean gold camps, mineralization is associated with major deformation zones and structural "breaks"; the Cadillac-Malartic Break in Val d'Or, the Porcupine-Destor Fault in Timmins, and the Larder Lake Break in Kirkland Lake. The Bankfield-Tombill Fault zone in Geraldton is part of a similar major structure. This fault zone is within a major deformed zone of dextral shear, and may represent a late brittle deformation within the zone. The deformation zone itself coincides with a reversal in structural facing between two packages of sedimentary rocks, shows evidence of being a long-lived zone of structural weakness and possible tectonic activity, and is parallel to and roughly spatially coincident with the subprovince boundary between the Wabigoon subprovince to the north and the Quetico subprovince to the south. This zone may represent a collisional tectonic margin, and more specifically a "docking" area between the two major tectonic zones, (Wabigoon and Quetico), similar to that envisioned for accreted suspect terranes in the Appalachian (Williams and Hatcher, 1983) and the Cordillera (Coney et al, 1980).

Williams (1986) interprets the Beardmore-Geraldton belt to be part of an accretionary prism consisting of trench and fore-arc sedimentary material which has been interspersed with layers of mafic volcanics and gabbros, cut by midly discordant gabbros and major and minor intrusions of leucogranite. He states that layer-parallel

shearing, thrusting and strain inhomogeneity have been
well-documented as the dominant mechanisms of deformation
in modern accretionary prisms, and that these features are
present in the Beardmore-Geraldton belt. He interprets
the predominance of a dextral shear component as evidence
for oblique subduction. Williams concludes that the
"Beardmore-Geraldton belt is an accretionary prism
developed on the southern margin of the Onaman Plutonic
Complex" to the north, "which represent(s) a volcanic arc
typical of the Wabigoon Subprovince".

The long-lived tectonic activity of this zone is
suggested by the presence of conglomerate and iron
formation along the entire length of the northern part of
the Beardmore-Geraldton belt. This distribution suggests
that the deposition of these rocks was controlled by some
sort of basin-margin faults or listric-type faults. Thus
what was originally a marginal basinal zone, may have
eventually become the site of subduction and subsequently,
dextral shearing.

The presence of discontinuous linear bodies of felsic
porphyry localized within this zone may be a result of
compressional shear melting at the base of the crust
during subduction and/or dextral shear deformation similar
to that suggested by Strong (1980) for granitoid plutonism
in the Appalachians. He postulated that the magmatism
following subduction and the closure of Iapetus was
"related to crustal melting caused by thickening due to

continued plate compression, and to both shearing and
extensional processes resulting from relative plate
motion, which produced a 'megashear' environment".
Alternatively, the magmas may be produced by
decompressional melting of the lower crust with or without
addition of volatiles.   These sources are consistent with
the garnet-residual REE patterns of the porphyries which
suggest a lower-crustal source area.   It is interesting to
note that the REE patterns of the Geraldton felsic
porphyritic intrusions are very similar in both shape and
abundance to the Timmins porphyries (Maloney, 1982) and
these latter porphyries also show a distinct spatial
coincidence with the Porpcupine-Destor Fault.

The timing of gold emplacement in the Geraldton area
has been show to be coincident with relatively late
structural features, and in absolute terms, mineralization
post-dated porphyry emplacement by 130 Ma, thus negating a
magmatic-hydrothermal association between these magmas and
the gold mineralization.   In both the Timmins and Val d'Or
gold camps preliminary age dating work suggests that there
is a similar large time gap between magmatism and
mineralization.   Thus gold was emplaced after the period
of magmatism that probably coincided with the subduction
event. The accretionary process may have been largely
complete, and the gold-bearing fluids introduced during
later, transcurrent faulting of a "new" craton.

From the above observations it appears that the spatial association of felsic porphyritic intrusions and gold mineralization in Archean lode gold deposits may be a somewhat fortuitous structural superposition, with the porphyries being the result of a major shear zone acting as a producer of these magmas and a conduit for their emplacement, and subsequently the same zone acting as a source?, and most surely as a conduit for the gold-bearing fluids, and providing sites of dilatancy and permeability for deposition of gold. The porphyritic intrusions are therefore a significant indicator of the tectonic environment required to ultimately produce lode gold deposits, although they probably do not have a primary control on mineralization.

The major alteration features in the Geraldton area include the introduction of CO_2 and Au and the loss of Sr. The latter is probably a result of the complete destruction of feldspars within these major shear zones. However, the source of the fluids, the CO_2 and the gold in Archean lode gold deposits continues to be one of the major unresolved problems in determining the mode of origin of these deposits.

CHAPTER 7

CONCLUSIONS

1. There is no primary enrichment of gold in any of the rocks in the Geraldton area. The background gold content of all rock types is less than 10 ppb.

2. There is no primary sulphide or carbonate facies iron formation in the Geraldton belt. All sulphide and carbonate minerals in iron formation are secondary alteration features associated with gold mineralization.

3. Gold-bearing veins occur in relatively young structures that crosscut all Archean rock types in the area, and overprint several earlier phases of deformation.

4. The major control on emplacement of veins is cleavage-parallel fractures and dilations, and zones of intense deformation localized at the contacts of rocks of differing ductility.

4. The gold deposits are hosted in a major, long-lived deformation zone, roughly coincident with the boundary between the Wabigoon subprovince to the north and the Quetico subprovince to the south.

5. The U/Pb zircon age of felsic porphyry intrusions is 2691 +3/-2 Ma.

6. The age of gold mineralization is 2556 +72/-76 Ma as determined by a secondary, continuous addition, lead isochron on pyrite from mineralized felsic porphyries.

7. The alteration associated with gold mineralization in the Geraldton area is characterized by addition of CO_2, S, As, K, Ba and H_2O, and loss of Sr.

REFERENCES

Abbey, S., 1968, Analysis of rocks and minerals by atomic absorption spectroscopy; Part 2; Determination of total iron, magnesium, calcium sodium and potassium. Geological Survey of Canada Paper 68-20.

Ayres, L.D., 1978, Metamorphism in the Superior Province of northwestern Ontario and its relationship to crustal development, in Fraser, J.A. and Heywood, W.W, eds. Metamorphism in the Canadian Shield, Geol. Surv. Can., Paper 78-10, p.25-36, 1978.

Barrett, T.J. and Fralick, P.W., 1985, Sediment redeposition in Archean iron formation: examples from the Beardmore-Geraldton greenstone belt, Ontario, Journal of Sedimentary Petrology, v.55, no.2, p.205-212.

Benedict, P.C. and Titcomb, J.A., 1948, Northern Empire Mine, in Structural Geology of Canadian Ore Deposits - a Symposium. CIMM Special Volume.

Berthe D., Choukroune, P. and Jegouzo, P., 1979, Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the South Armorican Shear Zone. Journal of Structural Geology, v.1, p.31-42.

Blackburn, C.E., Bond, W.D., Breaks, F.W., Davis, D.W., Edwards, G.R., Poulsen K.H., Trowell, N.F. and Wood, J., 1985, Evolution of Archean volcanic-sedimentary sequences of the Western Wabigoon Subprovince and its margins: a review. in Ayres, L.D., Thurston, P.C., Card, K.D. and Weber, W., eds. Evolution of Archean Supracrustal Sequences. GAC Special Paper 28, 1985.

Borradaile, G.J., 1976, "Structural facing" (Shackleton's Rule) and the Paleozoic rocks of the Malaguide Complex near Vélez Rubio, SE Spain, in Proceedings Konn Klijke Nederlandse Akademie van Wetenschappen, Amsterdam, Series B vol 79, p.330-336.

Bruce, E.L., 1935, Little Long Lac gold area, Ontario Department of Mines Annual Report vol 44, pt 3.

Bruce, E.L., 1937a, The Eastern part of the Sturgeon River area; Ontario Department of Mines Annual Report vol 45, pt 2, p.1-59.

Bruce, E.L., 1937b, New developments in the Little Long Lac area; Ontario Department of Mines Annual Report vol 45, pt 2, p.118-140.

Buck, S., and Williams, H.R., 1984, A traverse across a gold bearing deformation zone, Geraldton. [abs] Geoscience Research Seminar and Open House '84. OGS.

Card, K.D., 1983, Regional geological synthesis, central Superior Province: reconnaissance investigations in the Nakina area, Ontario; in Current Research, Part A, Geological Survey of Canada, Paper 83-1A, p.25-27.

Cherry, M.E., 1983, The association of gold and felsic intrusions - examples form the Abitibi belt, in Colvine, A.C. ed. The Geology of Gold in Ontario, Ontario Geological Survey Miscellaneous Paper 110, p.48-55.

Colvine, A.C, Andrews, A.J., Cherry, M.E., Durocher, M.E., Fyon, A.J. Lavigne Jr., M.J., Macdonald, A.J. Marmont, Soussan, Poulsen, K.H., Springer, J.S., and Troop, D.G., 1984; An integrated model for the origin of Archean Lode Gold Deposits, Ontario Geological Survey Open File Report 5524, 98p.

Condie, K.C., 1981, Archean Greenstone Belts, Elsevier, Amsterdam.

Coney,P.J., Jones, D.L., and Monger, J.W.H., 1980, Cordilleran suspect terranes, Nature, v.288, p.329-333.

Cummins, W.A. and Shackleton, R.M., 1955, The Ben Lui recumbent syncline (S.W. Highlands). Geological Magazine v.92, p.353-363.

Davis, D.W., Krough, T.E., Hinzer, J., and Nakamura, E., 1985; Zircon dating of polycyclic volcanism at Sturgeon Lake and implications for base metal mineralization, Economic Geology, v.80, p.1942-1952.

Doe, B.R., and Zartman, R.E., 1979, Plumbotectonics I, the Phanerozoic; in Geochemistry of Hydrothermal ore deposits, 2nd edition, H.L.Barnes, ed.; John Wiley and Sons, New York.

Drury, S.A., 1979, Rare-earth and other trace element data bearing on the origin of Archaean granitic rocks from Yellowknife, Northwest Territories, Canadian Journal of Earth Sciences, v. 16, p. 809-815.

Faure, G. 1977, Principles of Isotope Geology. Smith-Wiley Intermediate Geology Series.

Franklin, J.M., Roscoe, S.M., Loveridge, W.D., and Sangster, D.F., 1983, Lead isotope studies in Superior and Southern Provinces. Geological Survey of Canada Bulletin 351.

Franklin, J.M., and Thorpe, R.I., 1982, Comparative metallogeny of the Superior, Slave and Churchill provinces; in H.S. Robinson Memorial Volume, Precambrian Sulphide Deposits, R.W. Hutchinson, C.D. Spence, and J.M. Franklin, editors. Geological Association of Canada Special Paper 25, p.3-90.

Goodwin, A.M., 1977, Archean volcanism in Superior Province, Canadian Shield, in Baragar, W.R.A., Coleman, L.C., and Hall, J.M., eds., Volcanic Regimes in Canada, Geological Association of Canada Special Paper 16, p.205-241.

Grant, J.A., 1986, The Isocon Diagram - a simple solution to Gresens' equation for metasomatic alteration, Economic Geology, v. 81 , p.1976-1982.

Gross, G.A., 1965 Geology of iron deposits of Canada - Volume 1, General geology and evaluation of iron deposits, Geological Survey of Canada, Economic Geology Report No.22, 181p.

Hanes, J. A., Archibald, D.A., and Hodgson, C.J., 1986, Timing of Archean Au-mineralization in Sigma Mine by 40Ar/39Ar Dating, (unpublished abstract for GAC-MAC metting, Saskatoon, 1986).

Hanmer, S., 1986, Asymmetrical pull-aparts and foliation fish as kinematic indicators. Journal of Structural Geology, vol.8, p.113-122.

Hodgson, C.J. and MacGeehan, P.J., 1982, Geological characteristics of gold deposits in the Superior Province of the Canadian Shield, in Hodder, R.W. and Petruk, W. editors, Geology of Canadian Gold Deposits, CIM Special Volume 24.

Horwood, H.C., 1948, General structural relationships of ore deposits in the Little Long Lac - Sturgeon River area in Structural Geology of Canadian Ore Deposits - a Symposium, Canadian Institute of Mining and Metallurgy.

Horwood, H.C. and Pye, E.C., 1955, Geology of Ashmore Township, Ontario Department of Mines Annual Report, vol 60, part 5, 105 pp.

Hutchinson, R.W., 1976, Lode gold deposits: the case for volcanogenic derivation. in Proceedings Volume Pacific Northwest Mining and Metals Conference Portland, Oregon, 1975. Oregon Dept Geology and Mineral Ind., p.64-105.

Hutchinson, R.I. and Burlington, J.L., 1984, Some broad characteristics of greenstone belt lode gold deposits, in Foster, R.P., ed., Gold '82: The geology, geochemistry and genesis of gold deposits: Geological Society of Zimbabwe, Special Paper No. 1, p.339-371.

IUGS (International Union of Geological Sciences) 1973, Plutonic rocks - classification and nomenclature recommended by the IUGS Subcommision on the Systematics of Igneous Rocks, Geotimes, October, p.26-30.

Kehlenbeck, M.M, 1986, Folds and folding in the Beardmore-Geraldton fold belt, Canadian Journal of Earth Sciences, vol. 23, p.158-171.

Kehlenbeck, M.M, 1983, Structural studies in the Beardmore-Geraldton area, Ontario Geological Survey Miscellaneous Paper 116, p.210-203.

Kerrich, R., 1983, Geochemistry of gold in the Abitibi greenstone belt, Canadian Institute of Mining and Metallurgy Special Paper 27, 75p.

Krogh, T.E., 1982, Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique, Geochimica et Cosmochimica Acta, v.46, p.637-649.

Lavigne, M.J., 1983, Gold deposits of the Geraldton area, Ontario Geological Survey Miscellaneous Paper 116, p.198-200.

Macdonald, A.J., 1983, The iron formation - gold association: evidence from Geraldton area, in Colvine, A.C. ed., The Geology of Gold in Ontario, Ontario Geological Survey Miscellaneous Paper 110, p.75-83.

Macdonald, A.J., 1984, Gold mineralization in Ontario; I; the role of banded iron formation, in CIM Special Volume 34, Chibougamau Stratigraphy and Mineralization, p.412-430.

Macdonald, A.J. and Hodgson, C.J., 1986, The case for the magmatic-hydrothermal origin of Archean lode gold deposits, in Gold '86 Poster Paper Abstracts volume, p.98-99.

MacDonald, R.D., 1943, Geology of the Hutchinson Lake area, Ontario Department of Mines Annual Report vol 50, part 3, 21p.

Mackasey, W.O. 1975, Geology of Dorothea, Sandra, and Irvin Townships, District of Thunder Bay; Ontario Geological Survey, Geological Report 122, 83p.

Mackasey, W.O., Blackburn, C.E., and Trowell, N.F., 1974, A regional approach to the Wabigoon-Quetico belts and its bearing on exploration in northwestern Ontario; Ontario Division of Mines, Miscellaneous Paper 58, 29p.

Maloney, J.A., 1982, A comparison of the geology and geochemistry of alkali rich rocks of the Timiskaming Group, with felsic porphyritic igneous rocks found in the Dome Mine, Timmins, Ontario., unpub BSc thesis, University of Waterloo, 78p.

Marmont, S., 1983, The role of felsic intrusions in gold mineralization, in Colvine, A.C. ed., The Geology of Gold in Ontario, Ontario Geological Survey Miscellaneous Paper 110, 38-47.

Masliwec, A., York, D., Kuybida, P., and Hall, C.M., 1985, The dating of Ontario's gold deposits: Grant 233; _in_ V.G. Milne, ed., Geoscience Research Grant Program, Summary of Research 1984-1985: Ontario Geological Survey Miscellaneous Paper 127, p.223-228.

Mason, J.K., amd McConnell, C.D., 1982, Gold mineralization in the Beardmore-Grealdton area, _in_ Colvine, A.C. ed., The Geology of Gold in Ontario, Ontario Geological Survey Miscellaneous Paper 110, p.84-97.

Mason, J., White, G., and McConnell, C., 1985, Field guide to the Beardmore-Geraldton metasedimentary-metavolcanic belt; Ontario Geological Survey Open File Report 5538, 73p.

Matheson, A.F., 1948a, Jellicoe Mine, _in_ Structural Geology of Canadian Ore Deposits, CIMM Special Volume, p.399-401.

Matheson, A.F., 1948b, Bankfield and Tombill Mines, _in_ Structural Geology of Canadian Ore Deposits, CIMM Special Volume, p.401-406.

Matheson, A.F., and Douglas, J.H., 1948, Hard Rock Mine,_in_ Structural Geology of Canadian Ore Deposits, CIMM Special Volume, p.406-413.

Maxwell, J.A., 1968, Rock and mineral analysis. Interscience, New York, p.393-396.

McGlynn, J.C., 1970, Geology of the Canadian Shield-Superior Province; _in_ R.J. Douglas, ed., Geology and Economic Minerals of Canada, Economic Geology Report No.1, p.54-71.

McKay, G.A., Cormie, A.M., and Coulson, C.J., 1948, Leitch Mine, _in_ Structural Geology of Canadian Ore Deposits, CIMM Special Volume.

Ojakangas, R.W., 1985, Review of Archean clastic sedimentation, Canadian Shield: major felsic volcanic contributors to turbiditic and alluvial fan facies associations, _in_ Ayres, L.D., Thurston, P.C. Card, K.D., and Weber, W., eds., Evolution of Archean Supracrustal Sequences, Geological Association of Canada Special Paper 28.

Pettijohn, F.J., 1975, Sedimentary Rocks: New York, Harper and Row, Third edition, 628p.

Phillips, G.N., Groves,D.I., and Martyn, J.E., 1984, An epigenetic origin for Archean banded iron-formation-hosted gold deposits, Economic Geology v.79, no.1, p.162-171.

Pirie, J. and Mackasey, W.O.,1978. Preliminary examination of regional metamorphism in parts of Quetico Metasedimentary Belt,, Superior Province, Ontario; in Metamorphism in the Canadian Shield, Geol. Surv. Can., Paper 78-10, p.37-48, 1978.

Platt, J.P., 1984, Secondary cleavages in ductile shear zones. Journal of Structural Geology, v. 6, p.439-442.

Ponce de Leon, M.I. and Choukroune,P., 1980, Shear zones in the Iberian Arc. Journal of Structural Geology, v. 2, p.63-68.

Poulsen, K.H., Borradaile, G.J., and Kehlenbeck, M.M., 1980, An inverted Archean succession at Rainy Lake, Canadian Journal of Earth Sciences, vol.17, p.1358-1369.

Pye, E.G., 1952, Geology of Errington Township, Little Long Lac area, Ontario Department of Mines Annual Report, vol 60, part 6, 140p.

Pye, E.G., Harris, F.R., Fenwick, K.G., and Baillie, J., Tashota-Geraldton Sheet, Thunder Bay and Cochrane Districts, 1965; Ontario Department of Mines Geological Compilation Series Map 2102, scale 1 inch to 4 miles or 1:253,440.

Ramsay, J.G., 1967, Folding and Fracturing of Rocks, McGraw-Hill Book Company, 568p.

Reid, J.A., 1945, The Hardrock Porphyry of the Little Long Lac. Economic Geology, v. 40, p.509-516.

Russell, R.D. and Farqhhar, R.M., 1960, Lead Isotopes in Geology. Interscience Publishers Inc., New York, 243 pages.

Shegelski,R.J., 1978, Stratigraphy and geochemistry of Archean iron formations in the Sturgeon Lake-Savant Lake greenstone terrain, Northwestern Ontario. PhD thesis, unpublished, University of Toronto, 251p.

Sinclair, A.J., 1976, Applications of probability graphs in mineral exploration, Special Volume No. 4, The Association of Exploration Geochemists.

Stacey, J.S., and Kramers, J.D., 1975, Approximation of terrestrial two-stage lead isotope evolution by two-stage model, Earth and Planetary Science Letters, volume 6, p.16-25.

Steiger and Jager, 1977, Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology, Earth and Planetary Science Letters, v.36, p.359-362.

Stockwell, C.H., 1964, Age determinations and geological studies part II: Fourth report on structural provinces, orogenies and time classification of rocks of the Canadian Precambrian Shield, Geological Survey of Canada Paper 64-17, p.1-29.

Strong, D.F., 1980, Granitoid rocks and associated mineral deposits of Eastern Canada and Western Europe, in D.W. Strangway ed., The Continental Crust and its Mineral Deposits, Geological Association of Canada Special Paper 20, p.741-769.

Taylor, S.R. and Gorton, M.P., 1977, Geochemical application of spark source mass spectrography - III. Element sensitivity, precision and accuracy, Geochimica et Cosmochimica Acta, v.41, p.1375-1380.

Thorpe, R.I., 1982, Lead isotope evidence regarding Archean and Proterozoic metallogeny in Canada, Revisita Brasileira de Geologicas, volume 12, p.510-521.

Valliant, R.I., and Bradbrook, C.J., 1986, Relationship between stratigraphy, faults and gold deposits, Page-Williams Mine, Hemlo, Ontario, Canada, in A.J. Macdonald ed., Gold '86 Proceedings Volume, Toronto, 1986, p.355-361.

van Breemen, O., Davidson, A., Loveridge, W.D., and Sullivan, R.W., 1986, U-Pb zircon geochronology of Grenville tectonites, granulites and igneous precursors, Parry Sound, Ontario, in Moore, J.M., Davidson, A. and Baer, A.J., eds., The Grenville Province, Geological Association of Canada Special Paper 31, p.191-207.

Walker, R.G., 1979, Turbidites and associated coarse clastic deposits, in Walker, R.G., ed., Facies Models, Geoscience Canada Reprint Series 1. Fourth Printing, 1981, p.91-104.

Weijermars, R., and Rondeel, H.E., 1984, Shear band foliations as an indicator of sense of shear: Field observations in central Spain. Geology, v.12, p.603-606.

Williams, H., and Hatcher, R.D. Jr., 1983, Appalachian suspect terranes. Geological Society of America Memoir 158, p.33-53.

Williams, H.R., 1986, Grant 242 Structural studies in the Beardmore-Geraldton Belt, Northern Ontario, in Milne, V.G. ed. Geoscience Research Grant Program Summary of Research, 1985-1986, Ontario Geological Survey Miscellaneous Paper 130, p.138-146.

Wood, P.C, Burrows, D.R., Thomas, A.V and Spooner, E.T.C., 1986, The Hollinger-McIntyre Au-quartz vein system, Timmins, Ontario, Canada; geologic characteristics, fluid properties and light stable isotope geochemistry, in A.J. Macdonald ed., Gold '86 Proceedings Volume, Toronto, 1986, p.56-80.

York, D.,1969, Least squares fitting of a straight line with correlated errors, Earth and Planetary Science Letters v. 5, p.320-324.

Appendix A-1. Sedimentary rocks

The geochemical analyses of Geraldton clastic sedimentary rocks are listed in Tables A-1 and A-2. All major element analyses were done at the Geological Survey of Canada (GSC) except samples 486, 488, 499 and 500 which were done at Memorial University (MUN). All trace element analyses were done at the GSC except for the same four samples listed above which were done at MUN. ALL Ba and V analyses were done at MUN. (See Appendix B for analytical methods. All #JFRA samples of all rock types were analysed for gold at Xray Assay Laboratories (XRAL), and all #JFRA were analysed for gold at Chemex Laboratories, Ltd.).

Table A-1. Major element geochemistry of sedimentary rocks
Table A-2. Trace element geochemistry of sedimentary rocks

APPENDIX A - LISTING OF GEOCHEMICAL ANALYSES

Appendix A-I. Sedimentary rocks

The geochemical analyses of Geraldton clastic sedimentary rocks are listed in Tables A-1 and A-2. All major element analyses were done at the Geological Survey of Canada (GSC) except samples 486, 488, 499 and 500 which were done at Memorial University (MUN). All trace element analyses were done at the GSC except for the same four samples listed above which were done at MUN. ALL Ba and V analyses were done at MUN. (See Appendix B for analytical methods. All 82FRA samples of all rock types were analysed for gold at Xray Assay Laboratories (XRAL), and all 83FRA were analysed for gold at Chemex Laboratories, Ltd.).

Table A-1. Major element geochemistry of sedimentary rocks
Table A-2. Trace element geochemistry of sedimentary rocks

Table A-1.

MAJOR ELEMENT GEOCHEMISTRY OF SEDIMENTARY ROCKS, GERALDTON

SAMPLE NO.	SIO2	TIO2	AL2O3	FEO	FE2O3	MNO	MGO	CAO	NA2O	K2O	P2O5	LOI	FE2O3T	H2O	CO2	S	C	TOT
02ZFHA001	58.6	0.65	16.4	5.30	1.40	0.06	4.04	1.25	3.90	4.41	0.17	-0-	-0-	3.70	1.10	-0-	0.03	100.9
02ZFHA002	58.6	0.54	14.7	2.30	2.30	0.06	2.97	1.81	3.00	1.93	0.17	-0-	-0-	3.60	1.90	-0-	0.09	100.5
02ZFHA005	47.1	1.16	15.1	8.70	4.30	0.17	3.95	1.03	3.30	1.23	0.21	-0-	13.9	3.90	6.60	-0-	0.09	100.4
02ZFHA012	64.6	0.68	15.6	4.30	1.60	0.07	2.63	1.03	3.30	2.01	0.11	-0-	-0-	3.30	1.60	-0-	0.00	100.4
02ZFHA037	54.7	0.79	19.0	6.70	1.40	0.09	4.17	0.64	5.20	3.40	0.16	-0-	-0-	2.80	0.90	-0-	0.00	100.6
02ZFHA038	55.4	0.66	19.3	6.30	0.90	0.12	2.61	0.95	6.50	3.09	0.13	-0-	-0-	2.00	1.90	-0-	0.00	100.5
02ZFHA056	59.6	0.76	17.1	5.60	1.40	0.08	3.15	1.60	2.60	3.18	0.14	-0-	8.40	2.80	1.60	-0-	0.00	100.3
02ZFHA067	59.1	0.64	16.2	6.20	2.20	0.05	3.05	0.44	1.80	2.52	0.14	-0-	9.30	4.60	2.50	-0-	0.13	100.3
02ZFHA068	62.0	0.63	15.9	6.00	1.00	0.11	3.52	0.29	2.80	2.42	0.13	-0-	8.00	3.40	0.10	-0-	0.05	100.3
02ZFHA071	60.9	0.62	15.9	5.60	1.00	0.08	3.45	0.83	0.60	2.54	0.13	-0-	8.00	4.20	2.60	-0-	0.00	100.4
02ZFHA076	55.6	0.90	13.4	8.30	1.40	0.06	3.42	1.98	3.00	1.37	0.11	-0-	12.9	4.40	2.60	-0-	0.00	100.3
02ZFHA088	62.6	0.90	13.5	8.30	1.40	0.06	3.42	1.00	3.00	1.37	0.11	-0-	9.40	3.50	2.30	-0-	0.40	100.3
02ZFRA173	65.7	0.61	14.4	5.10	1.10	0.05	2.43	0.91	3.10	1.79	0.17	-0-	6.00	2.60	1.70	-0-	0.16	99.90
02ZFRA179	47.4	0.44	11.5	12.60	1.50	0.06	2.68	1.87	2.70	1.92	0.17	-0-	1.30	1.30	12.1	0.29	-0-	100.5
02ZFRA249	55.9	0.61	14.5	5.60	1.50	0.10	3.14	4.54	1.40	3.15	0.13	-0-	7.50	2.40	8.50	0.08	-0-	100.3
03ZFRA251	57.1	0.68	17.7	5.60	0.30	0.09	1.96	2.33	1.70	2.69	0.10	3.74	6.50	3.20	2.50	0.27	-0-	100.3
03ZFRA257	50.0	0.75	16.0	7.90	1.50	0.09	2.49	2.60	0.00	2.70	0.13	-0-	6.50	3.20	5.40	0.12	-0-	100.3
03ZFRA3320	50.9	0.13	15.3	6.20	1.90	0.06	2.80	2.66	2.70	1.92	0.14	-0-	4.60	3.30	1.40	0.08	-0-	98.92
03ZFRA333	56.7	0.75	18.7	6.20	1.90	0.07	3.78	2.79	2.70	2.76	0.14	-0-	8.00	4.60	-0-	0.04	-0-	100.3
03ZFRA334	55.3	0.74	18.7	4.50	1.10	0.07	3.54	1.63	3.20	2.57	0.13	-0-	8.40	4.50	0.50	0.01	-0-	100.6
03ZFRA335	52.6	0.61	15.9	4.50	1.10	0.08	2.54	1.34	3.20	2.32	0.13	-0-	6.50	3.50	2.40	0.07	-0-	99.10
03ZFRA344	62.0	0.68	16.1	5.20	4.00	0.06	2.55	0.54	3.00	2.31	0.12	-0-	6.70	4.40	2.00	0.05	-0-	100.8
03ZFRA351	64.3	0.68	15.9	4.70	1.50	0.08	6.42	1.44	4.60	0.71	0.15	-0-	9.00	4.40	0.60	0.08	-0-	100.4
03ZFRA354	54.5	0.64	14.0	5.20	0.80	0.08	1.44	2.26	4.60	1.32	0.11	-0-	14.3	4.40	0.60	0.00	-0-	100.4
03ZFRA357	50.9	0.64	16.4	4.40	1.50	0.33	1.70	4.72	2.50	1.31	0.11	-0-	4.40	3.40	2.50	0.01	-0-	100.6
03ZFRA358	50.3	0.59	16.4	4.70	0.70	0.06	1.53	2.60	3.60	2.93	0.14	-0-	5.20	3.40	1.60	0.06	-0-	100.9
03ZFRA368	67.3	0.72	17.0	4.20	0.80	0.08	3.54	0.95	2.50	2.26	0.16	-0-	5.50	3.30	1.10	0.07	-0-	100.6
03ZFRA384	58.7	0.59	15.9	3.60	1.90	0.03	1.41	1.22	2.30	2.57	0.14	-0-	9.00	2.70	0.70	0.06	-0-	99.50
03ZFRA386	67.1	0.67	16.3	3.90	0.70	0.05	1.63	2.07	3.00	2.00	0.17	-0-	9.80	2.40	3.40	0.07	-0-	98.70
03ZFRA396	55.4	0.36	13.3	4.90	6.20	0.07	1.25	1.56	2.00	1.90	0.22	-0-	27.0	4.20	0.60	0.37	-0-	98.90
03ZFRA398	63.6	0.56	15.1	4.40	1.20	0.07	2.19	0.33	5.50	0.65	0.16	-0-	6.10	3.20	2.80	0.21	-0-	99.40
03ZFRA399	66.7	0.58	14.5	2.60	1.20	0.07	2.57	2.11	2.30	2.46	0.15	-0-	4.90	3.20	2.00	0.00	-0-	99.40
03ZFRA400	66.1	0.54	15.3	2.80	1.20	0.04	1.76	1.16	3.10	2.38	0.07	-0-	4.30	3.10	0.50	0.03	-0-	99.50
03ZFRA421	68.1	0.62	14.8	4.70	1.20	0.08	2.66	0.20	3.20	1.61	0.18	-0-	11.9	4.40	1.20	0.22	-0-	99.40
03ZFRA422	65.8	0.64	15.9	6.70	0.50	0.10	3.00	0.92	1.00	3.32	0.23	-0-	5.40	4.40	1.70	0.86	-0-	99.40
03ZFRA441	59.4	0.61	15.9	2.60	1.20	0.07	2.48	2.49	3.00	2.62	0.17	-0-	5.40	3.30	1.20	0.00	-0-	99.60
03ZFRA442	66.0	0.58	11.6	3.90	0.70	0.10	2.20	3.31	2.40	1.43	0.10	-0-	5.70	3.30	2.70	0.00	-0-	99.00
03ZFRA443	67.4	0.53	15.1	3.80	1.40	0.07	2.09	0.70	3.70	1.82	0.15	-0-	5.90	4.10	0.08	0.00	-0-	99.60
03ZFRA444	62.9	0.62	16.4	4.40	1.00	0.06	3.39	1.13	3.00	2.31	0.20	-0-	5.90	4.10	2.50	0.00	-0-	100.4
03ZFRA465	58.5	0.63	14.9	5.20	0.90	0.05	3.41	3.18	1.70	2.50	0.07	-0-	6.40	2.90	2.50	0.07	-0-	100.4
03ZFRA466	58.6	0.63	14.9	4.50	0.90	0.05	3.03	1.02	3.41	2.73	0.15	3.20	-0-	-0-	-0-	-0-	-0-	96.05
03ZFRA488	64.0	0.36	15.0	-0-	-0-	0.06	1.02	0.73	1.60	3.23	0.08	3.08	-0-	-0-	-0-	-0-	-0-	98.85
03ZFRA499	76.7	0.30	14.6	-0-	-0-	0.03	0.87	0.66	1.00	2.31	0.11	4.04	3.36	-0-	-0-	-0-	-0-	99.25
03ZFHA500	66.9	0.16	13.2	-0-	-0-	0.05	1.38	1.53	1.53	1.78	0.09	-0-	4.40	-0-	-0-	-0-	-0-	99.19

Table A-2.

TRACE ELEMENT GEOCHEMISTRY OF SEDIMENTARY ROCKS, GERALDTON

SAMPLE NO.	Cu	Pb	Zn	Ni	Co	Cr	Au	As	Ba	V	Br	U	Th	Rb	Sr	Zr	Y	Nb
82FRA001	36	28	28	93	28	185		54	1142	154		2	20	133	256	146	17	5
82FRA002	42	22	26	76	25	225		25	952	93		4	10	20	242	159	14	5
82FRA005	39	10	50	90	40	261		7	464	306		12	19	35	239	78	24	2
82FRA012	54	12	40	68	35	203	22		165	165		23	12	64	152	151	21	5
82FRA037	17	31	125	76	35	186	2	15	1060	140		8	16	93	336	165	15	2
82FRA038	17	10	81	95	33	203	2	20	1568	155	1	5	10	82	151	165	12	1
82FRA058	45	15	67	83	33	212	10	20	544	147		5	8	113	75	136	15	
82FRA067	10	8	77	78	17	173	10	267	672	209		5	7	72	151	135	9	5
82FRA068	53	9	64	100	17	191	6	5	606	164		9	11	62	130	135	13	3
82FRA071	8	15	100	83	20	181	6	16	615	188		5	5	130	125	101	18	1
82FRA076	53		78	78	25	171	6	16		804	175		5	8	86	73	13	
82FRA080	86	10	44	55	25	45		45					8	35	91	131		
82FRA158	47	11	84	51	23	141	8	46	1142	154		4	7	58	110	146	16	5
82FRA173	84	7	59	45	24	119	6	1	948	141		0	6	90	104	72	14	3
82FRA179	85	4	74	65	33	175	1	199	786	143		5	4	77	152	131	19	5
83FRA246	47	8	77	48	21	130	21	60				14	13	120	290	190	13	2
83FRA249	58	7	64	75	23	100	6	79				4	11	97	210	180	15	6
83FRA251	15	9	91	95	32	190		52		117		9	11	81	310	97	13	5
83FRA257	15		110	30		60										88	8	5
83FRA320	51	5	99	83	29	140	9	60			35	5	3	100	160	130	12	6
83FRA333	60	4	98	77	29	200	3	65	609			1	15	79	160	150	18	5
83FRA334	51	24	77	58	30	140	2	68				5	7	73	130	130	18	5
83FRA335	46	8	89	58	21	180	1	55				2	10	79	130	150	18	5
83FRA344	13		89	74	37	200	3	22				3	7	47	330	62	15	6
83FRA351	99	4	85	46	29	150	4	40				1	12	45	330	95	16	5
83FRA353	26		46	47	9	42	1	12				3	7	27	39	24	6	1
83FRA357	48	6	47	64	43	150		40				4	11	93	120	160	11	7
83FRA358	33	6	59	55	16	170	6	28				3	12	55	120	150	12	2
83FRA359	50	8	100	81	29	140	2	42				5	6	78	140	140	18	4
83FRA361	15	9	50	38	20	86	1	16				5	4	65	79	100	8	1
83FRA361	52	6	75	77	30	170	57	190				7	16	110	200	140	10	7
83FRA384	26	6	57	34	16	84		11				3	8	84	45	90	7	2
83FRA396	62		64	46	21	130	1	27				2	19	71	200	90	10	4
83FRA398	71	11	65	43	16	140	92	48				6	18	87	250	140	8	1
83FRA399	26	16	82	19	7	110		700				1	13	76	190	130	7	6
83FRA400	18	3	92	56	21	140	2	48				2	9	53	140	150	12	7
83FRA420	46		98	67	20	90		25				2	10	120	110	270	8	5
83FRA421	18		52	41	21	158		5				8	14	95	270	150	5	6
83FRA422	44	2	42	14	9	60		13				2	7	69	370	130	4	6
83FRA441	55	12	70	48	21	130		24				9	14	60	320	130	11	6
83FRA442	34		51	59	21	210		22				4	7	82	320	150	9	6
83FRA443	26	9	68	56	18	150		22				4	7	59	390	140	12	8
83FRA474	38	5	84	49	17	320		4				12	12	80	120	150	9	5
83FRA486	38	16	222	53	23	150		62		131	67	8	7	96	288	123	14	7
83FRA488	71	7	25	23		68			868			4	13	69	153	109	12	6
83FRA499	34		41	31	17	123			727	99		2	9	76	208	131	12	6
83FRA500	34	14	65	45		109			556	105			15	59	240	121	15	

Appendix A-II. Iron formation

The geochemical analyses of Geraldton iron formation samples are listed in Tables A-3 and A-4. All major and trace element analyses were done at the GSC, except for Ba and V, and sample 465 which were analysed at MUN.

Table A-3. Major element geochemistry of iron formation

Table A-4. Trace element geochemistry of iron formation

Table A-3.

MAJOR ELEMENT GEOCHEMISTRY OF IRON FORMATION, GERALDTON

SAMPLE NO.	SIO2	TIO2	AL2O3	FEO	FE2O3	MNO	MGO	CAO	NA2O	K2O	P2O5	LOI	FE2O3T	H2O	CO2	S	C	TOT
82FRA003	60.6	0.50	13.9	5.00	10.0	0.05	1.66	0.43	1.60	2.83	0.19	-0-	2.40		1.10	-0-	0.01	100.4
82FRA010	44.3	0.17	4.50	12.6	25.8	1.05	1.85	3.59	0.30	0.23	0.13	-0-	39.8		5.50	-0-	0.12	100.9
82FRA026	47.4	0.03	1.00	6.30	39.8	0.04	0.25	1.29	0.10	0.04	0.05	-0-	-0-		2.20	-0-	0.00	99.70
82FRA046	39.9	0.17	5.90	6.30	30.6	0.11	1.27	0.61	0.10	2.47	0.16	-0-	0.60		4.50	-0-	0.08	98.50
82FRA072	45.2	0.08	2.70	3.30	49.9	0.05	0.47	1.78	0.30	0.07	0.19	-0-	59.5		2.50	-0-	0.06	100.6
82FRA072	33.0	0.19	4.40	0.30	59.2	0.07	1.78	0.93	0.00	0.07	0.19	-0-	45.9		3.00	-0-	0.06	100.6
82FRA072	32.3	0.19	3.70		45.9	0.22	0.40	1.16	0.40	0.11	0.17	-0-	41.1		1.10	-0-	12.4	105.7
82FRA074	43.0	0.28	6.60	13.1	26.5	0.10	1.54	2.06	0.40	0.82	0.17	-0-	45.2		2.30	-0-	0.09	98.90
82FRA075	38.0	0.35	6.20	14.9	29.6	0.17	2.77	2.28	0.00	0.57	0.26	-0-	32.2		2.70	-0-	0.27	99.30
82FRA150	42.0	0.32	6.80	6.20	42.0	0.04	1.08	0.70	0.10	0.32	0.20	-0-	49.8		1.80	-0-	0.04	99.40
82FRA164	36.5	0.41	8.60	14.9	29.5	0.13	2.27	0.63	0.10	1.35	0.19	-0-	40.9		1.20	-0-	0.15	100.4
82FRA167	29.7	0.20	4.40	16.7	41.5	0.10	1.13	1.13	1.20	0.01	0.14	-0-	-0-		2.30	-0-	0.07	98.60
82FRA166	36.2	0.21	5.50	16.7	36.2	0.47	0.80	1.80	1.20	0.09	0.27	-0-	37.8		1.10	-0-	0.08	99.60
82FRA175	46.6	0.25	7.20	10.0	28.0	0.06	1.44	2.64	1.40	0.96	0.26	-0-	32.2		3.40	-0-	0.00	100.6
82FRA181	43.6	0.42	7.70	11.7	21.9	0.15	3.27	2.19	0.80	0.62	0.23	-0-	45.0		1.60	-0-	0.00	98.50
82FRA192	37.5	0.12	3.70	13.2	41.6	0.09	1.11	0.31	0.00	0.00	0.21	-0-	56.3		1.10	-0-	14.7	100.3
83FRA247	26.7	0.37	9.20	28.7	13.0	0.09	3.04	0.04	0.80	0.43	0.39	-0-	38.3		4.90	-0-	1.30	98.90
83FRA246	34.0	0.19	3.30	13.6	38.0	0.12	1.72	0.72	0.10	0.47	0.15	-0-	39.7		1.30	-0-	7.72	98.90
83FRA250	21.0	0.14	4.80	28.8	38.8	0.12	1.72	0.72	0.10	1.03	0.15	-0-	38.8		1.40	-0-	10.6	98.90
83FRA251	40.4	0.14	3.50	15.2	33.5	0.15	1.57	1.57	0.00	0.19	0.23	-0-	50.4		1.00	-0-	0.20	100.0
83FRA253	57.1	0.36	10.6	9.60	13.1	0.09	2.23	0.65	0.30	0.29	0.29	-0-	33.7		0.50	-0-	0.19	100.3
83FRA323	56.0	0.33	7.90	18.4	16.9	0.05	0.45	2.42	0.10	1.91	0.19	-0-	28.5		0.50	-0-	0.19	100.0
83FRA324	39.1	0.17	4.00	14.9	33.5	0.06	1.59	0.42	0.10	0.69	0.23	-0-	41.9		3.60	-0-	0.16	100.0
83FRA330	39.2	0.15	2.60	13.2	42.1	0.04	0.59	1.31	0.30	0.00	0.22	-0-	50.0		1.70	-0-	0.00	98.60
83FRA337	32.6	0.10	1.90	18.3	41.8	0.08	0.82	0.39	0.00	0.06	0.06	-0-	62.4		0.90	-0-	0.03	98.70
83FRA337	33.6	0.06	1.00	18.4	45.2	0.07	0.40	0.30	0.00	0.03	0.17	-0-	60.4		0.60	-0-	0.00	99.50
83FRA339	38.8	0.21	4.60	13.7	35.3	0.07	0.49	0.49	0.30	0.57	0.20	-0-	60.4		0.50	-0-	0.00	100.3
83FRA340	42.8	0.20	5.80	13.6	27.1	0.10	1.09	1.18	1.40	0.05	0.15	-0-	42.2		1.60	-0-	0.43	98.70
83FRA343	42.7	0.29	7.90	28.0	26.0	0.09	1.95	1.95	0.60	0.25	0.10	-0-	43.4		0.40	-0-	0.00	100.4
83FRA347	46.8	0.14	3.80	12.1	32.5	0.04	0.44	0.31	1.40	0.14	0.10	-0-	45.0		0.80	-0-	0.00	99.30
83FRA349	46.1	0.04	0.90	8.70	42.4	0.06	0.15	0.54	0.60	0.02	0.10	-0-	52.3		0.40	-0-	0.01	99.00
83FRA149	32.5	0.05	1.50	16.3	35.1	0.17	1.62	0.48	0.00	1.16	0.07	-0-	53.2		2.70	-0-	0.00	100.5
83FRA352	48.4	0.05	1.50	13.3	34.4	0.06	0.16	0.40	0.30	0.02	0.11	-0-	49.2		1.00	-0-	0.00	99.10
83FRA355	44.3	0.34	7.30	26.1	41.0	0.08	1.36	1.86	1.30	0.90	0.18	-0-	57.2		1.50	-0-	0.00	100.2
83FRA358	54.3	0.14	4.20	12.9	26.1	0.04	0.24	0.99	0.70	0.03	0.20	-0-	54.1		2.80	-0-	0.05	100.4
83FRA369	20.7	0.13	3.50	9.70	35.3	0.05	0.06	0.72	0.00	0.63	0.10	-0-	35.1		1.60	-0-	19.1	100.4
83FRA369	36.1	0.21	5.30	10.5	39.1	0.02	0.72	1.57	1.66	0.05	0.20	-0-	34.7		10.8	-0-	23.1	97.00
83FRA373	44.1	0.34	8.70	5.50	33.6	0.04	1.61	1.61	1.10	1.82	0.26	-0-	38.8		3.40	-0-	0.01	100.5
83FRA374	44.8	0.24	5.90	8.70	23.5	0.06	0.84	1.14	2.20	0.13	0.14	-0-	38.3		6.60	-0-	0.02	100.0
83FRA378	56.3	0.16	4.90		19.8	0.04	0.86	0.82	2.46	0.10	0.09	-0-	33.2		6.60	-0-	5.70	100.1
83FRA380	33.0	0.16	3.60	1.90	39.7	0.03	0.06	0.36	0.00	0.44	0.18	-0-	19.8		5.90	-0-	0.03	99.30
83FRA381	31.6	0.09	2.60		39.7	0.03	0.06	0.78	0.00	0.20	0.19	-0-	51.8		3.50	-0-	27.2	106.1
83FRA382	41.3	0.25	5.40	2.60	27.2	0.50	1.14	0.75	2.30	0.49	0.25	-0-	29.7		0.30	-0-	16.4	99.60
83FRA387	44.6	0.33	1.30	4.90	50.7	0.01	0.08	0.05	0.70	0.23	0.25	-0-	45.5		0.60	-0-	0.02	99.60
83FRA395	42.1	0.18	1.30	1.90	49.6	0.07	1.08	0.24	0.70	0.12	0.23	-0-	51.9		1.20	-0-	0.08	99.10
83FRA398	38.8	0.11	3.60	3.80	47.6	0.15	0.72	0.12	0.00	0.09	0.14	-0-	51.8		1.60	-0-	0.05	99.30

Table A-4.

MAJOR ELEMENT GEOCHEMISTRY OF IRON FORMATION, GERALDTON (CONT.)

SAMPLE NO.	SIO2	TIO2	AL2O3	FEO	FE2O3	MNO	MGO	CAO	NA2O	K2O	P2O5	LOI	FE2O3T	H2O	CO2	S	C	TOT
83FAH391	48.7	0.31	9.90	3.80	29.6	0.13	0.72	0.40	1.90	1.65	0.29	-0-	32.9	3.40	0.40	0.05	-0-	100.5
83FAH393	45.1	0.22	6.40	2.60	38.0	0.06	0.61	0.25	1.40	1.90	0.25	-0-	42.4	0.60	0.60	0.08	-0-	100.6
83FAH394	45.2	0.25	7.40	2.50	38.1	0.16	0.61	0.24	0.60	1.90	0.25	-0-	40.2	3.10	0.40	0.08	-0-	99.60
83FAH395	41.3	0.09	2.70	1.60	50.7	0.05	0.11	0.20	0.00	0.77	0.18	-0-	52.4	1.80	0.30	0.08	-0-	99.80
83FAH400	47.0	0.34	9.20	11.9	21.1	0.06	2.23	0.86	1.70	0.84	0.17	-0-	34.3	2.90	1.60	0.06	-0-	100.0
83FAH401	41.2	0.17	5.20	13.7	29.0	0.09	1.13	0.86	1.90	0.23	0.36	-0-	44.2	1.00	3.20	0.14	-0-	100.1
83FAH402	41.0	0.04	1.00	1.10	54.6	0.03	0.07	0.17	0.00	0.08	0.09	-0-	54.6	0.40	1.00	0.08	-0-	100.4
83FAH405	39.0	0.26	6.30	10.3	37.7	0.08	1.53	0.66	2.10	0.00	0.24	-0-	49.2	0.40	0.70	0.00	-0-	100.7
83FAH406	41.3	0.41	10.3	13.4	24.1	0.11	2.73	1.02	0.70	1.41	0.21	-0-	38.9	3.70	1.00	0.05	-0-	100.4
83FAH407	42.5	0.24	6.30	12.9	31.3	0.06	1.02	0.83	0.10	1.19	0.10	-0-	45.7	2.10	2.10	0.00	-0-	99.80
83FAH408	36.1	0.10	2.10	14.2	44.3	0.07	0.40	0.95	0.50	0.00	0.15	-0-	60.0	0.50	1.20	0.00	-0-	100.6
83FAH409	37.2	0.19	4.50	13.5	47.0	0.04	1.40	0.40	0.10	0.00	0.19	-0-	62.8	0.50	2.30	0.00	-0-	100.4
83FAH410	39.2	0.27	5.00	18.5	37.7	0.03	1.40	0.53	0.30	0.07	0.22	-0-	57.9	2.30	0.60	0.00	-0-	100.2
83FAH411	47.0	0.11	2.70	12.0	34.8	0.03	0.51	0.23	0.30	0.25	0.12	-0-	48.1	1.00	0.40	0.00	-0-	99.20
83FAH412	31.1	0.25	5.60	17.2	40.6	0.10	0.93	0.35	0.70	0.52	0.16	-0-	59.8	1.00	0.60	0.01	-0-	100.0
83FAH413	33.4	0.08	2.20	8.80	53.4	0.06	0.05	0.44	0.70	0.00	0.22	-0-	63.1	0.30	0.10	0.00	-0-	99.70
83FAH415	44.1	0.31	8.60	3.50	33.6	0.08	0.67	0.92	1.70	1.32	0.28	-0-	37.5	2.00	1.00	0.00	-0-	99.60
83FAH465	38.5	0.38	13.5	-0-	23.6	0.08	1.46	0.74	1.90	3.29	0.16	-0-	23.6	4.30	5.40	1.34	-0-	98.90
83FAH466	37.4	0.13	3.90	0.60	51.1	0.02	0.02	0.37	0.00	0.04	0.31	-0-	51.8	0.30	0.80	0.03	-0-	98.90
83FAH467	42.6	0.04	2.60	6.10	45.0	0.04	0.23	0.40	1.30	0.33	0.24	-0-	51.7	1.60	0.50	0.02	-0-	100.2
83FAH468	44.3	0.23	5.90	8.40	26.4	0.30	2.38	2.25	1.40	0.78	0.20	-0-	14.7	4.30	3.50	0.02	-0-	99.70
83FAH469	54.4	0.54	14.5	10.5	7.80	0.10	2.74	2.64	1.40	1.90	0.20	-0-	14.5	4.60	3.80	0.16	-0-	99.70
83FAH472	53.8	0.54	14.4	10.5	2.80	0.10	2.90	2.80	1.30	1.90	0.17	-0-	49.2	2.00	3.80	0.03	-0-	99.20
83FAH473	41.1	0.45	11.7	3.00	42.5	0.05	1.40	0.37	0.50	3.11	0.22	-0-	24.8	2.00	2.00	0.03	-0-	100.5
83FAH475	53.1	0.13	7.30	4.40	20.6	0.05	1.40	0.81	0.80	1.85	0.20	-0-	11.6	3.30	1.00	0.05	-0-	100.4
83FAH476	49.2	0.60	16.6	2.30	20.8	0.06	2.39	1.49	0.00	2.59	0.20	-0-	11.6	2.90	2.00	0.04	-0-	99.60
83FAH477	50.8	0.31	8.40	5.20	14.1	0.10	1.40	2.14	2.90	1.57	0.18	-0-	33.3	4.30	0.20	0.04	-0-	100.5
83FAH478	50.9	0.23	7.10	7.50	27.5	0.10	1.49	0.51	0.50	1.18	0.22	-0-	40.4	2.90	0.30	0.04	-0-	99.40
83FAH479	46.9	0.17	4.70	5.30	32.0	0.07	1.23	0.50	0.20	0.45	0.15	-0-	46.9	2.50	0.20	0.02	-0-	100.5
83FAH480	43.1	0.37	11.0	5.60	41.0	0.07	2.16	0.27	0.00	1.90	0.20	-0-	35.3	2.50	0.40	0.05	-0-	99.40
83FAH501	49.7	0.30	10.4	5.60	26.3	0.04	2.33	0.41	0.30	0.82	0.20	-0-	53.3	4.10	0.10	0.05	-0-	100.1
83FAH503	46.2	0.16	4.40	2.30	30.2	0.09	3.11	0.31	0.00	2.48	0.17	-0-	33.2	4.90	0.80	0.00	-0-	99.20
83FAH504	35.4	0.45	12.3	8.30	50.8	0.05	2.36	0.91	0.00	9.78	0.20	-0-	22.2	3.90	1.20	0.05	-0-	99.20
83FAH505	52.3	0.16	8.30	5.00	26.7	0.04	2.36	2.27	0.00	2.48	0.17	-0-	33.2	3.90	0.20	0.05	-0-	100.4
83FAH506	50.7	0.37	8.30	5.00	26.7	0.03	2.54	0.26	0.00	2.78	0.18	-0-	33.2	3.90	0.20	0.00	-0-	100.1
83FAH507	55.1	0.57	12.4	6.10	13.7	0.10	2.73	0.63	1.50	2.83	0.20	-0-	20.4	4.30	0.30	0.03	-0-	99.90

Table A-4.

TRACE ELEMENT GEOCHEMISTRY OF IRON FORMATION, GERALDTON

SAMPLE NO.	Cu	Pb	Zn	Ni	Co	Cr	Au	As	Ba	V	Br	U	Th	Rb	Sr	Zr	Y	Nb
82FFA003	36	21	78	53	27	146	1	6	952	93		0	9	122	153	130	18	3
82FFA010	12	27	61	0	20	14	-	45	-0-	-0-	93	0	0	12	138	35	10	4
82FFA028	20	25	39	0	5	14	1	2	165	16		13	0	0	18	25	0	-
82FFA040	18	24	37	10	5	33	-	8	817	67		28	0	65	46	18	5	0
82FFA049	15	41	40	24	9	72	-	0	1494	96		14	0	60	63	30	15	3
82FFA070	39	48	40	9	15	48	2	27	-0-	-0-	96	0	8	5	32	30	15	0
82FFA072	15	40	40	56	13	72	-	40	-0-	-0-	-	9	0	0	32	35	5	3
82FFA074	21	24	57	13	70	47	-	4400	1455	75		0	7	39	72	70	10	5
82FFA075	38	25	97	15	14	64	3	2	351	84		7	9	24	83	54	12	-
82FFA150	19	17	0	14	36	66	2	2	246	52		0	0	77	65	17	7	1
82FFA164	24	25	58	11	16	36	-	2	618	66		4	0	46	19	33	2	2
82FFA166	7	36	95	37	23	118	-	7	117	66		0	0	0	104	79	9	-
82FFA167	14	28	28	19	15	76	-	22	117	105		4	0	2	67	32	30	0
82FFA166	6	28	49	18	15	71	-	22	101	123		0	7	72	67	9	14	8
82FFA175	15	24	18	24	12	41	-	34	106	116		66	0	44	88	66	13	7
82FFA180	35	31	57	24	14	83	-	327	365	70		4	3	13	103	55	13	-
82FFA182	123	31	21	52	12	41	-	176	452	79		2	0	20	88	13	20	2
83FFA247	11	21	37	40	4	31	1	0	-0-	-0-		5	0	0	32	15	5	0
83FFA248	260	38	130	40	24	92	4600	120	-0-	-0-		4	18	36	13	72	5	4
83FFA250	38	15	48	36	7	75	2	220	-0-	-0-		3	13	11	20	15	5	3
83FFA252	13	17	46	10	10	31	-	0	-0-	-0-		5	0	21	50	16	2	1
83FFA253	70	12	46	48	24	46	2330	130	-0-	-0-		5	0	21	54	21	2	3
83FFA323	17	20	20	48	13	28	5	0	-0-	-0-		5	0	0	37	37	6	5
83FFA324	31	10	50	56	32	86	6	6	-0-	-0-		7	16	19	68	14	6	5
83FFA330	41	11	40	64	14	70	-	10	-0-	-0-		7	0	14	73	73	9	5
83FFA331	6	11	61	41	7	40	10	60	-0-	-0-		3	0	28	47	46	10	2
83FFA337	6	15	48	4	7	36	-	20	-0-	-0-		12	16	24	55	29	3	3
83FFA338	3	15	42	2	2	23	-	7	-0-	-0-		12	26	42	33	14	4	0
83FFA339	5	22	48	5	2	11	-	0	-0-	-0-		10	27	37	25	12	1	0
83FFA340	6	28	22	4	9	11	-	15	-0-	-0-		5	20	32	12	18	1	0
83FFA341	4	11	16	8	9	15	-	0	-0-	-0-		11	16	19	17	17	-	3
83FFA342	19	11	51	18	6	53	25	6	-0-	-0-		6	15	7	65	21	2	2
83FFA343	14	11	50	32	4	71	19	19	-0-	-0-		12	10	42	21	37	2	-
83FFA346	12	16	32	7	4	33	20	10	-0-	-0-		13	18	33	32	16	4	0
83FFA347	7	11	24	24	8	23	-	5	-0-	-0-		5	16	21	19	15	4	-
83FFA348	34	16	50	25	10	30	-	20	-0-	-0-		11	41	41	44	45	4	2
83FFA349	7	12	22	4	3	54	-	6	-0-	-0-		17	33	17	24	4	-	-
83FFA350	27	20	43	12	5	13	-	20	-0-	-0-		24	30	20	63	19	8	1
83FFA352	27	32	55	32	13	62	-	6	-0-	-0-		10	38	44	19	55	8	-
83FFA355	20	27	52	7	13	55	9250	13	1300	-0-		6	18	27	18	22	4	5
83FFA356	16	5	27	14	17	63	10001	70000	500	-0-		8	0	30	15	62	2	1
83FFA366	23	14	31	39	6	41	-	94	-0-	-0-		6	2	30	62	28	8	7
83FFA369	18	8	19	18	8	53	500	0	30	-0-		10	3	20	97	28	4	0
83FFA370	28	7	36	15	16	63	-	0	120	-0-		5	0	17	49	36	4	1
83FFA373	52	11	30	18	6	60	-	4	-0-	-0-		9	0	42	120	49	3	-
83FFA374	16	8	33	30	9	68	10001	220	-0-	-0-		5	0	12	71	36	3	1
83FFA378	6	9	25	12	7	32	895	260	-0-	-0-		5	36	27	36	32	2	2
83FFA380	51	16	28	7	8	46	-	24	-0-	-0-		4	0	44	42	32	21	1
83FFA378	17	21	36	21	6	78	10001	1500	-0-	-0-		7	0	2	21	21	1	2
83FFA382	47	18	20	33	12	41	9400	0	13000	-0-		6	0	9	53	31	49	-
83FFA383	18	15	33	7	8	43	-	24	-0-	-0-		3	0	26	15	15	27	5
83FFA385	18	13	17	8	6	36	-	4	-0-	-0-		11	0	31	31	30	4	1
83FFA387	31	4	48	10	8	43	-	3	-0-	-0-		4	0	18	66	28	6	2
83FFA390	14	16	47	7	7	22	-	3	-0-	-0-		19	0	27	15	13	0	1

TRACE ELEMENT GEOCHEMISTRY OF IRON FORMATION, GERALDTON (CONT)

SAMPLE NO.	Cu	Pb	Zn	Ni	Co	Cr	Au	As	Ba	Br	U	Th	Rb	Sr	Zr	Y	Nb
83FRA391	18	16	48	28	28	12	82	2	14	-0-	9	17	70	63	51	9	2
83FRA393	14	17	40	14	8	5	57	2	18	-0-	12	24	41	45	36	6	2
83FRA394	29	11	41	24	8	9	67	5	20	-0-	14	18	74	33	50	4	2
83FRA395	13	9	29	42	19	14	21	1	7	-0-	9	17	30	15	12	8	3
83FRA401	20	7	28	13	8	7	24	9	7	-0-	7	12	65	51	51	9	1
83FRA402	14	3	29	8	6	4	39	3	8	-0-	5	11	15	75	22	5	2
83FRA405	5	15	17	8	0	9	9	13	17	-0-	2	28	23	70	45	5	3
83FRA406	6	13	44	19	8	4	59	4	6	-0-	2	19	40	54	27	5	3
83FRA407	31	-0-	97	44	14	53	100	2	27	-0-	3	14	43	63	52	5	1
83FRA408	24	29	41	17	7	14	55	2	13	-0-	4	15	16	17	52	4	2
83FRA409	4	22	26	8	0	7	24	3	12	-0-	19	39	43	41	6	2	0
83FRA410	17	12	47	17	8	3	43	3	23	-0-	8	50	11	27	21	5	3
83FRA411	5	18	12	26	8	10	67	12	26	-0-	9	36	14	47	33	5	1
83FRA412	15	13	70	10	2	2	41	40	41	-0-	8	28	19	14	11	6	2
83FRA413	14	17	73	19	6	6	50	10	23	-0-	12	19	47	27	33	5	1
83FRA415	4	19	23	13	0	8	22	1	-0-	161	1	40	16	31	9	6	0
83FRA465	25	10	78	59	31	11	79	4	8	-0-	7	24	43	158	52	18	4
83FRA466	20	8	59	82	46	15	78	2	21	-0-	5	18	59	99	54	7	2
83FRA467	24	4	82	46	11	7	92	0	7	-0-	11	23	10	110	86	7	3
83FRA469	12	11	38	3	7	5	35	0	8	-0-	23	30	56	26	21	2	2
83FRA470	14	12	13	12	3	3	51	1	16	-0-	29	25	40	100	15	5	2
83FRA471	65	-0-	80	57	57	13	140	0	9	-0-	20	12	35	100	36	5	2
83FRA472	20	8	81	57	17	4	140	0	14	-0-	17	22	74	170	110	11	2
83FRA473	13	8	39	38	8	15	55	2	13	-0-	3	10	30	81	23	4	3
83FRA475	17	14	39	18	4	4	110	0	14	-0-	3	22	12	65	95	3	1
83FRA477	57	14	40	69	10	26	64	0	10	-0-	3	13	43	69	39	5	1
83FRA476	20	-0-	75	27	18	6	58	0	15	-0-	8	18	60	130	120	16	4
83FRA479	17	2	43	11	8	9	60	0	12	-0-	8	23	47	56	23	8	6
83FRA480	17	11	35	10	9	6	36	1	8	-0-	9	9	25	42	24	6	2
83FRA481	32	5	68	51	30	97	110	0	16	-0-	3	16	31	33	60	10	4
83FRA582	45	8	69	36	8	24	110	0	15	-0-	8	14	81	37	17	11	4
83FRA583	16	13	43	51	21	37	37	0	15	-0-	7	24	36	17	55	8	4
83FRA584	44	4	64	13	23	110	110	0	9	-0-	6	19	65	55	14	14	2
83FRA585	25	8	45	16	17	3	65	0	14	-0-	4	18	44	25	43	8	7
83FRA586	25	0	40	16	8	25	60	0	9	-0-	10	14	16	34	27	9	0
83FRA587	65	0	64	62	20	150	160	0	12	-0-	14	6	6	37	89	10	5

Appendix A-III. Mafic intrusive rocks

The geochemical analyses of Geraldton mafic intrusive rocks are listed in Tables A-5 and A-6. All major element analyses of 82FRA samples were done at the GSC. All major element analyses of 83FRA samples, except sample numbers 328, 329, 419, 423, 425, 439, and 451, were done at MUN. The samples listed above were analysed at the GSC. All trace element analyses of 82FRA samples were done at the GSC, except Ba and V which were done at MUN. All 83FRA samples were analysed for trace elements at MUN except for the samples listed above which were analysed at the GSC.

Table A-5. Major element geochemistry of mafic intrusive rocks

Table A-6. Trace element geochemistry of mafic intrusive rocks

Table A-5.

MAJOR ELEMENT GEOCHEMISTRY OF MAFIC INTRUSIVE ROCKS, GEEHALTON

SAMPLE NO.	SIO2	TIO2	AL2O3	FEO3	FE2O3	MNO	MGO	CAO	NA2O	K2O	P2O5	LOI	FE2O3T	H2O	CO2	S	C	TOT
83FFA036	65.4	0.79	12.1	5.100	0.00	0.07	3.35	2.38	2.40	0.96	0.12	-0-	-0-	2.90	2.70	0.38	-0-	100.0
82FFA061	65.3	1.19	14.0	-0-	10.1	0.09	2.74	2.54	1.50	0.54	0.17	-0-	10.1	3.60	3.40	1.15	-0-	100.0
82FFA003	43.5	0.75	14.8	-0-	9.90	0.18	10.8	10.8	1.03	1.03	0.07	-0-	9.90	4.20	5.60	0.00	-0-	100.6
82FFA007	46.3	1.19	14.3	9.400	2.40	0.28	3.61	7.50	3.00	1.05	0.05	-0-	12.4	2.90	7.60	0.04	-0-	100.4
82FFA100	43.7	0.46	13.5	5.400	4.70	0.19	13.0	13.5	0.00	0.37	0.03	-0-	3.60	4.10	0.90	0.03	-0-	100.7
82FFA157	49.2	0.91	15.5	6.400	3.10	0.17	5.14	4.14	5.20	0.50	0.18	-0-	10.2	3.00	7.10	0.05	-0-	100.7
82FFA165	55.3	1.07	15.9	6.400	0.20	0.26	4.80	3.60	4.70	0.74	0.23	-0-	12.6	4.20	1.20	0.05	-0-	100.5
82FFA183	48.7	1.05	14.2	6.500	4.60	0.20	9.33	9.23	2.70	0.32	0.26	-0-	-0-	3.30	0.30	0.00	-0-	100.6
82FFA193	48.0	0.97	14.1	-0-	0.17	0.17	6.90	7.33	4.06	0.63	0.08	3.70	13.4	-0-	-0-	-0-	-0-	99.96
83FFA028	46.1	0.90	10.1	-0-	0.20	0.20	13.1	9.59	1.72	0.11	0.11	3.05	13.0	-0-	-0-	-0-	-0-	100.1
83FFA053	48.4	0.73	13.4	-0-	0.18	0.18	10.5	10.0	2.29	0.68	0.24	2.89	11.6	-0-	-0-	-0-	-0-	100.9
83FFA055	49.6	0.49	11.5	-0-	0.16	0.16	10.4	4.44	2.86	0.32	0.18	6.70	11.9	-0-	-0-	-0-	-0-	99.03
83FFA059	49.9	0.60	14.3	-0-	0.16	0.16	5.76	4.60	3.71	1.52	0.07	6.77	11.2	-0-	-0-	-0-	-0-	99.23
83FFA060	53.6	0.89	14.8	-0-	0.10	0.10	4.56	2.59	2.51	2.71	0.07	5.07	12.1	-0-	-0-	-0-	-0-	98.22
83FFA061	48.4	1.19	13.8	-0-	0.18	0.18	6.15	7.82	3.04	0.70	0.09	4.90	13.6	-0-	-0-	-0-	-0-	99.02
83FFA062	49.3	1.04	13.6	-0-	0.16	0.16	7.03	3.75	1.02	1.02	0.06	6.54	13.8	-0-	-0-	-0-	-0-	99.73
83FFA063	47.4	0.40	11.9	-0-	0.14	0.14	7.91	2.54	2.54	2.44	0.06	4.58	13.3	-0-	-0-	-0-	-0-	93.41
83FFA066	46.5	0.48	11.9	-0-	0.18	0.18	12.0	6.86	0.36	1.16	0.06	9.24	13.5	-0-	-0-	-0-	-0-	99.96
83FFA067	45.2	0.20	13.9	-0-	0.15	0.15	7.26	7.43	1.99	1.93	0.14	9.37	10.7	-0-	-0-	-0-	-0-	98.26
83FFA072	40.7	0.55	13.4	-0-	0.19	0.19	7.59	6.43	3.03	0.34	0.05	3.94	13.3	-0-	-0-	-0-	-0-	99.56
83FFA073	46.6	1.07	13.1	-0-	0.15	0.15	7.41	7.95	1.12	1.16	0.05	9.25	13.5	-0-	-0-	-0-	-0-	100.1
83FFA074	44.4	1.07	13.1	-0-	0.16	0.16	7.70	7.95	1.12	0.41	0.09	9.10	15.4	-0-	-0-	-0-	-0-	99.00
83FFA075	47.4	1.03	13.0	-0-	0.21	0.21	7.70	6.94	2.37	0.21	0.09	7.10	13.6	-0-	-0-	-0-	-0-	100.3
83FFA076	48.3	1.09	14.6	-0-	0.20	0.20	6.34	6.24	3.04	0.27	0.10	2.98	14.0	-0-	-0-	-0-	-0-	100.5
83FFA25S	54.0	0.97	14.1	-0-	0.19	0.19	5.98	6.86	2.37	0.33	0.08	1.78	14.3	-0-	-0-	-0-	-0-	98.96
83FFA326	55.2	0.33	17.2	-0-	0.10	0.10	6.53	6.53	5.56	0.13	0.18	4.23	13.5	-0-	-0-	-0-	-0-	96.47
83FFA328	49.1	1.11	17.6	9.700	1.60	0.26	6.40	3.29	3.60	0.43	0.20	-0-	12.5	5.20	1.90	0.01	-0-	100.7
83FFA319	54.1	0.87	15.0	9.000	2.70	0.46	4.73	4.60	1.40	0.94	0.16	-0-	12.7	4.40	1.40	0.05	-0-	99.30
83FFA423	46.1	0.69	15.3	8.000	3.80	0.21	14.6	9.41	1.30	0.33	0.06	-0-	12.4	5.00	0.20	0.00	-0-	100.9
83FFA25	58.2	0.72	20.3	3.400	1.60	0.24	3.64	4.70	2.90	1.11	0.14	5.30	12.3	4.00	2.00	0.00	-0-	99.70
83FFA426	49.0	0.30	14.5	-0-	0.24	0.24	5.68	6.77	2.73	0.18	0.08	6.23	12.2	-0-	-0-	-0-	-0-	99.31
83FFA438	49.6	1.05	13.2	-0-	0.20	0.20	7.79	6.79	2.30	0.16	0.10	2.40	13.0	-0-	-0-	-0-	-0-	99.31
83FFA439	49.6	1.58	12.9	11.00	2.30	0.22	7.68	9.44	2.67	0.33	0.19	-0-	14.6	4.70	1.60	0.06	-0-	100.0
83FFA451	47.0	0.86	13.0	6.300	3.40	0.21	6.30	6.69	3.00	0.57	0.19	-0-	13.5	4.60	1.00	0.06	-0-	100.0
83FFA484	44.7	-0-	-0-	-0-	0.13	0.13	8.31	1.5	0.70	-0-	-0-	10.0	13.8	-0-	-0-	-0-	-0-	100.7
83FFA486	-0-	0.00	13.1	-0-	0.00	0.00	-0-	-0-	2.05	0.69	0.10	4.60	6.98	-0-	-0-	-0-	-0-	-0-
83FFA487	62.0	0.40	14.3	-0-	0.09	0.09	3.97	2.41	2.47	2.40	0.15	-0-	-0-	-0-	-0-	-0-	-0-	99.75

Table A-6.

TRACE ELEMENT GEOCHEMISTRY OF MAFIC INTRUSIVE ROCKS, GERALDTON

SAMPLE NO.	Cu	Pb	Zn	Ni	Co	Cr	Au	As	Ba	U	Br	U	Th	Rb	Sr	Zr	Y	Nb
82FHA036	55	6	49	50	34	156	2	-	31	400	186	-0-	2	23	84	111	17	3
82FHA061	95	13	63	14	31	-	100	-	52	-	-	8	3	-	62	44	25	3
82FHA063	27	6	90	110	40	594	3	5	5	-	-	3	0	31	156	51	20	4
82FHA067	129	11	98	89	63	176	4	33	33	-	-	8	0	44	92	71	25	0
82FHA100	15	18	85	131	63	793	2	33	14	-	-	6	0	4	752	24	6	2
82FHA157	31	8	93	38	43	236	1	-	23	-	-	-	0	21	224	90	18	3
82FHA165	13	16	123	77	51	329	-	-	-	-	-	1	0	31	211	106	22	0
82FHA183	13	21	103	79	50	382	-0-	-0-	-	-	-	-	0	15	159	52	21	3
82FHA203	83	4	61	51	-0-	30	-0-	-0-	-	117	322	-0-	0	37	210	59	26	-
83FHA220	38	5	94	254	-0-	795	-0-	-0-	-	194	305	-0-	0	26	382	59	15	-
83FHA254	14	3	157	210	-0-	562	-0-	-0-	-	264	236	-0-	4	52	711	33	10	2
83FHA255	21	6	78	210	-0-	842	-0-	-0-	-	267	243	-0-	0	52	100	71	10	-
83FHA258	95	8	40	64	-0-	153	-0-	-0-	-	207	289	-0-	12	37	136	26	26	3
83FHA260	4	9	20	85	-0-	155	-0-	-0-	-	429	410	-0-	0	62	85	63	19	5
83FHA261	21	9	57	46	-0-	112	-0-	-0-	-	130	418	-0-	0	15	125	73	17	4
83FHA262	3	9	59	83	-0-	162	-0-	-0-	-	101	407	-0-	0	15	146	76	35	4
83FHA263	2	7	65	101	-0-	179	-0-	-0-	-	267	496	-0-	1	49	57	78	13	2
83FHA266	36	9	90	65	-0-	386	-0-	-0-	-	130	290	-0-	3	33	96	49	3	3
83FHA267	84	9	91	87	-0-	192	-0-	-0-	-	723	391	-0-	0	66	402	47	31	2
83FHA272	84	6	98	67	-0-	181	-0-	-	-	87	370	-0-	5	10	277	64	31	4
83FHA273	100	8	101	85	-0-	205	-0-	-0-	-	67	404	-0-	0	7	118	76	27	2
83FHA274	58	6	90	86	-0-	224	2	-0-	-	76	371	-0-	2	30	37	70	28	3
83FHA275	13	15	101	74	-0-	125	4	-0-	-	54	360	-0-	0	10	419	88	17	5
83FHA325	94	3	94	114	-0-	221	4	-	-	18	235	-0-	3	6	65	49	25	3
83FHA326	31	2	74	46	-0-	197	-0-	8	-	62	213	-0-	5	16	153	110	14	5
83FHA328	62	3	105	92	-0-	122	1	-	-	58	-	-0-	1	29	89	58	58	-
83FHA429	62	3	92	92	-0-	239	1	-0-	-	16	-	-0-	2	73	100	32	37	1
83FHA482	56	0	54	35	-0-	10	-	-	6	376	423	-0-	1	6	298	360	13	2
83FHA484	0	7	46	46	-0-	142	-	-	26	290	322	-0-	4	4	360	48	12	4
83FHA487	44	12	48	77	-0-	278	-	-	22	277	322	-0-	5	7	71	79	37	3
83FHA328	53	0	314	-0-	-0-	84	-	-	26	617	-	-0-	3	-	113	66	29	-
83FHA329	73	4	130	74	49	1940	-	-	22	-	-	9	2	11	127	120	42	1
83FHA360	64	7	118	428	59	1800	-0-	-	22	464	-	-0-	0	42	96	45	63	5
83FHA423	55	0	360	67	67	220	-0-	-	10	400	-	-0-	0	19	301	52	29	-
83FHA425	33	9	36	19	19	43	-0-	-	4	348	-	-0-	-	19	124	62	35	2
83FHA439	50	2	62	60	47	43	-0-	-	-	350	-	-0-	1	38	172	51	22	2
83FHA451	27	1	82	190	47	790	-0-	-	-	151	-	-0-	5	65	289	129	16	7

Appendix A-IV. Felsic intrusive rocks

The geochemical analyses of Geraldton felsic intrusive rocks are listed in Tables A-7 and A-8. All major and trace element analyses of 82FRA samples were done at the GSC except Ba and V which were analysed at MUN. All major and trace element analyses of 83FRA samples were done at MUN.

Table A-7. Major element geochemistry of felsic intrusive rocks

Table A-8. Trace element geochemistry of felsic intrusive rocks

Table A-7.

MAJOR ELEMENT GEOCHEMISTRY OF FELSIC INTRUSIVE ROCKS, GERALDTON

SAMPLE NO.:	SIO2	TIO2	AL2O3	FEO	FE2O3	MNO	MGO	CAO	NA2O	K2O	P2O5	LOI	FE2O3T	H2O	CO2	S	C	TOT
83FHA011	62.3	0.35	17.0	2.300	1.00	0.04	0.86	3.07	5.20	2.21	0.14	-0-	3.60	2.00	3.40	0.25	-0-	100.3
83FHA146	66.9	0.27	16.0	2.000	0.80	0.03	0.59	1.81	6.60	1.56	0.09	-0-	3.00	1.60	3.30	0.40	-0-	100.3
83FHA156	64.1	0.32	16.9	0.700	1.70	0.04	0.58	3.54	4.40	2.67	0.12	-0-	2.50	1.40	3.90	0.00	-0-	100.5
83FHA182	65.6	0.36	15.3	-0-	-0-	0.05	2.17	3.83	4.58	2.10	0.18	1.91	3.95	-0-	-0-	-0-	-0-	100.3
83FHA205	63.7	0.39	15.0	-0-	-0-	0.06	2.41	4.58	4.41	1.60	0.16	2.05	5.34	-0-	-0-	-0-	-0-	99.67
83FHA207	65.9	0.35	16.2	-0-	-0-	0.05	2.00	3.63	5.00	1.53	0.15	0.81	4.24	-0-	-0-	-0-	-0-	99.86
83FHA208	64.6	0.35	15.3	-0-	-0-	0.07	2.07	4.64	5.43	0.83	0.16	1.48	4.38	-0-	-0-	-0-	-0-	100.2
83FHA209	64.8	0.34	15.2	-0-	-0-	0.05	2.10	3.90	4.90	1.47	0.16	3.00	4.04	-0-	-0-	-0-	-0-	100.4
83FHA214	63.8	0.33	15.2	-0-	-0-	0.03	1.14	4.37	5.19	2.11	0.09	5.71	1.77	-0-	-0-	-0-	-0-	99.57
83FHA215	64.3	0.32	15.5	-0-	-0-	0.03	0.92	3.02	4.77	2.60	0.08	4.13	1.75	-0-	-0-	-0-	-0-	97.42
83FHA220	64.3	0.33	16.4	-0-	-0-	0.02	0.72	2.55	5.96	2.11	0.17	2.92	1.74	-0-	-0-	-0-	-0-	98.77
83FHA221	66.0	0.31	16.4	-0-	-0-	0.03	0.39	2.07	6.14	3.69	0.10	2.00	2.11	-0-	-0-	-0-	-0-	98.30
83FHA226	63.8	0.34	15.1	-0-	-0-	0.03	0.15	3.24	5.00	2.51	0.11	4.01	3.03	-0-	-0-	-0-	-0-	99.62
83FHA256	65.0	0.30	15.1	-0-	-0-	0.04	0.75	3.79	4.68	2.27	0.14	4.35	1.95	-0-	-0-	-0-	-0-	98.29
83FHA256	67.3	0.01	13.2	-0-	-0-	0.04	1.43	1.08	0.57	10.1	0.08	2.15	2.65	-0-	-0-	-0-	-0-	98.46
83FHA259	65.0	0.40	16.3	-0-	-0-	0.03	1.12	1.53	5.09	2.94	0.09	2.74	3.69	-0-	-0-	-0-	-0-	99.57
83FHA264	64.5	0.38	14.8	-0-	-0-	0.04	1.11	2.28	5.63	2.63	0.08	2.93	4.55	-0-	-0-	-0-	-0-	98.73
83FHA266	64.6	0.35	16.6	-0-	-0-	0.04	0.84	2.30	6.36	1.50	0.08	2.46	4.55	-0-	-0-	-0-	-0-	99.91
83FHA403	66.7	0.13	16.6	-0-	-0-	0.03	0.50	1.70	5.33	2.64	0.18	2.89	2.49	-0-	-0-	-0-	-0-	98.98
83FHA414	57.4	0.23	14.8	-0-	-0-	0.06	4.15	4.76	4.36	2.06	0.09	8.36	3.61	-0-	-0-	-0-	-0-	99.68
83FHA441	64.9	0.40	17.4	-0-	-0-	0.03	2.55	2.69	3.50	1.33	0.10	2.16	2.16	-0-	-0-	-0-	-0-	100.6
83FHA463	66.6	0.33	13.8	-0-	-0-	0.01	0.28	3.60	3.50	0.86	0.02	0.72	1.33	-0-	-0-	-0-	-0-	99.93
83FHA600	67.9	0.25	15.5	-0-	-0-	0.05	1.64	3.41	3.36	3.92	0.12	0.65	2.69	-0-	-0-	-0-	-0-	100.1

APPENDIX B — ANALYTICAL METHODS

B-1. Major and ... procedures of the Geological ...

Table ... analytical accuracy of major element ... analyses, respective ... Analytical Chemistry Section, Geological Survey of ... Ottawa, Ontario.

Whole ... were determined by X-Ray Fluorescence ... Analyses (XRF), except Fe... analysed by rapid chemical ... are reported in weight ... = ... Fe_2O_3 (XRF) - 1.11134 FeO (volume...) ... all constituents lost on ... 1, 2, and 3.

Trace ... parts per million (ppm). ... were analysed by Energy ... Pb, and Zn, were determined ... absorption (AA) Spectrometry.

... detection limit...

Table A-8.

TRACE ELEMENT GEOCHEMISTRY OF FELSIC INTRUSIVE ROCKS, GERALDTON

SAMPLE NO.	Cu	Pb	Zn	Ni	Co	Cr	Au	As	Ba	V	Br	U	Th	Rb	Sr	Zr	Y	Nb
83FMA011	64	22	36	6	16	7	6	6	-	1018	53	22	14	10	64	242	124	4
83FMA146	17	19	54	11	-	26	270	84	947	48	-	12	-	11	38	394	96	6
83FMA156	3	23	55	12	9	14	10	15	481	56	-	-	13	15	71	540	127	4
83FMA02	35	10	38	18	-	45	-	-	638	64	-	6	4	4	81	493	138	9
83FMA05	55	-	48	16	-	56	8	-	906	57	-	-	5	-	79	528	121	7
83FMA07	221	9	37	16	-	51	12	-	373	58	-	6	-	4	60	932	133	6
83FMA280	245	28	20	4	4	64	2	214	868	58	-	-	10	10	31	621	138	8
83FMA09	40	-	77	4	-	63	4	-	643	53	-	-	-	5	52	812	135	4
83FMA14	14	5	5	-	-	29	8	140	724	53	-	9	5	5	50	530	130	4
83FMA215	14	6	18	3	-	27	7	-	919	49	-	-	-	1	79	242	94	3
83FMA20	12	3	20	4	1	24	-	172	565	419	-	3	5	5	96	319	94	3
83FMA21	33	7	28	19	-	-	-	-	705	95	-	-	20	5	55	561	58	4
83FMA22	14	3	24	19	-	-	-	-	661	59	-	4	-	1	55	95	101	6
83FMA226	15	6	12	12	-	-	-	-	484	56	-	-	-	8	221	419	81	-
83FMA259	11	4	23	23	3	-	-	-	652	-	-	9	-	8	36	260	88	6
83FMA260	13	-	16	3	-	-	-	-	972	56	-	-	-	6	15	517	90	5
83FMA268	13	12	25	2	-	-	8	-	-	-	-	-	-	-	-	443	82	3
83FMA414	11	5	38	78	78	355	-	-	758	92	-	-	-	-	76	268	58	2
83FMA481	18	9	11	32	1	31	-	-	378	56	-	-	-	-	24	388	74	2
83FMA483	21	7	4	1	-	-	-	-	-	30	-	-	-	-	15	273	62	2
83FMA600	13	29	33	19	32	62	-	-	1021	32	-	9	-	-	133	639	129	10

APPENDIX B   -   ANALYTICAL METHODS

B-I. Major and trace element analytical procedures at the
Geological Survey of Canada Laboratories.

Tables B-1 and B-2 list the analytical accuracy of
major element analyses and trace element analyses,
respectively, as determined by the Analytical Chemistry
Section, Geological Survey of Canada, Ottawa, Ontario.

Whole rock components (Table B-1) were determined by
X-Ray Fluourescence Wavelength Dispersive Analyses (XRF),
except FeO, H_2O, CO_2, and S which were analysed by rapid
chemical methods. All whole rock components are reported
in weight per cent (wt %). $Fe_2O_3 = Fe_2O_3$ (XRF) - 1.11134
FeO (volumetric). Volatiles represent all constituents
lost on ignition other than CO_2, H_2O, and S.

Trace elements are reported in parts per million
(ppm). As, Nb, Rb, Sr, Th, U, Y and Zr were analysed by
Energy Dispersive XRF. Co, Cr, Cu, Ni, Pb, and Zn, were
determined by Atomic Absorption (AA) Spectrometry.

Blank spaces represent values below detection limits.

Table B-1. Accuracy of whole rock analyses as reported by
the Geological Suvey of Canada.

ELEMENT	CALIBRATION RANGE (%)	ESTIMATE OF ERROR ABSOLUTE + RELATIVE %		DETERMINATION LIMIT
SiO_2	0 - 100	0.40	1	0.40
TiO_2	0 - 3	0.02	1	0.02
Al_2O_3	0 - 60	0.40	1	0.40
Fe_2O_3	0 - 90	0.10	1	0.10
FeO	0 - 30	0.20	2	0.20
MnO	0 - 1	0.01	2	0.01
MgO	0 - 50	0.10	1	0.10
CaO	0 - 35	0.10	1	0.10
Na_2O	0 - 10	0.50	1	1.50
K_2O	0 - 15	0.05	1	0.05
H_2O	0 - 5	0.10	5	0.10
CO_2	0 - 20	0.05	3	0.05
P_2O_5	0 - 1	0.02	1	0.02
S	0 - 3	0.04	5	0.04

Table B-2. Accuracy of trace element analyses as reported
by the Geological Survey of Canada.

ESTIMATE OF ERROR

ELEMENT	ABSOLUTE + (ppm)?	RELATIVE (% OF CONC.)
As	30	10
Nb	10	10
Pb	30	10
Rb	10	10
Sr	10	10
Th	30	10
U	30	10
Y	10	10
Zr	10	10
Co	10	10
Cr	10	10
Cu	7	10
Ni	15	10
Zn	7	10

B-II. Analytical procedures at Memorial University of
Newfoundland (MUN).

Major element contents were determined at MUN (G.
Andrews, analyst) using a Perkin-Elmer 306 atomic
absorption spectrophotometer. The techniques used are
adapted from Langmhyr and Paus (1968) and Abbey (1968).
Phosphorus contents were determined by colorimetric
techniques of Maxwell (1968).

From replicate analyses, analytical errors are
estimated at; less than 2% for SiO_2 and Al_2O_3, less than
5% for MgO, CaO, and Fe_2O_3T, less than 10% for MnO, Na_2O,
K_2O, and LOI, and greater than 10% for TiO_2 and P_2O_5. The
large errors in TiO2 and P2O5 analyses are considered due
to the low abundances of these elements in the rocks
analysed (less than 0.5% and less than 0.3% respectively).

For trace element analyses, pressed sample pellets
were prepared. The sample pellets consisted of 10 grams
(+/- 0.05 g) of rock powder mixed with 1.50 grams (+/-
0.05 g) of bakelite resin. The mixture was pressed into
40mm diameter pellets at 25 tons pressure and then baked
at $200^{O}C$ to set the binding compound.

The trace element sample pellets were analysed with a
Phillips 1450 X-ray fluorescence spectrometer. To reduce

instrument drift between sample runs, a monitor saturated
with trace elements was calibrated against standards, and
every element ratioed to this monitor.

Based on replicate analyses, the precision of the XRF
data is estimated to be within 10% for Rb, Sr, Y, Ba and
Zr, within 15% for Ni, Cr, Cu and Zn, and higher for U,
Th, Nb and Pb.

APPENDIX C - LEAD ISOTOPE ERRORS

The data were obtained from Geospec Consultants Limited of Edmonton Alberta, and performed on a Micromass MM-30 mass spectrometer. The uncertainties in reproducibility, quoted at the two-sigma level of error, quoted by Geospec Consultants were derived by repeated analysis of National Bureau of Standards NBS981 standard, and are 0.042,0.052, 0.058,and 0.028% for the ratios $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, and $^{207}Pb/^{206}Pb$. Analyses for specimen pairs (some not strictly duplicates) submitted by R.I.Thorpe of the Geological Survey of Canada to the Geospec laboratory, and repeat analyses completed to check on within-run reproducibility indicate maximum uncertainty of 0.058, 0.060. 0.061, and 0.044% respectively.

Table D-1. Rare earth element analyses of mafic and felsic intrusive rocks.

Analyses were done by Nuclear Activation Services, Hamilton, Ontario by induced neutron activation

ROCK TYPE	MAFIC INTRUSIONS				STURGEON LAKE BASALT		
SAMP. NO.	254	261	228	266	(3 REPEATS OF 1 SAMPLE)		
ELEMENT DET. LIM.***							
Ba 20.00	260	220	290	160	240	260	240
La 0.10	8.2	4.2	5.8	5.9	6.2	6.5	6.2
Hf 0.20	0.9	1.9	1	1.3	1.2	1.5	1.2
Ta 0.50	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Wn 1.00	12	-9	-10	19	6	110	10
Au** 5.00	-5	-5	7	6	-5	-5	-5
Ce 1.00	19	13	15	17	13	14	14
Nd 3.00	12	8	9	9	7	7	7
Sm 0.10	2.97	2.85	2.74	1.93	1.86	1.91	1.92
Eu 0.05	1.15	0.95	0.81	0.68	0.65	0.64	0.71
Tb 0.10	0.5	0.7	0.5	0.3	0.3	0.4	0.5
Yb 0.05	1.84	3.80	1.42	1.33	1.7	1.76	1.74
Lu 0.01	0.20	0.49	0.23	0.22	0.27	0.28	0.28
Sr 100.00	1000	100	400	100	100	200	200
Rb 5.00	18	22	37	35	15	22	15

ROCK TYPE	WESTERN PORPHYRIES				EASTERN PORPHYRIES			CLS****
SAMP. NO.	221	214	215	226	207	207(rep.)	209	600
ELEMENT DET. LIM.***								
Ba 20.00	870	1000	590	630	800	890	960	1300
La 0.10	18.7	16.9	15.3	7.4	25.8	27.3	31.9	53.8
Hf 0.20	3.2	3.2	3.2	2.2	4	3.7	3.9	4.1
Ta 0.50	0.5	0.6	0.5	0.5	0.8	0.8	1	1.9
Wn 1.00	98	110	62	96	110	110	110	220
Au** 5.00	-5	270	9	5	18	21	5	-5
Ce 1.00	43	37	32	16	53	59	61	97
Nd 3.00	18	17	14	7	25	25	26	34
Sm 0.10	3.22	3.03	2.67	1.33	3.99	4.21	4.52	5.28
Eu 0.05	0.77	0.69	0.6	0.38	0.94	1.05	0.86	0.96
Tb 0.10	0.2	0.3	0.2	0.1	0.3	0.4	0.3	0.3
Yb 0.05	0.33	0.4	0.29	0.25	0.73	0.75	0.73	0.82
Lu 0.01	0.07	0.06	0.04	0.04	0.11	0.11	0.14	0.13
Sr 100.00	600	500	300	500	1000	1000	900	600
Rb 5.00	78	65	200	100	85	93	74	190

Notes

-0.5 denotes less than 0.5

*These samples were crushed in a tungsten carbide shatter box so there may be some W contamination

**All analyses are reported in ppm except for Au which is in ppb

***DET. LIM. = detection limit

****CLS = Croll Lake Stock

Table D-2. Chondrite normalization values used for REE plots.
Values are from Taylor and Gorton (1977).

ELEMENT	NORMALIZATION FACTOR
La	0.315
Ce	0.813
Pr	0.116
Nd	0.597
Sm	0.192
Eu	0.0722
Gd	0.259
Tb	0.049
Dy	0.325
Ho	0.0730
Er	0.213
Tm	0.0300
Yb	0.208
Lu	0.0323

483011

ELEMENT	NORMALIZATION FACTOR
La	0.315
Ce	0.813
Pr	0.118
Nd	0.597
Sm	0.192
Eu	0.0722
Gd	0.259
Tb	0.049
Dy	0.325
Ho	0.0720
Er	0.213
Tm	0.0360
Yb	0.209
Lu	0.0323

46