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Cover photo. *Drilling at the Fyre Lake property. Photo by Mike Burke.*

Abstract

The Fyre Lake sulphide-magnetite deposit is located in the Finlayson Lake massive sulphide district in the Yukon-Tanana Terrane, southeastern Yukon Territory, Canada. It is hosted by quartz-chlorite-actinolite schist derived from (probable) Devono-Mississippian-aged mafic volcanic rocks. Overlying the deposit are intercalated metasedimentary and metavolcanic rocks. This mixed sequence is, in turn, overlain by a thick sequence of graphitic phyllite.

The deposit consists of three northwest-trending stratiform lenses comprised of massive and semimassive sulphide and magnetite iron formation. Pyrite is the dominant sulphide mineral in the deposit, with lesser amounts of pyrrhotite, chalcopyrite, and locally, sphalerite. The sulphide mineralization is copper- and cobalt-rich and locally contains significant concentrations of zinc and gold. It has low to trace amounts of lead, barium, arsenic, antimony, tin and selenium.

Lithogeochemical results indicate that the host mafic metavolcanic rocks are strongly depleted of light rare-earth elements (LREE) and high field strength elements (HFSE), and contain elevated levels of MgO, Ni and Cr. SiO_2 in the host rocks ranges from 53 to 58%. Chemically, the mafic metavolcanic rocks are similar to boninitic rocks found in some suprasubduction zone ophiolites such as those at Cyprus. The primitive boninitic chemistry of the host metavolcanic rocks implies that they originated as melts from a depleted mantle in a rifted setting. The presence of felsic metasedimentary rocks below, within and overlying the host metavolcanic rocks suggests that the Fyre Lake deposit was formed in or near a mature tectonic setting, possibly a continental arc or an evolved island arc.

The host mafic metavolcanic rocks are chemically distinct from other mafic and intermediate metavolcanic rocks that outcrop on the Fyre Lake property. A clastic metavolcanic rock unit lies stratigraphically below the deposit. It consists of fragmental LREE- and HFSE-enriched transitional subalkaline basalts. Other discontinuous bodies of metavolcaniclastic and metaflow rocks occur stratigraphically above and peripheral to the Fyre Lake deposit. These are enriched in LREE and Th, and relatively depleted in Nb, Ta and Ti, and generally display the chemical features of transitional basalts and andesites erupted in a continental arc or evolved island arc setting.

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INTRODUCTION

The Fyre Lake deposit (also known as the Kona deposit), is located within the Finlayson Lake volcanogenic massive sulphide (VMS) district, southeastern Yukon Territory (Fig. 1). It lies within Paleozoic layered metasedimentary and metavolcanic rocks of the Yukon-Tanana Terrane. Three stratiform pyrite- and magnetite-rich lenses trend southeast and collectively form an estimated resource of 15.4 million tonnes within which 8.2 million tonnes grade 2.1% copper, 0.11% cobalt and 0.73 g/t gold (Pacific Ridge Exploraton Ltd., Project Overview, company website, 2004).

This paper presents a compilation of data and research by the authors based on mapping, diamond drilling and geochemical work by the staff of Columbia Gold Mines Ltd. (currently Pacific Ridge Exploration Ltd.) and the Yukon Geology Program (precursor of the Yukon Geological Survey). This work was completed prior to 2001 and some of the more recent work is not included as part of this compilation. The report includes: 1) a description of the stratigraphy, mineralization and alteration of the deposit; 2) suggestions for the paragenesis of mineralized rock; and 3) a lithogeochemical assessment of the affinity and tectonic setting of the metasedimentary and metavolcanic rocks on the Fyre Lake property.

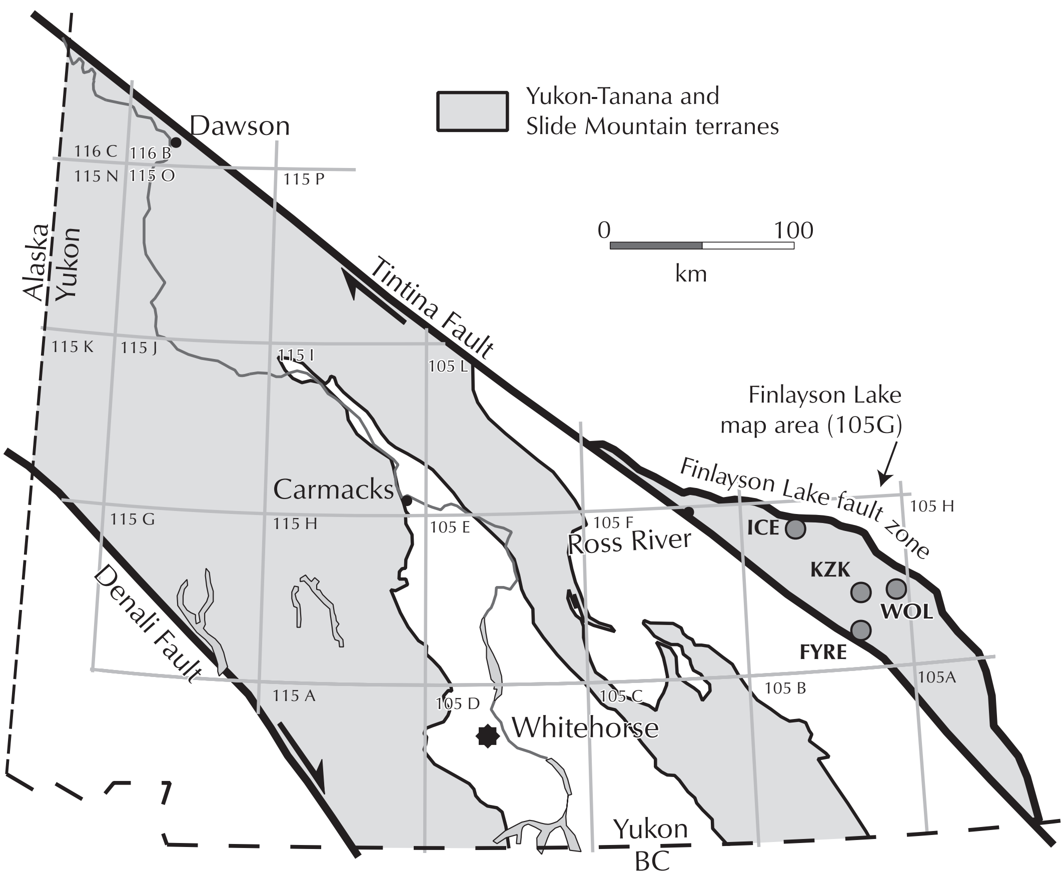


Figure 1. *Location of Fyre Lake deposit (FYRE), as well as the Ice (ICE), Kudz Ze Kayah (KZK) and Wolverine (WOL) volcanogenic massive sulphide deposits. It is hosted within Paleozoic rocks of the Yukon-Tanana Terrane, northwest of Watson Lake, Yukon (after Murphy, 2004b).*

OVERVIEW OF REGIONAL GEOLOGY

The Finlayson Lake district is primarily underlain by rocks of the Yukon-Tanana Terrane, a large enigmatic terrane that lies between the ancestral North American continental margin to the east and exotic terranes to the west (Mortensen, 1992, and references therein). In the Finlayson Lake area, the Yukon-Tanana Terrane is lozenge-shaped, approximately 400 km long and up to 50 km wide. It is juxtaposed against Proterozoic and Paleozoic miogeoclinal strata of the ancestral North American continental margin along the Tintina fault zone to the southwest, and along the Finlayson Lake fault zone to the northeast (Fig. 1). The Yukon-Tanana Terrane is made up of Middle to Late Paleozoic polydeformed pelitic to quartzo-feldspathic metasedimentary schist and gneiss with minor marble, and deformed mafic to felsic metavolcanic and metaplutonic rocks. Most units display a penetrative ductile deformation fabric and have been affected by regional-scale thrust faulting (e.g., Mortensen and Jilson, 1985; Mortensen, 1992; Dusel-Bacon et al., 1998; Murphy, 2004).

Recent mapping in the Finlayson Lake District by Murphy (1997b), Murphy and Timmerman (1997a,b), Murphy (1998), Murphy and Piercey (1999, 2000), Murphy et al. (2002), and Murphy (2004a) has refined earlier mapping by Mortensen and Jilson (1985). In the area of Fire Lake, the layered Paleozoic metasedimentary and metavolcanic rocks have been assigned to the Upper Devonian Grass Lakes group, which is divided into the following units (from oldest to youngest). Lowermost are quartz-feldspar-rich metasedimentary rocks of the North River formation. This unit consists of interbedded biotite-muscovite-feldspar-quartz psammite schist and quartz-biotite-muscovite metapelitic schist, with thin intervals of calcareous schist and marble. Overlying the North River formation are rocks of the Fire Lake formation, which is composed of mafic metavolcanic rocks, plagioclase-chlorite schist, muscovite-quartz-rich phyllite and schist, and lesser carbonaceous phyllite. Uppermost in the Grass Lakes group is the Kudz Ze Kayah formation. The Kudz Ze Kayah formation is divided into a lower unit of carbonaceous phyllite and quartzite, and an upper unit, which consists of feldspar-muscovite-quartz schist, pale siliceous, locally quartz-amygdaloidal phyllite or schist, and minor feldspar-augen schist (representing metaporphyry and felsic metavolcanic rocks). Interbeds of carbonaceous phyllite and rare limestone are also present. The copper-cobalt-gold-bearing Fyre Lake deposit lies at the contact between mafic metavolcanic rocks of the Fire Lake formation and carbonaceous phyllite of the Kudz Ze Kayah formation.

In the area of Fire Lake, the layered Paleozoic rocks are intruded by variably serpentinized Late Devonian ultramafic rocks. The ultramafic rocks are spatially associated with the Fire Lake formation and are interpreted to intrude it (Murphy, 2004a). The eastern section of the Fyre Lake property is underlain by intrusive rocks of the Simpson Range metaplutonic suite, which are in fault contact with the layered Paleozoic rocks to the west. The Simpson Range metaplutonic suite is composed of metamorphosed and foliated diorites, monzonites, granodiorites and granites. These rocks are of Mississippian age (dated at ~360 Ma; Mortensen, 1992) with granites and granodiorites ranging from about 345 to 349 Ma (Grant, 1997 and J.K. Mortensen, pers. comm., 1997). Other intrusive rocks cut Paleozoic lithologies in the Finlayson Lake area and include Triassic mafic dykes and weakly foliated Cretaceous granite.

PROPERTY GEOLOGY

PROPERTY STRATIGRAPHY

A simplified geology plan map and a schematic stratigraphic column for the Fyre Lake property are presented in Figures 2 and 3. The North River, Fire Lake and Kudz Ze Kayah formations correspond to units 1, 2 and 3 of Hunt and Murphy (1998), and thus the map and column in Figures 2 and 3 have those unit designations. Ultramafic rock bodies mapped on the property have been included in the Fire Lake formation (unit 2).

North River formation

North River formation rocks outcrop to the north and west of Kona cirque and just east of Fire Lake (Fig. 2). North River formation is made up of grey to brown muscovite-quartz-rich and biotite-muscovite-quartz-rich phyllite, biotite-quartz-rich schist and chlorite-muscovite-quartz schist. The chlorite-muscovite-quartz schist is strongly deformed and the interpreted protolith is feldspar- and quartz-rich sediments. Local lenses of metavolcanic rocks are contained in this lithology. The biotite-quartz-rich schist is intercalated with biotite-muscovite-quartz-rich phyllite (Photo 1, lower), and is locally calcareous, containing up to 10% recrystallized calcite layers <1 cm thick (Photo 2). The biotite-quartz schist is interpreted to be a quartz- and feldspar-rich metasandstone. The phyllite is generally weakly carbonaceous and locally contains significant biotite and garnet. The phyllite has a mudstone and siltstone protolith.

Fire Lake formation

Fire Lake formation overlies the metasedimentary rocks of the North River formation and is composed of green chlorite-actinolite and quartz-chlorite-actinolite schist after mafic to intermediate metavolcanic rocks. It also contains a subordinate volume of intercalated metasedimentary rocks.

The metavolcanic rocks are comprised of several laterally discontinuous and chemically distinct subunits known as the Lake Zone, Outfitter's Creek, Kona Bowl and Kona Cirque (Figs. 2 and 3). Layers of biotite-quartz-rich schist after metasandstone and phyllite separate the metavolcanic rocks from each other and cap them.

On the Fyre Lake property, metavolcanic rocks labelled as the Lake Zone occur lowermost in the Fire Lake formation. This subunit is in excess of 100 m thick and forms an east-dipping belt on the east side of Fire Lake (Figs. 2 and 4). The Lake Zone is largely composed of thinly bedded, fine-grained, mafic metavolcaniclastic rock (Deighton et al., 1997; Photo 1, upper and Fig. 4). Many coarser grained sandy layers are feldspar-rich and locally display normal grading and may in part have been emplaced by turbidites. It also contains minor coarse-grained lapilli tuff or lapillistone beds and weakly foliated massive layers, which may be flows or large blocks of lava. The basal contact of the Lake Zone metavolcanic rocks is locally gradational with metasedimentary rocks of North River formation (Fig. 4).

Overlying the Lake Zone metavolcanic rocks is a mixed sequence of highly strained green quartz-chlorite-actinolite schist and lesser brown biotite-quartz schist, light green chlorite-muscovite-quartz schist and phyllite. The green quartz-chlorite-actinolite schist and light green chlorite-muscovite-quartz-rich schist layers represent intercalated mafic or intermediate volcaniclastic rocks. The biotite-quartz schist is outwardly similar to that of North River formation and is interpreted as metamorphosed felsic siltstone and sandstone.

Green biotite-quartz-chlorite-actinolite-rich schists up to 75 m thick make up the Outfitter's Creek and Kona Bowl metavolcanic rocks. They lie above the metavolcanic rocks hosting the Fyre Lake deposit (Fire Lake formation, or unit 2m: Fig. 2 and 3) and represent original flow rocks and bedded volcaniclastic rocks. Both the Outfitter's Creek and Kona Bowl metavolcanic rocks thin to the east where they interfinger with phyllites of Kudz Ze Kayah formation (Fig. 2 and 3).

The Kona Cirque mafic schist of the Fire Lake formation outcrops to the north of Kona Cirque and hosts the Fyre Lake deposit (unit 2m: Figs. 2). It is described in more detail in the local geology section. Geological mapping indicates that the Kona Cirque mafic schist is a metavolcanic rock unit that is lower in the stratigraphy than the Outfitter's Creek and Kona Bowl metavolcanic rocks (Fig. 3). The Kona Cirque mafic schist is at least locally underlain by carbonaceous phyllite in the west, and this phyllite may be part of the North River or Fire Lake formations. In terms of elevation, the Kona Cirque mafic schist lies above the Lake Zone metavolcanic rocks.

In the northeast corner of the Fyre Lake property, the Kona Cirque mafic schist is underlain by variably strained metamorphosed mafic intrusive and ultramafic rocks of the Fire Lake formation (unit 2mum and 2um; Deighton et al., 1997; Hunt and Murphy, 1998). The mafic intrusive rocks

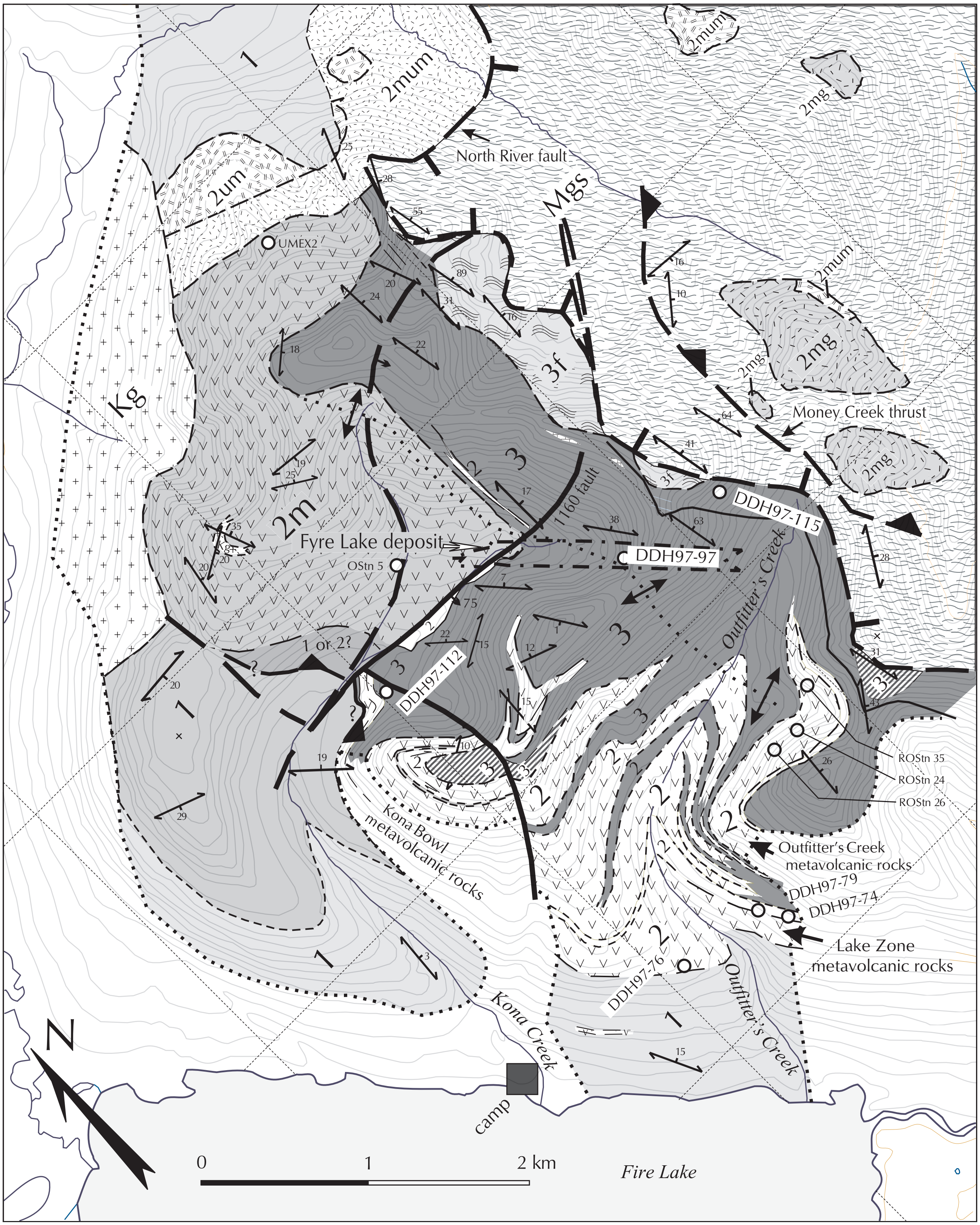
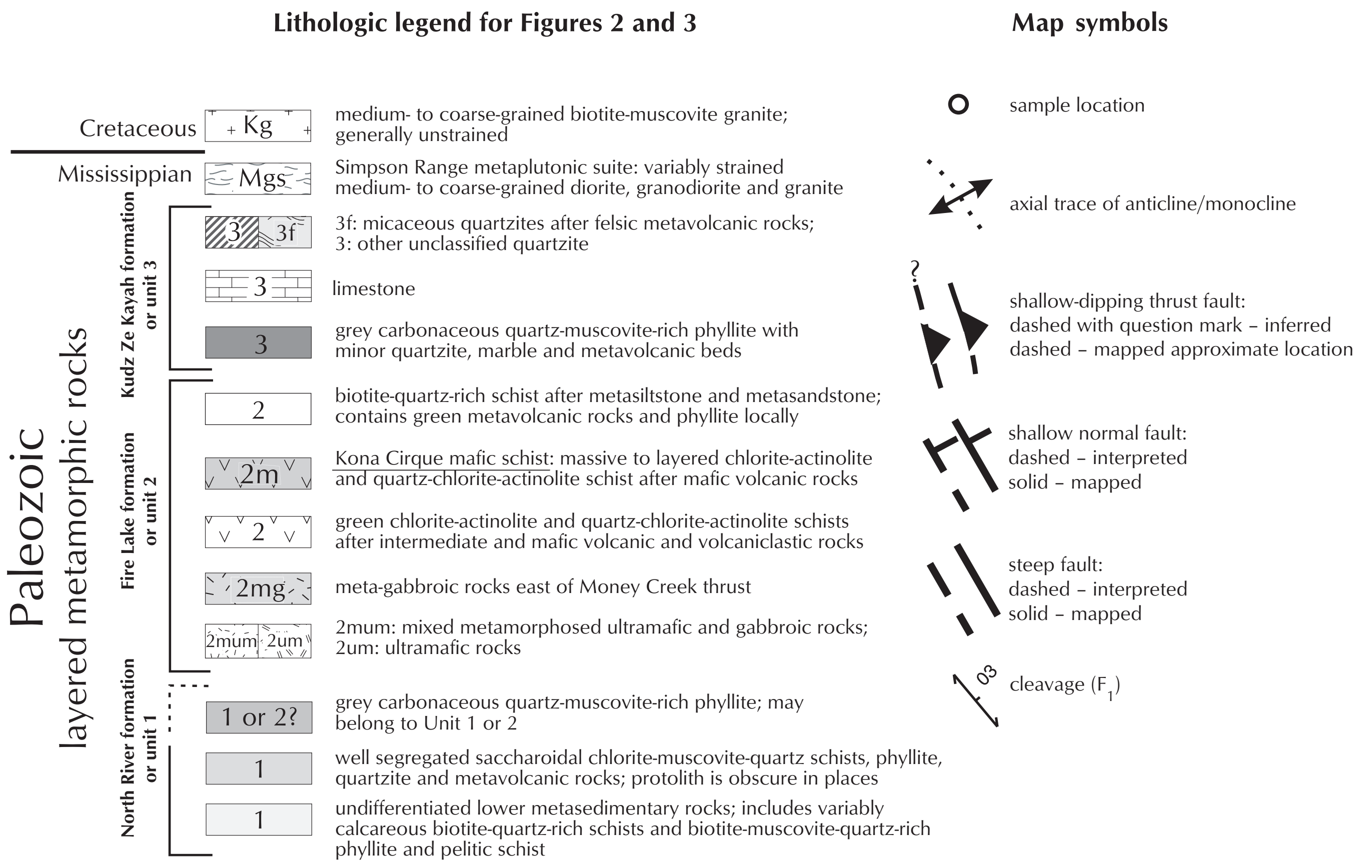


Figure 2. Simplified geological plan of the Fyre Lake area. The massive sulphide and magnetite mineralization outcrops just to the north of Kona Cirque. The Fyre Lake deposit is marked by the dashed and dotted outline. The map is adapted from Hunt and Murphy (1998) and includes geology from Deighton et al. (1997) and Murphy (2004a). Legend on facing page.



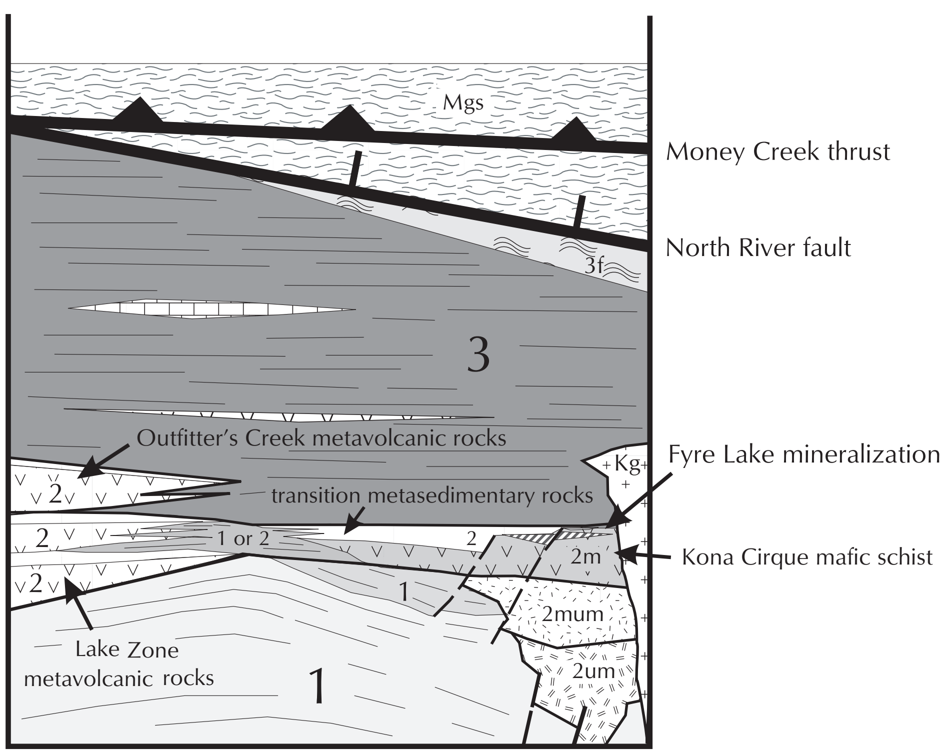


Figure 3. *A schematic stratigraphic column of the Fyre Lake deposit area depicts the spatial relationship of the major rock units.*

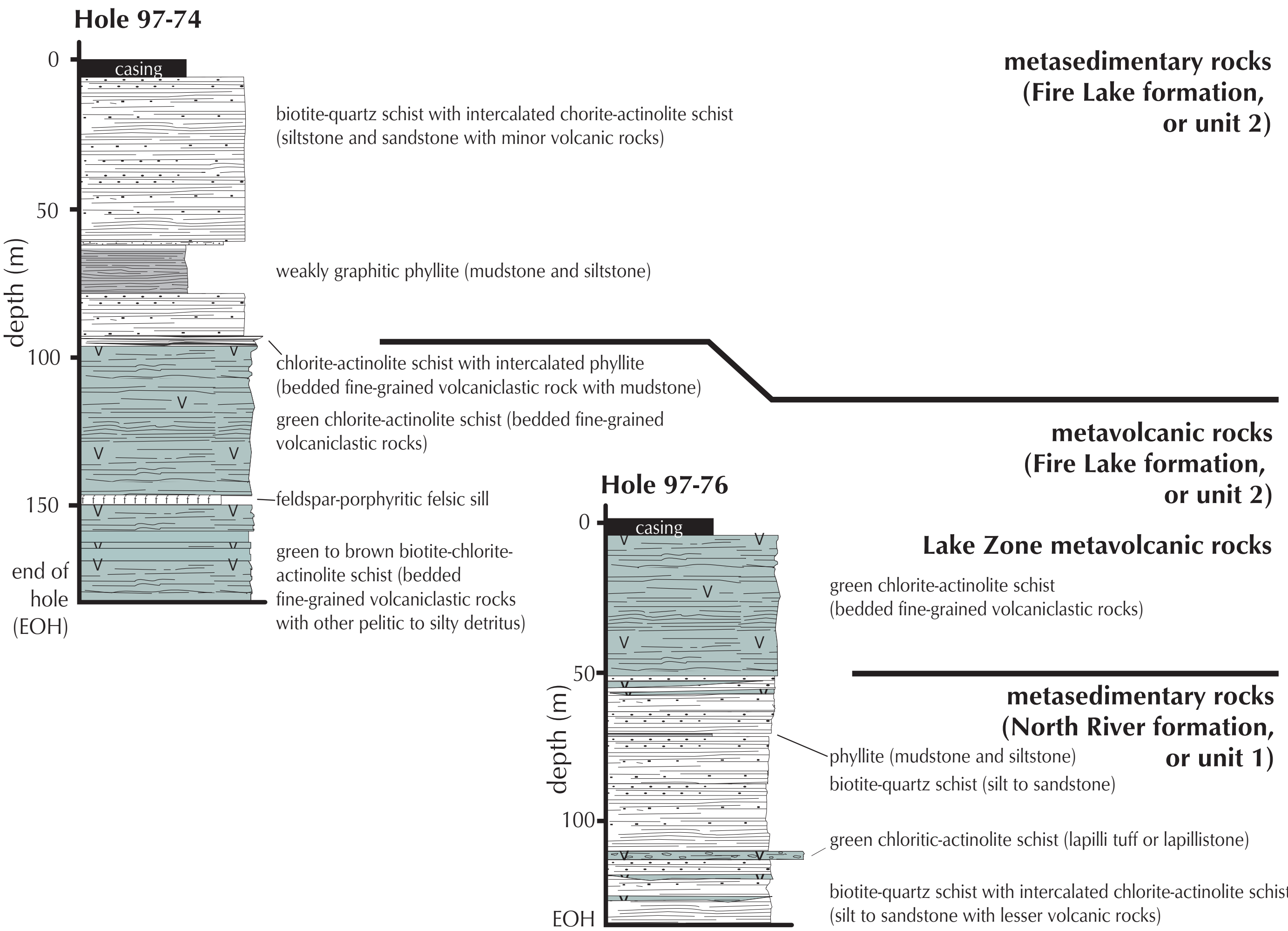


Figure 4. *A section of the Lake Zone stratigraphy presented as graphic logs of Drill Holes 97-74 and 97-76. Location of holes shown on Figure 2.*

are fine- to coarse-grained feldspar-pyroxene-amphibole gabbros. The ultramafic rocks are altered and contain talc, serpentine, tremolite, phlogopite, orthopyroxene, chromite and olivine (Hunt and Murphy, 1998). Regional mapping by Murphy (1997a,b, 1998) suggests that the metagabbroic and metaultramafic rocks cross-cut the metavolcanic rocks of North River formation and form intrusive bodies, which are spatially in intimate contact with the metavolcanic rocks of Fire Lake formation.

Kudz Ze Kayah formation

Kudz Ze Kayah formation consists of carbonaceous, biotite-muscovite-quartz phyllite that is up to 580 m thick. It overlies and laterally interfingers with rocks of Fire Lake formation (Figs. 2 and 3). Minor bodies of feldspar-porphyritic felsic metavolcanic or metaplutonic rocks (Kudz Ze Kayah formation, or unit 3f, Fig. 2 and 3) are located in the upper parts of the phyllite exposed on the eastern ridge of Kona Cirque. One of two samples examined in thin section was plagioclase porphyry and the other was K-feldspar porphyry (Leitch, 1998).

Simpson Range metaplutonic suite (Mgs)

Mississippian-aged Simpson Range metaplutonic rocks consist of a pluton of K-feldspar-biotite-hornblende granite on the Fyre Lake property. Isolated bodies of mafic and ultramafic rocks of the Fire Lake formation (unit 2mg and 2mum) lie within the Simpson Range suite (Fig. 2).

The pluton is separated from the layered Paleozoic metasedimentary and metavolcanic rocks by a large east-dipping fault. This fault was initially interpreted to be the Money Creek thrust (Hunt and Murphy, 1998; Murphy, 1998: Fig. 2). However, re-evaluation of the Paleozoic stratigraphy to the north of Fire Lake, in the Wolverine Lake map area (105G/8), suggests the presence of a shallow normal fault based on the juxtaposition of younger over older rock units (Murphy, 2004a). This fault has been dubbed the North River fault and its trace is interpreted to correspond to the faulted boundary of the western edge of the Simpson Range metaplutonic rocks east of Kona Cirque. The Money Creek thrust is interpreted to correspond to a second shallow-dipping fault structure mapped to the east of the North River fault (Fig. 2).

Cretaceous plutonic rocks (Kg)

Medium-grained, weakly foliated biotite-muscovite granite (Kg; Fig. 2) underlies part of the Fyre Lake property (Hunt and Murphy, 1998). These rocks are the southern part of a large Cretaceous stock that cuts Paleozoic rocks of the Yukon-Tanana Terrane in this area (Fig. 3).

STRUCTURE

The presence of biotite and garnet in the metasedimentary and metavolcanic rocks indicate upper greenschist facies metamorphism in the Fire Lake area. A strong schistosity (F_1) is present in all the layered Paleozoic lithologies on the Fyre Lake property. It is parallel to compositional layering and generally dips shallowly eastward or southward. A strong mineral lineation (L_1) occurs in the plane of the (F_1) foliation. It trends 120° to 140° and plunges shallowly to the southeast. Interfolial folds are well developed in some metasedimentary units (Photo 3) and the fold axes are generally parallel to the L_1 mineral elongation. At the property-scale, rocks in the area of the Fyre Lake deposit are gently folded along a northerly trending anticlinal to monoclinal structure (Fig. 2).

Shallow-dipping faults and shears

A major north-trending, east-dipping fault, the North River fault, marks the eastern limit of the layered Paleozoic rocks on the property (Fig. 2). Murphy (2004a) postulates a mid-Cretaceous age of movement for the North River fault based on cooling ages of titanite, hornblende and biotite found in the footwall of the fault.

The Money Creek thrust cuts rocks of the Simpson Range plutonic suite to the east of the North River fault (Fig. 2). The Money Creek fault is a major regional-scale thrust fault, which juxtaposes older over younger rocks within the Paleozoic stratigraphy. Movement on the Money Creek thrust is interpreted to have occurred in a northeast direction in the Early Permian (Murphy, 2004a). Several other subparallel reverse and thrust faults, possibly related to the Money Creek thrust, cut the metavolcanic and metasedimentary rocks in the area of the Fyre Lake deposit in Kona Cirque.

High-strain zones, with mylonitic textures, parallel to the F_1 foliation, are developed in sections of the metavolcanic and metasedimentary rocks west of the Fyre Lake deposit lying above the Lake Zone metavolcanic rocks. Near Kona Bowl, a 60-m-thick, shallow east-dipping, shear zone was intersected in drill hole 97-112 (Fig. 2). It contains well foliated, sheared, cataclastic rocks, and is located at the contact between less strained metasedimentary and metavolcanic rocks of Fire Lake formation above, and highly strained chlorite-muscovite-quartz schist of North River formation below. The slip direction and total movement on this structure is unknown.

Steeply dipping faults

The 1160 fault outcrops at the entrance to Kona Cirque (Fig. 2). It forms a splayed, sheared, 75° south-dipping zone, which strikes about 105° azimuth. It offsets the stratigraphy to the south sinistrally and downwards. Another east-trending steep fault appears to cut metasedimentary rocks in the crest of the eastern ridge of Kona Cirque to the north of the 1160 fault (Fig. 2); it appears to down-drop the stratigraphy to the south. A north-trending, steeply dipping fault cuts rocks in the Kona Bowl area (Fig. 2).

LOCAL GEOLOGY OF THE FYRE LAKE DEPOSIT

STRATIGRAPHY

The Fyre Lake deposit is contained in a dark green, fine-grained quartz-chlorite and quartz-chlorite-actinolite schist of the Fire Lake formation (dubbed the Kona Cirque mafic schist or unit 2m). The sulphide-magnetite mineralized rock is located close to the contact with an overlying package of intercalated biotite-quartz and chlorite-actinolite schist, and phyllite known as the Transition Zone. A thick sequence of carbonaceous phyllite (Kudz Ze Kayah formation, or unit 3) succeeds the Transition Zone. Figure 5 provides a graphic log of Hole 97-97 and serves to illustrate the local stratigraphy of the Fyre Lake deposit.

Kona Cirque mafic schist (Fire Lake formation, or unit 2m)

In thin section, the Kona Cirque mafic schist is made up of tremolite-actinolite amphibole (0–60%), quartz (10–40%), relict plagioclase (10–30%), chlorite (0–20%), biotite (1–10%), epidote (0–10%), carbonate (0–3%), garnet (0–2%), minor sericite, and accessory rutile, apatite, sphene and opaques (Leitch, 1998). Relict volcanic textures are locally visible in the lower portions of deep drill holes and include metre-scale flows and intercalated clast- and matrix-supported breccias. The breccias contain angular and lobate blocks <20 cm across (Photo 4). The upper sections of the Kona Cirque mafic schist are generally chlorite-rich and highly strained. Rare amygdaloidal fragments and small lava blocks are discernible in a fine-grained well foliated matrix.

Given its mineralogy and texture, the Kona Cirque mafic schist is interpreted to be a metamorphosed succession of mafic flows, breccias and fine-grained mafic-rich volcaniclastic rocks. The Kona Cirque mafic schist is locally interbedded with metasedimentary rocks, and contains layers of biotite-quartz or chlorite-biotite-quartz metasiltstone and metasandstone up to 10 m thick. These metasedimentary rocks bear resemblance to those cored in the Transition Zone described below.

Transition Zone (Fire Lake formation, or unit 2)

The Transition Zone is composed of intercalated metasedimentary and metavolcanic rocks. It displays dramatic changes in thickness, and ranges from 6 to >200 m thick. It is roughly wedge-shaped, thickening to the south and westward of the deposit (Foreman, 1998). The different rock units making up the Transition Zone are described below in order of abundance.

Biotite-quartz schist is the most abundant unit. Individual beds in the Transition Zone range from <1 to >20 m thick. It is generally fine-grained and thinly banded and consists of centimetre-scale biotite-, quartz- and feldspar-rich bands and beds. Some sections of the subunit are hematite-stained and contain significant quartz in the matrix. These sections may have been cherty or were silicified after emplacement. Recrystallized calcite laminations are present in places and local layers have a calcareous matrix. The protolith of this unit is interpreted to be thinly bedded quartz- and feldspar-rich felsic siltstone and sandstone.

Green chlorite-actinolite schist occurs as fine-grained layers varying in thickness from centimetres to several metres. It is generally intimately intercalated within the biotite-quartz schist (e.g., above the West Kona Zone in Hole 97-97: Fig. 5 and Photo 5). Fragments and lava blocks over 10 cm in diameter are locally contained within layers of the chlorite-actinolite schist. Its thin-layered nature and the presence of lava fragments suggest that this subunit is a metamorphosed metavolcanic of volcaniclastic origin. The lava blocks imply that the source of the volcaniclastic rocks was closer than that of the associated felsic metasedimentary rocks.

The proportion of chlorite-actinolite schist tends to increase downwards within the Transition Zone, where thicker layers (>10 m) are found locally. Some of these lower layers are more massive and represent local mafic flows.

Phyllite occurs in the Transition Zone as layers ranging from <1 m to 30 m thick. It is finely banded to laminated and carbonaceous. The protolith was mudstone and siltstone.

Green, friable chlorite and muscovite schist layers vary from <1 m to 6 m in thickness. Locally, this subunit is coarse-grained and displays lensey fragmental textures. Other layers are pale, fine-grained, soft and very muscovite-rich. The coarse-grained examples may be metamorphosed lapilli tuff, while the fine-grained layers may represent strongly altered and metamorphosed fine-grained ash-rich beds.

Chert occurs locally at the base of the Transition Zone sequence, overlying portions of the mineralization. It contains up to 10% sulphide minerals as fracture-fillings and patches, and may be of hydrothermal origin. Other hard, reddish brown hematite-stained and biotite-rich cherty or quartzite beds occur higher in the Transition Zone.

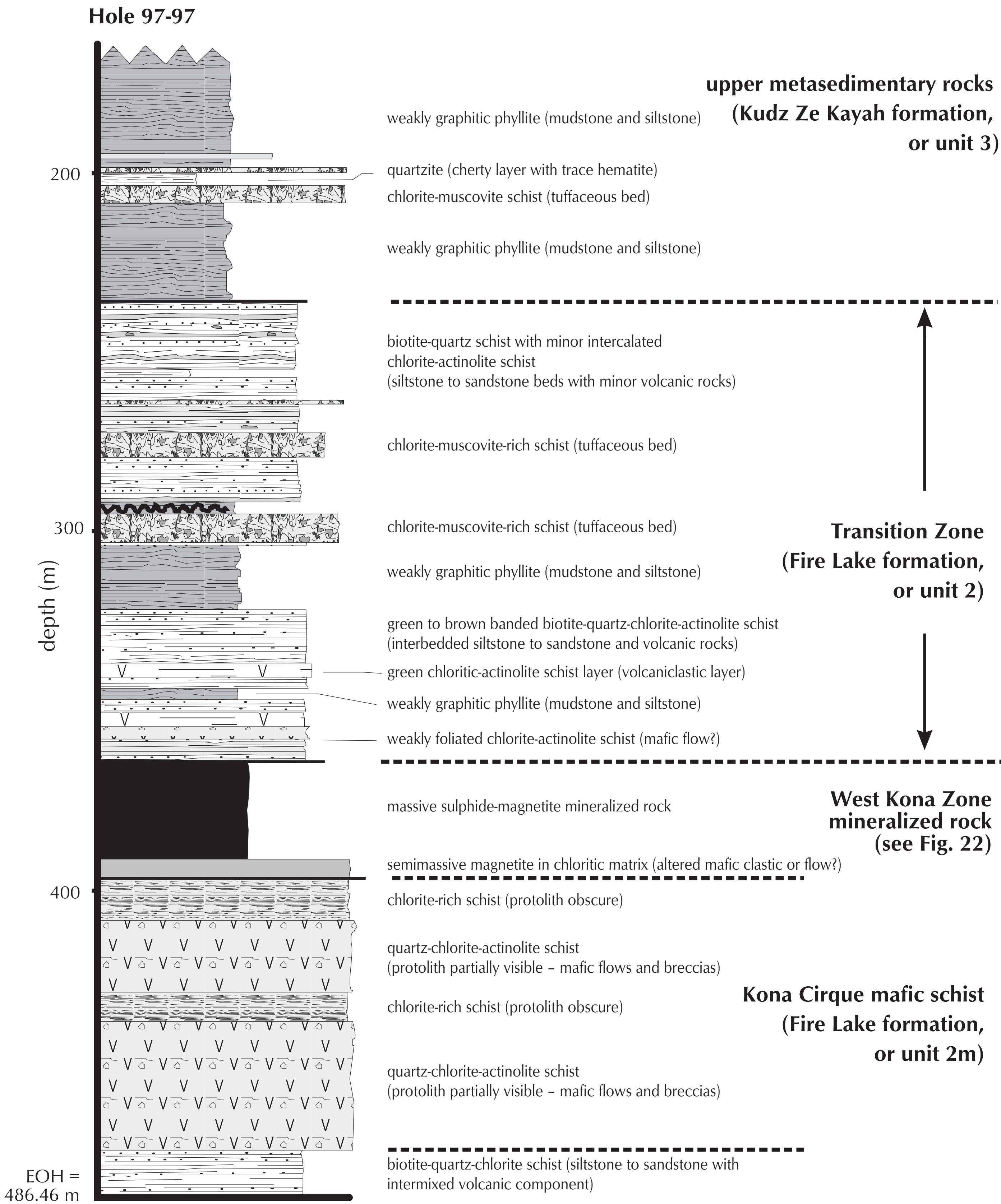


Figure 5. *Graphic log showing the stratigraphy of the Fyre Lake deposit in the area of the West Kona Zone as cored in Hole 97-97. The massive sulphide-magnetite mineralized rock is located at the contact between metasedimentary rocks of the Transition Zone (unit 2) above, and metavolcanic rocks of unit 2m below. Semimassive magnetite and variably chlorite-rich mafic schist of unit 2m directly underlie the massive mineralization.*

Notably, the Transition Zone contains original depositional textures. Bedding, load casts, angular unconformable contacts, flame structures, and centimetre-scale slump faults and folds are visible locally in the metasedimentary and metavolcanic rocks. The metasandstone and green metavolcanic layers contain rare mudstone fragments, and the bedding within the Transition Zone is commonly lensey and discontinuous. The original depositional textures and other features suggest that deposition of the sandy parts of the Transition Zone were in a moderate-energy regime. Scouring may have produced the angular unconformable contacts, ripped-up the mudstone fragments, and produced the discontinuous bedding. The small slump faults, folds and discontinuous bedding may be due to disturbance of the unconsolidated sediments by local shifting, compaction and sediment loading caused by local volcanic and tectonic activity.

The Transition Zone likely represents a period of waning volcanism combined with deposition of large volumes of quartzo-feldspathic sediment. The presence of meta-sandstone and -siltstone layers in the Kona Cirque mafic schist suggests that it and the Transition Zone are at least partly coeval. The phyllite layers in the Transition Zone likely represent mud and silt deposited in more quiescent periods of low-energy deposition.

Phyllite (Kudz Ze Kayah formation, or unit 3)

Carbonaceous, biotite-muscovite-quartz phyllites and pelitic schists make up the bulk of Kudz Ze Kayah formation. They are generally pale to dark grey, weakly graphitic and finely banded to laminated. Some less strained sections of phyllite consist of distinct alternating silty and muddy laminae up to 2 cm thick. Blanchflower (1997) interpreted the phyllites as metamorphosed finely bedded to laminated mudstone and siltstone, which may have been emplaced by small turbidites and settling of fine suspended clay and silt. Generally, the phyllite represents a distal quiescent sedimentary facies. Kudz Ze Kayah formation also contains minor layers of pale limestone, friable muscovite-chlorite schist and weakly micaceous quartzite layers (Blanchflower, 1997; Foreman, 1998; Hunt and Murphy, 1998).

LITHOGEOCHEMISTRY

Samples of Kona Cirque, Lake Zone, Outfitter's Creek, Kona Bowl and felsic metavolcanic rock were collected from drill core and outcrop. They were chemically analysed by ICP-MS at Activation Laboratories Ltd., Ancaster, Ontario. Five least-altered samples of the Kona Cirque mafic schist were collected away from known mineralization. Intervals containing large quantities of metamorphic quartz segregations and veins were avoided. Least-altered samples of the Kona Cirque mafic schist include three from the lower section of Holes 97-97 and 97-115 (Fig. 2) where original volcanic textures are visible and large degrees of metasomatism are unlikely. Table 1 provides a summary of the geochemical results.

GENERAL LITHOGEOCHEMISTRY OF THE INDIVIDUAL ROCK UNITS

Least-altered Kona Cirque mafic schist of the Fire Lake formation (unit 2m: Fig. 2 and 3) contains between 54 and 58% SiO_2 on a loss-on-ignition (LOI) -free basis (Fig. 6a), which is typical of an andesitic volcanic rock. However, it is strongly mafic in composition (Table 1). The magnesium content is high, ranging from 9% to 15% MgO (Fig. 6b); Fe content (reported as Fe_2O_3) is between 7.6 and 8.8% (Table 1). Cr and Ni contents are between 340 and 1030 ppm (Fig. 6c), and 110 and 310 ppm, respectively, and are equivalent to or greater than that found in normal mid-ocean-ridge basalt (NMORB; Fig. 7a). Most high field strength elements (HFSE[1]) are depleted compared to NMORB (Fig. 7a) and other tholeiites. For

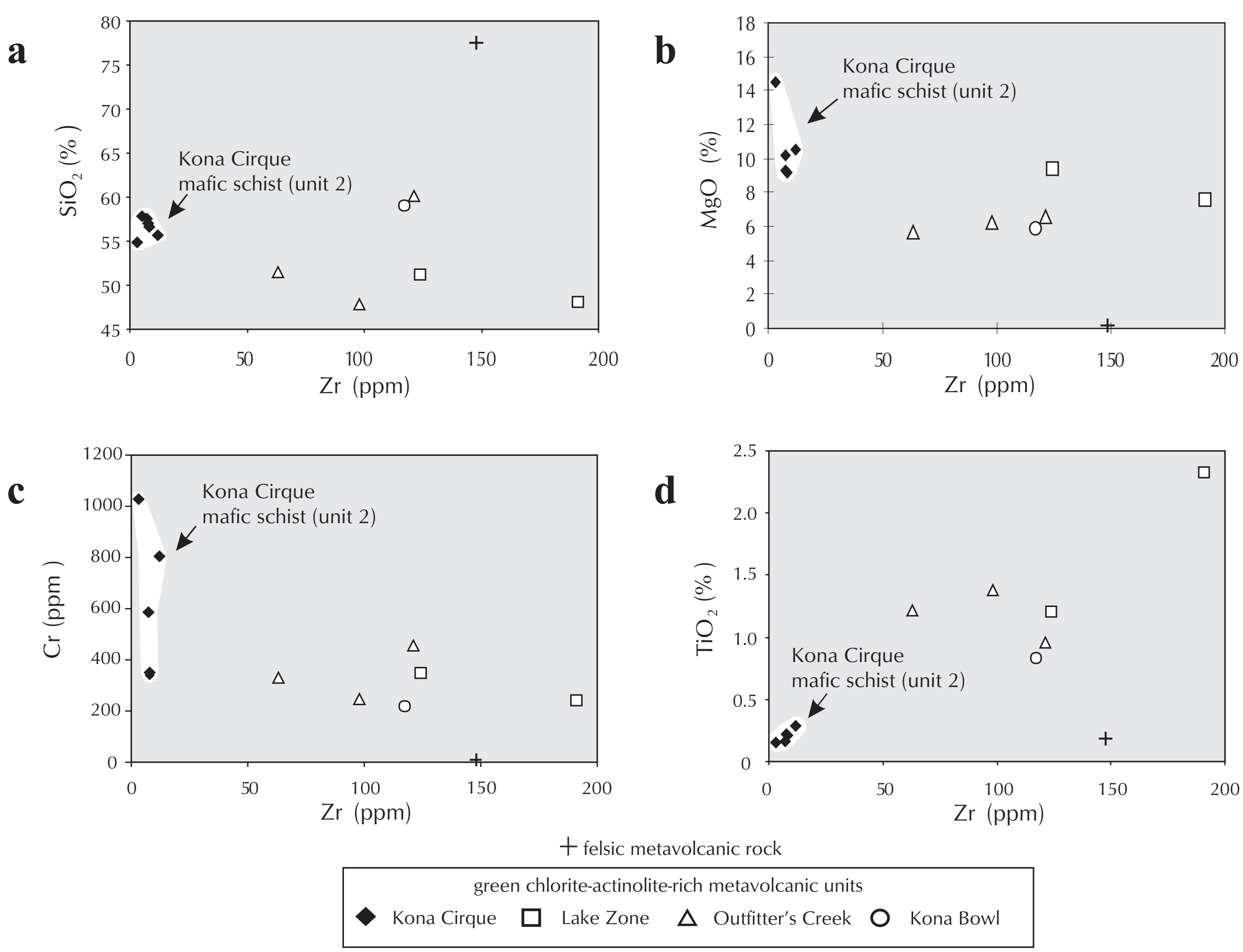


Figure 6. *Binary plots of:* ***(a)*** *SiO_2,* ***(b)*** *MgO,* ***(c)*** *Cr, and* ***d)*** *TiO_2, versus Zr for the metavolcanic rocks at the Fyre Lake property. Element concentrations are calculated on an LOI-free basis.*

[1]HFSE are elements with charge/size ratio >2, including the rare-earth series elements (La to Lu), Ti, Th, U, Ta, Nb, Hf and Zr.

Table 1a. *Composition of metavolcanic rocks from the Fyre Lake property.*

	Sample /Drill Hole depth (m)									
	97-97 -460.5	97-97 -446	UMEX2	97-115 -805.5	OStn 51	97-76 -36	97-78 -109	R0 STN24	R0 STN35	R0 STN26
	unit 2m					unit 2		unit 2		
	Kona Cirque mafic schist least-altered samples					Lake Zone		Outfitter's Creek Zone		
%										
SiO_2	55.50	55.54	53.88	56.29	53.19	49.57	47.15	46.73	50.46	59.35
TiO_2	0.21	0.21	0.28	0.16	0.15	1.17	2.28	1.35	1.19	0.95
Al_2O_3	13.51	14.10	13.10	12.08	10.83	16.19	17.11	15.91	17.31	13.24
Fe_2O_3	8.11	7.64	8.17	8.76	8.57	9.00	11.15	11.05	10.02	7.87
MnO	0.17	0.15	0.09	0.14	0.13	0.14	0.20	0.14	0.20	0.13
MgO	10.17	9.22	10.52	9.30	14.54	9.45	7.57	6.24	5.70	6.53
CaO	6.24	7.99	8.07	8.84	8.72	8.67	10.20	15.04	10.65	6.49
Na_2O	3.72	3.82	2.87	2.60	1.59	2.31	2.76	1.76	2.91	3.24
K_2O	0.50	0.26	0.58	0.38	0.16	0.79	0.38	0.23	0.44	1.48
P_2O_5	0.02	0.02	0.03	0.05	0.02	0.29	0.43	0.28	0.14	0.32
LOI	2.30	1.17	1.92	1.57	2.61	2.01	1.75	1.88	1.21	0.94
Total	**100.44**	**100.11**	**99.52**	**100.17**	**100.51**	**99.58**	**100.98**	**100.61**	**100.22**	**100.53**
ppm										
Cr	341	346	805	584	1029	351	244	245	330	457
Ni	116	112	210	177	310	131	142	62	61	41
Co	35	39	41	38	48	35	42	41	36	19
V	226	162	213	263	192	204	293	237	250	182
Cu	41	200	b.d.	85	38	b.d.	55	45	48	b.d.
Pb	6	14	b.d.	b.d.	b.d.	b.d.	b.d.	10	12	7
Zn	125	105	29	61	60	43	86	76	91	88
Rb	21	7.4	6.7	10	2.5	15	6.3	4.3	14	41
Cs	4.0	2.0	0.7	3.0	0.9	6.4	1.0	0.4	2.8	1.6
Ba	969	629	153	1024	90	492	94	140	199	1941
Sr	62	73	54	165	52	451	354	622	388	398
Ta	0.02	0.01	0.02	0.02	b.d.	0.61	0.66	0.17	0.11	0.76
Nb	0.6	0.6	0.7	b.d.	b.d.	10	11	4.2	2	12
Hf	0.3	0.3	0.4	0.3	0.2	3.5	4.7	2.5	1.9	3.4
Zr	7.7	8.1	12	7.2	3.3	124	191	98	63	121
Y	7.1	7.6	8.5	6.6	5	22	35	32	25	23
Th	0.10	0.10	0.16	0.11	0.07	10.60	2.26	0.73	0.36	7.00
U	0.09	0.21	0.12	0.25	0.07	1.16	0.59	0.22	0.18	2.15
La	0.44	0.41	0.69	0.55	0.29	33.8	16.8	13.9	4.71	28.1
Ce	1.01	0.97	1.56	1.17	0.67	62.6	40.2	26.3	10.2	51.8
Pr	0.13	0.14	0.22	0.15	0.09	6.76	5.02	3.69	1.64	5.67
Nd	0.87	0.91	1.37	0.89	0.54	31.5	28.2	20.8	10.7	26.9
Sm	0.34	0.37	0.54	0.32	0.23	5.73	6.55	5.01	3.26	5.18
Eu	0.12	0.18	0.20	0.10	0.10	1.56	2.14	1.60	1.12	1.27
Gd	0.63	0.65	0.83	0.50	0.44	4.47	6.41	4.99	3.88	4.32
Tb	0.15	0.16	0.21	0.13	0.11	0.78	1.20	0.95	0.78	0.78
Dy	1.17	1.20	1.44	0.97	0.78	4.28	6.88	5.63	4.70	4.38
Ho	0.27	0.29	0.35	0.24	0.20	0.85	1.40	1.14	1.00	0.88
Er	0.89	0.96	1.09	0.81	0.65	2.48	3.89	3.40	2.87	2.59
Tm	0.14	0.15	0.18	0.14	0.11	0.34	0.54	0.47	0.40	0.35
Yb	0.99	1.11	1.23	1.03	0.80	2.25	3.55	3.04	2.61	2.33
Lu	0.16	0.20	0.20	0.19	0.12	0.34	0.52	0.47	0.38	0.36

Table 1b. *Composition of metavolcanic and metasedimentary rocks from the Fyre Lake property.*

	Sample /Drill Hole depth (m)								
	97-112 -114.5	97-115 -605.4	97-115 -625.8	97-115 -650.55	97-115 -679.5	97-115 -676.9	97-115 -648.3	97-115 -613.45	JH97-75
	unit 2	unit 2			unit 2				unit 3f
	Kona Bowl	metasandstones Transition Zone			metavolcanics rocks Transition Zone				felsic metavolcanic rocks
%									
SiO_2	57.01	71.75	74.43	72.93	54.19	51.35	57.54	57.05	76.66
TiO_2	0.80	0.43	0.40	0.38	0.23	0.18	0.17	0.19	0.18
Al_2O_3	15.69	12.85	10.38	11.90	13.39	11.50	11.47	10.84	10.90
Fe_2O_3	7.96	4.75	4.76	4.35	9.43	9.40	9.27	9.04	1.69
MnO	0.10	0.10	0.15	0.12	0.24	0.24	0.25	0.54	0.02
MgO	5.93	3.44	2.84	3.34	10.97	13.01	11.23	11.64	0.14
CaO	5.74	1.18	2.57	1.75	6.50	8.54	6.38	6.63	1.52
Na_2O	2.51	1.90	2.07	2.32	1.19	1.62	1.45	0.72	0.25
K_2O	1.35	2.32	1.03	1.89	2.01	1.37	0.97	0.26	7.74
P_2O_5	0.21	0.08	0.11	0.44	0.04	0.02	0.03	0.02	0.04
LOI	3.35	1.74	1.40	0.99	2.20	1.93	2.14	2.83	1.59
Total	**100.64**	**100.54**	**100.14**	**100.38**	**100.38**	**99.16**	**100.89**	**99.75**	**100.74**
ppm									
Cr	223	35	44	47	646	1074	844	780	11
Ni	10	31	30	32	208	317	265	277	b.d.
Co	26	9.1	15	12	44	51	52	48	1
V	147	67	115	92	176	214	144	171	15
Cu	30	32	78	54	b.d.	b.d.	b.d.	b.d.	b.d.
Pb	25	26	29	14	10	10	7	6	15
Zn	95	76	76	98	91	94	160	115	26
Rb	44	47	39	61	53	35	35	7.4	193
Cs	1.6	4.5	3.7	7.0	8.3	5.5	4.9	1	1.2
Ba	950	4258	2116	6335	3224	2013	1648	327	2962
Sr	434	38.2	59.6	134	756	337	159	66.3	58
Ta	0.59	0.5	0.29	0.48	0.05	0.02	0.02	0.05	0.79
Nb	9.6	7.5	4.7	6.9	0.7	b.d.	b.d.	1	7.0
Hf	3.4	4.0	2.3	3.9	0.5	0.5	0.3	0.5	4.4
Zr	117	136	81	138	14	15	9.3	18	148
Y	19	22	18	22	7.0	6.6	7.1	6.6	24
Th	7.89	10.4	4.96	10.8	0.17	0.14	0.13	0.52	15
U	2.27	3.32	1.64	3.31	0.17	0.11	0.09	0.25	2.40
La	28.8	29.5	16.8	31.9	1.16	0.63	0.69	2.69	40.0
Ce	52.4	57.3	32.7	60.1	2.00	1.08	1.08	4.02	77.0
Pr	5.62	5.98	3.74	6.57	0.31	0.17	0.19	0.67	8.32
Nd	26.7	27.9	18.1	30.8	1.73	1.07	1.17	3.61	32.0
Sm	4.79	5.16	3.66	5.71	0.55	0.40	0.41	0.90	6.00
Eu	1.21	0.90	0.75	0.94	0.06	0.07	0.11	0.23	1.13
Gd	3.76	4.04	3.22	4.39	0.77	0.65	0.67	0.98	5.00
Tb	0.65	0.73	0.61	0.80	0.18	0.15	0.17	0.21	0.80
Dy	3.68	4.18	3.63	4.61	1.22	1.09	1.22	1.33	4.10
Ho	0.70	0.86	0.74	0.89	0.29	0.25	0.29	0.30	0.90
Er	2.08	2.56	2.29	2.69	0.93	0.80	0.96	0.93	2.50
Tm	0.29	0.38	0.34	0.40	0.15	0.13	0.16	0.15	0.35
Yb	1.91	2.63	2.30	2.61	1.09	0.93	1.18	1.07	2.20
Lu	0.29	0.40	0.36	0.41	0.17	0.16	0.20	0.17	0.34

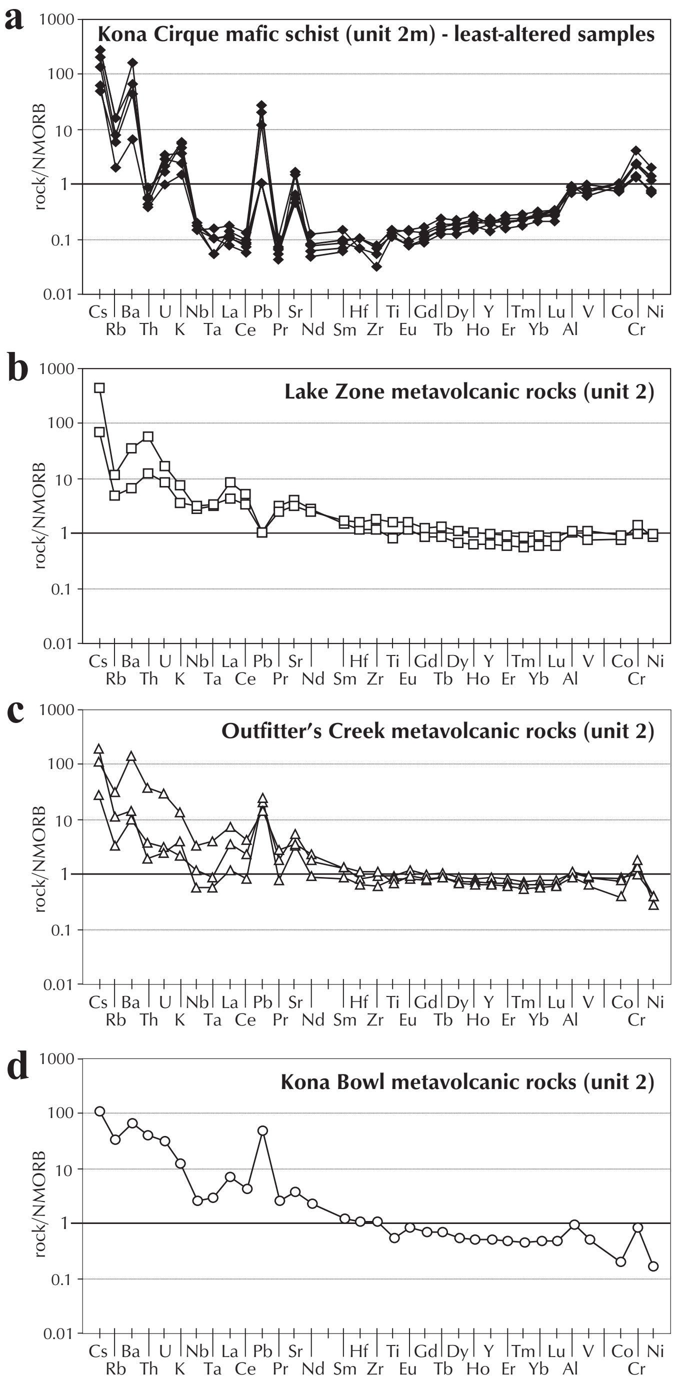


Figure 7. *NMORB-normalized spider diagrams for Fire Lake formation (unit 2) metavolcanic rocks.* ***(a)*** *Five least-altered samples of the Kona Cirque mafic schist (see Table 2).* ***(b)*** *Two samples from the Lake Zone metavolcanic rocks.* ***(c)*** *Three samples of green metavolcanic rocks from the Outfitter's Creek area.* ***(d)*** *One sample from green metavolcanic rock in Kona Bowl. See text for discussion. NMORB-normalizing values are from Hofmann (1988).*

example the TiO_2 content is atypically low, ranging from 0.15 to 0.3%; Zr contents are between 3 and 12 ppm (Fig. 6); and concentrations of rare-earth elements (REE) are lower than NMORB. In contrast, Pb, Th and U are enriched compared to REE, and equivalent to or higher than NMORB. Low field strength or large-ion lithophile element (LILE[2]) concentrations including Cs, Rb, Ba, K and Sr are also elevated with respect to the REE, and Cs, Ba, Rb and K are enriched compared to NMORB (Fig. 7a). The elevated LILE content must be viewed with caution as LILE elements may be reconcentrated by hydrothermal and metamorphic fluids. However, the pattern of LILE enrichment displayed by the least-altered samples is consistent and this suggests that the LILE enrichment in the Kona Cirque mafic schist may be a primary feature.

Chondrite-normalized REE patterns of five least-altered samples of Kona Cirque mafic schist display a distinctive spoon shape (Fig. 8a) and are depleted in light rare-earth elements (LREE[3]). Altered specimens display generally similar REE patterns to least-altered samples, excepting that europium (Eu) is depleted in many of the altered samples (Fig. 8b). Lanthanum (La) and cerium (Ce) are slightly enriched with respect to praseodymium (Pr) in most of the samples.

Two samples of Lake Zone metavolcanic rocks of the Fire Lake formation (unit 2, Fig. 2 and 3) are of volcaniclastic origin and their chemistry may have been modified by the addition of other detrital material and cement. Analysed samples display whole rock chemistry typical of basaltic volcanic rocks (Table 1), with SiO_2 contents between 47 and 50% (Fig. 6a). The content of MgO ranges from 7.5 to

Figure 8 (facing page) . *Chondrite-normalized rare-earth element plots.* ***(a)*** *Five least-altered samples of Kona Cirque mafic schist (unit 2m: see Table 2).* ***(b)*** *Ten variably altered samples from the Kona Cirque mafic schist (unit 2m) from Hole 97-115.* ***(c)*** *Two samples from mafic metavolcanic rocks of the Lake Zone (unit 2).* ***(d)*** *Three samples of green intermediate to mafic metavolcanic rocks from the Outfitter's Creek area (unit 2).* ***(e)*** *Green metavolcanic rock from Kona Bowl (unit 2).* ***(f)*** *Four samples from green metavolcanic rock layers contained in the Transition Zone metasedimentary rocks (unit 2) above the Kona West Zone.* ***(g)*** *Three samples of metasandstones in the Transition Zone (unit 2). Average upper crust composition is from Taylor and McLennan (1983).* ***(h)*** *Felsic metavolcanic rock (unit 3f). See text for discussion. Normalizing values are from Evensen (1978).*

[2]LILE, also known as low field strength elements, have a charge/size ratio <2 and include Cs, Ba, K, Rb and Sr.
[3]LREE include lanthanum (La), cerium (Ce), praesodymium (Pr) and neodymium (Nd).

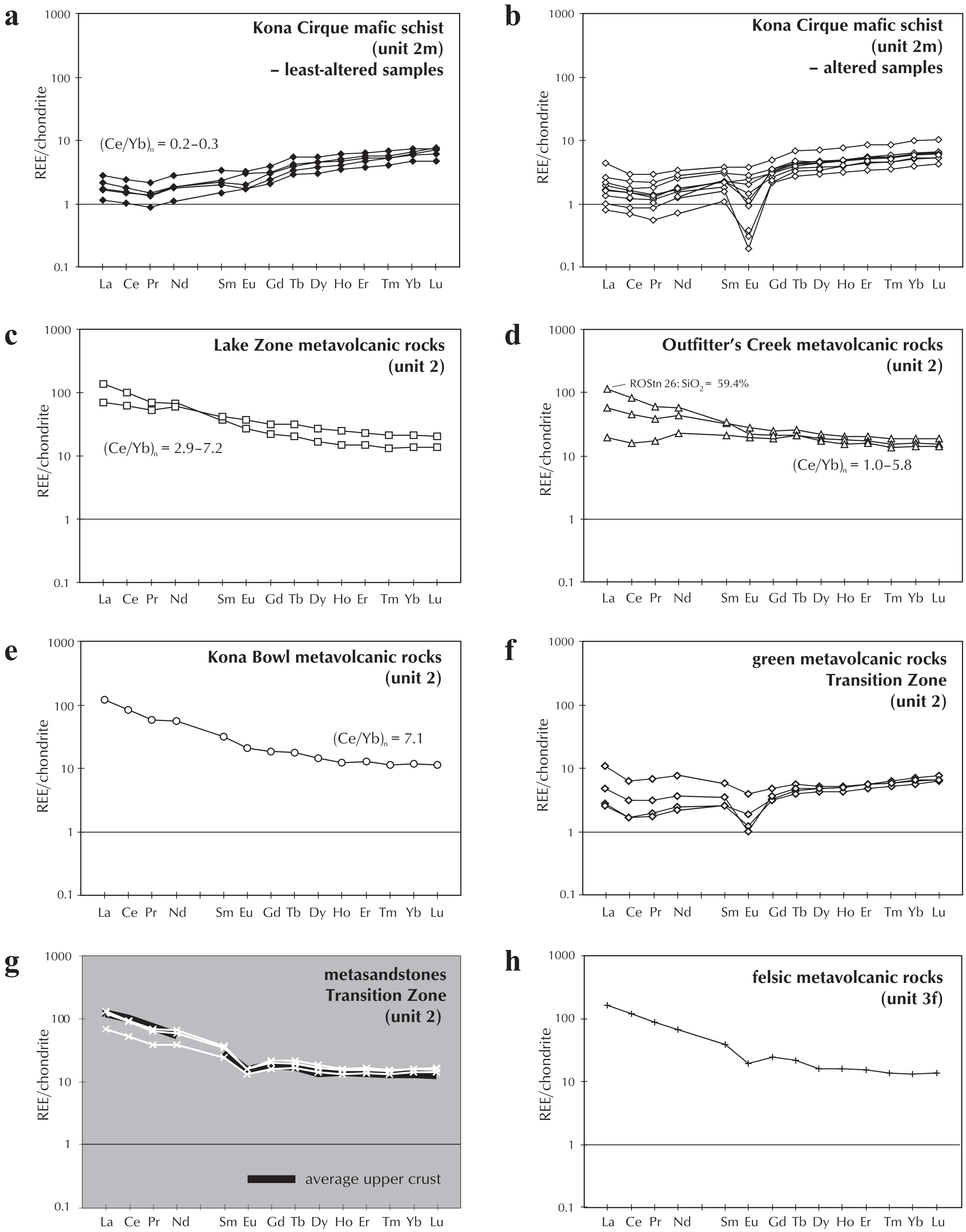


Figure 8. *(caption previous page)*

***Table 2.** Comparison of average compositions of selected rocks of boninitic affinity to the Kona Cirque mafic schist.*

		Chichijima boninites	Troodos, Cyprus Upper Pillow Lavas	Kopi boninite New Zealand	Tasmania Cleveland	Kona Cirque mafic schist
SiO_2	%	59.30	54.05	54.69	51.80	56.34
TiO_2	%	0.14	0.24	0.19	0.23	0.21
Al_2O_3	%	11.33	12.72	13.44	14.65	13.06
Fe_2O_3	%	9.78*	2.18	3.10		
FeO	%		6.10	6.39	9.90*	7.62*
MnO	%	0.17	0.15	0.18	0.18	0.14
MgO	%	12.72	12.39	11.48	9.76	11.04
CaO	%	7.50	11.05	10.92	11.37	8.18
Na_2O	%	1.67	0.91	1.50	1.69	3.00
K_2O	%	0.46	0.22	0.13	0.37	0.39
P_2O_5	%	0.02	0.02	0.01	0.05	0.03
Cr	ppm	919	797	1133	n.a.	621
Ni	ppm	235	265	224	111	185
V	ppm	190	218	n.a.	437	211
Nb	ppm	n.a.	2	<2	n.a.	<1
Zr	ppm	19	10	9	11	8
Y	ppm	4	8	8	13	7

* Total Fe averages are LOI free.
n.a. = not available
Average for Chichijima is of data from Taylor et al. (1994).
Average for Troodos is of Type III lavas from Cameron (1985).
Kopi average is from Wood (1980).
Average of Tasmanian rocks is from data of Brown and Jenner (1989).

9.5% (Fig. 6b) and TiO_2 contents are between 1.2 and 2.3%, and are equivalent to or higher than NMORB (Fig. 6d and 7b). Chromium content in Lake Zone metavolcanic rocks is slightly higher than in the average NMORB (Fig. 7b), while levels of Ni and Co are roughly equivalent to NMORB. Zr and Th contents range from 120 to 190 ppm, and 2.3 to 10.6 ppm, respectively, and are significantly elevated compared to NMORB. Nb, Ta, LREE and most LILE are also higher with respect to NMORB, while the heavy rare-earth elements (HREE[4]) are slightly lower. Chondrite-normalized REE profiles for the Lake Zone samples exhibit LREE enrichment, with a fairly smooth increase from HREE to LREE (Fig. 8c).

Three samples of Outfitter's Creek metavolcanic rocks from the Fire Lake formation (unit 2: Fig. 2 and 3) include both flow (ROStn 24 and 35) and fine-grained volcaniclastic rocks (ROStn 26). The metavolcaniclastic sample contains about 59% SiO_2, but this value may be higher due to the addition of felsic detritus. The two metaflow samples of Outfitter's Creek metavolcanic rocks contain between 46 and 51% SiO_2 (Table 1 and Fig. 6a). MgO in the Outfitter's Creek metavolcanic rocks is between 5.7 and 6.5% (Fig. 6b), and TiO_2 varies between 0.9 and 1.4% (Fig. 6d). Cr contents range from 240 to 460 ppm, which is equivalent to NMORB (Fig. 6c). Ni content is 41 to 62 ppm and somewhat lower than levels found in NMORB. Zr content is between 63 and 121 ppm and on average slightly lower than NMORB. The levels of Ta and Nb are between 0.1 and 0.2, and 2 to 4 ppm respectively, in the metaflow samples, and are equivalent to, or slightly lower than levels in NMORB (Fig. 7c). Also, Ta and Nb are depleted with respect to La, Ce and Th. Th, U and LILE are enriched compared to NMORB while HREE concentrations are slightly depleted compared to NMORB (Fig. 7c). Two samples of Outfitter's Creek metavolcanic rocks display LREE enrichment, including the volcaniclastic sample, while the second metaflow rock samples display a flat REE pattern (Fig. 8d). Compared to the metavolcaniclastic rocks of the Lake Zone, the metaflow rocks in the Outfitter's Creek area are less enriched in HFSE and LREE (Table 1 and Fig. 7) and contain less MgO and Ni (Table 1).

One sample was taken of the metavolcanic rocks cored at the mouth of Kona Bowl (Fire Lake formation, or unit 2: Fig. 2). It is massive in appearance and is interpreted as a lava flow rock. It has an intermediate chemical composition with a SiO_2 content of ~57%. Compared to NMORB (Fig. 7d), Cr content is similar at 223 ppm, while Ni, Co, Ti and HREE concentrations are lower. The Zr content is slightly elevated with respect to NMORB, while Th, U, LILE and the LREE are significantly elevated (Fig. 7d). Nb and Ta are relatively depleted compared to La and Ce. The chondrite-normalized REE pattern of the Kona Bowl sample is LREE enriched (Fig. 8e).

Green chlorite-actinolite schist or Transition Zone metavolcanic rocks (Fire Lake formation, or unit 2: Fig. 3) taken above the massive sulphide mineralized zone are chemically similar to samples of the Kona Cirque mafic schist (see Table 1). Four samples were analysed and these contain low HFSE concentrations, are high in MgO, Cr and Ni and have somewhat similar REE patterns (Fig. 8f). This chemical result is significant in that it implies that there is interfingering between the Kona Cirque mafic schist and the felsic metasedimentary rocks of the Transition Zone.

[4]HREE include Erbium (Er), Thulium (Tm), Ytterbium (Yb) and Lutetium (Lu).

Three samples of Transition Zone metasandstone (Fire Lake formation, or unit 2: Fig. 3) taken above the sulphide mineralization contain SiO_2 in excess of 71%. Al_2O_3 content ranges between 10 and 13%, and TiO_2 content is about 0.4%. The combined MgO and Fe (as Fe_2O_3) content is >7.5%. The chondrite-normalized REE patterns of the metasandstone samples display strong LREE enrichment, which is similar to that displayed by average upper crust (Fig. 8g).

Only one sample of potassium feldspar-porphyritic felsic metavolcanic or metaplutonic rock (Kudz Ze Kayah formation, or unit 3f, Fig. 3) was analysed. It has a rhyolitic composition and contains 76.7% SiO_2, 10.9% Al_2O_3, 0.18% TiO_2, and <2% combined MgO and Fe_2O_3 (Table 1). The felsic metavolcanic rock is LREE-enriched (Fig. 8h) and the chondrite-normalized profile displays a significant change in slope at Eu. The REE pattern is similar to those of the metasandstones in the Transition Zone (Fig. 8g).

ASSESSMENT OF THE MAGMATIC AFFINITY AND PROVENANCE OF THE METAVOLCANIC ROCK UNITS

The Kona Cirque mafic schist of the Fire Lake formation (unit 2m), which hosts the Fyre Lake mineral deposit is distinctly chemically different from other green chlorite-actinolite metavolcanic rocks (unit 2) on the property. The Kona Cirque mafic schist contains more MgO and Cr (Fig. 6b and 6c), less Al_2O_3 (Table 1), and substantially less TiO_2 (Fig. 6d) and Zr (Fig. 6). Also, REE patterns for Kona Cirque mafic schist samples are spoon-shaped and LREE-depleted whereas other mafic/intermediate metavolcanic rocks of Fire Lake formation display LREE enrichment (Fig. 8).

The Kona Cirque mafic schist displays a primitive mafic chemistry combined with intermediate levels of SiO_2 and uncommonly low concentrations of HFSE. The low HFSE content of the Kona Cirque mafic schist suggests that the volcanic protolith was derived from a depleted source region. The Kona Cirque mafic schist is broadly similar in composition to boninitic rocks such as those found at Chichijima, Bonin Islands or in the Troodos Ophiolite (Table 2). However, the chemistry of the Kona Cirque mafic schist displays some dissimilarities to boninites erupted in primitive island arcs such as those at Chichijima. Boninites erupted in primitive island arcs tend to display elevated LILE, LREE and Zr with respect to Ti, middle rare-earth elements (MREE) and frequently HREE (Beccaluva and Serri, 1988). In contrast, samples of the Kona Cirque mafic schist are consistently LREE-depleted and their spoon-shaped REE patterns are significantly different from the bowl-shaped patterns of the Chichijima boninites (Fig. 9). Compared to the Chichijima boninites, the Kona Cirque mafic schist has a lower Zr content (generally <15 ppm) and significantly higher Ti/Zr ratios (see Table 2).

The composition of the Kona Cirque mafic schist most closely resembles that of refractory, transitional, high-Ca boninites as classified by Beccaluva and Serri (1988), and Crawford et al. (1989). Examples of such rocks include Type III lavas contained in the Upper Pillow Lavas and Arakapas Fault Belt of the Troodos Ophiolite, Cyprus (e.g., Cameron, 1985). These rocks are chemically very similar to the Kona Cirque mafic schist (Table 2), and contain about 54% SiO_2, 12% MgO, extremely low concentrations of Zr (usually <20 ppm, frequently <10 ppm), and Nb concentrations near the detection limit (~2 ppm). The REE patterns of the Kona Cirque mafic schist and Type III lavas are also similar. Both

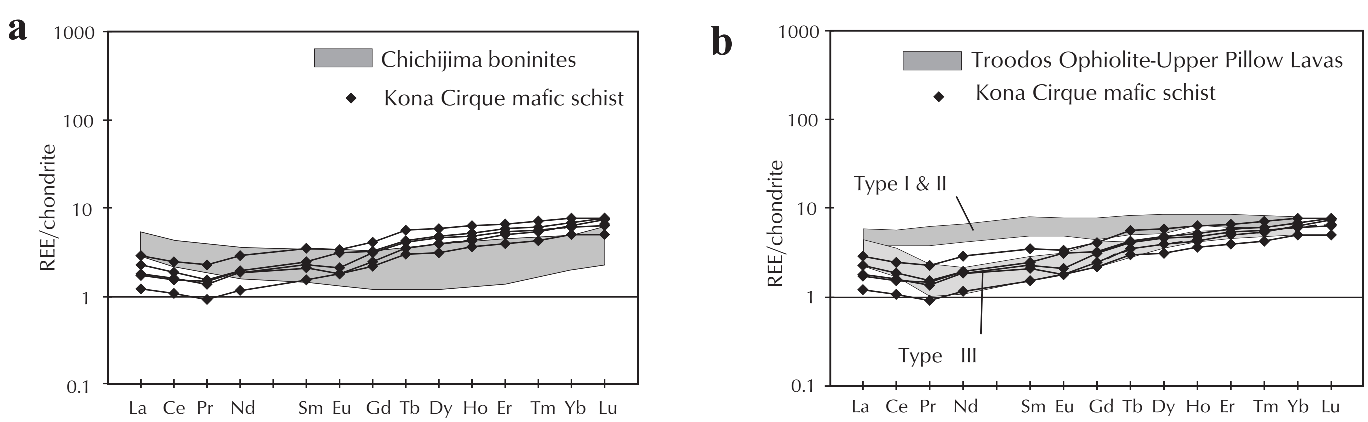


Figure 9. *Chondrite-normalized rare-earth element plots compare the Kona Cirque mafic schist (unit 2m) to other rocks of boninitic affinity.* ***(a)*** *Comparison to the Chichijima boninites (data from Taylor et al., 1994).* ***(b)*** *Comparison to the Troodos Ophiolite Upper Pillow Lavas and Arakapas Fault Belt Types I, II and III (data from Cameron, 1985).*

rocks display spoon-shaped profiles with general LREE depletion and slight enrichment of La and Ce relative to Pr and Nd (Fig. 9b).

The lavas of the Troodos Ophiolite are interpreted to have erupted in a rifted forearc or backarc setting given their depleted HFSE contents compared to MORB, spoon-shaped REE patterns and variable ε^{Nd} values (e.g., Pearce, 1975; Cameron et al., 1983; Cameron, 1985; Flower and Levine, 1987; Lytwyn and Casey, 1993). Given its chemical similarity to some of the Troodos lavas, the Kona Cirque mafic schist may also have been erupted in a rifted arc setting. This supposition is reinforced by the LILE enrichment displayed by the Kona Cirque mafic schist, which is a characteristic of arc-related volcanic rocks (e.g., Perfit et al., 1980; Pearce, 1982). Initial chemical data suggests that the Lake Zone metavolcaniclastic rocks were derived from volcanic rocks with chemical features of both primitive tholeiitic and more evolved calc-alkaline volcanic rocks. Like calc-alkaline volcanic rocks, the Lake Zone metavolcanic rocks are enriched in LREE, Th, U and LILE compared to NMORB, but their Cr, Ni, Co and MgO content is elevated and more like that of primitive tholeiitic volcanic rocks such as NMORB (Fig. 7b). Ratios of relatively immobile elements of differing compatibility such as Zr/Y can provide an indication of magmatic affinity (MacLean and Barrett, 1993). Zr/Y ratios vary between 5.5 and 5.6 for the Lake Zone rocks and are equivalent to those of transitional volcanic rocks (Fig. 10). The Lake Zone samples display slight depletion in Nb and Ta relative to LREE, which is a feature suggestive of arc-related volcanic rocks (Fig. 7b). The LREE enrichment in the Lake Zone metavolcanic rocks is similar to volcanic rocks erupted in mature arc settings containing continental-style crust such as the Sunda Arc (described by Whitford et al., 1979, Fig. 11a). However, unlike many arc-related basalts, the Lake Zone rocks contain higher levels of LREE and HFSE and bear similarity to within-plate volcanic rocks such as EMORB (enriched MORB) and OIB (oceanic island basalt), and also to some continental flood basalts (Fig. 12). Ti/V ratios for the Lake Zone metavolcanic rocks fall within the range for rift-related backarc basalts (Fig. 13).

Outfitter's Creek metavolcanic rocks tend to be enriched in LREE and LILE, Th and U with respect to NMORB, but display depletion of Nb and Ta with respect to LREE

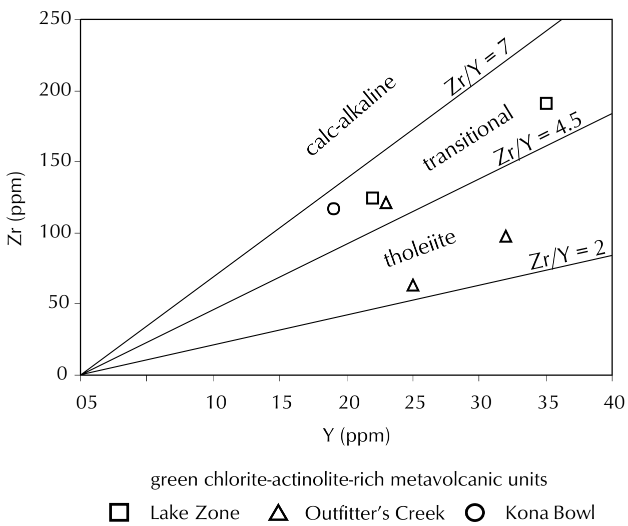


Figure 10. *Zr versus Y discrimination plot for determining the magmatic affinity of volcanic rocks (Barrett and MacLean, 1999). Plotted samples are of unit 2 metavolcanic rocks from the Lake Zone, Outfitter's Creek and Kona Bowl. See text for discussion.*

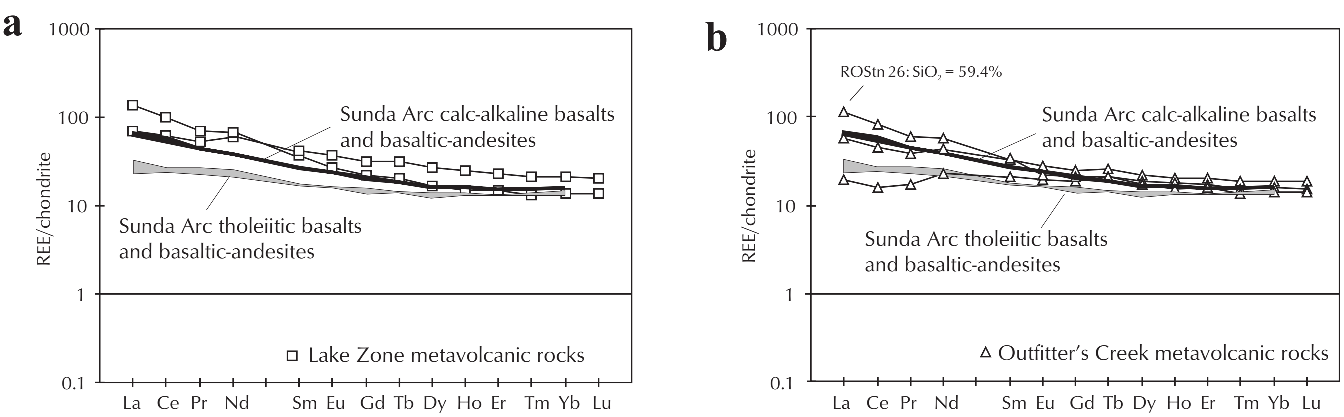


Figure 11. *Comparison of REE profiles of the* ***(a)*** *Lake Zone metavolcanic rocks and* ***(b)*** *Outfitter's Creek area metavolcanic rocks to average basalt and basaltic-andesite of tholeiitic and calc-alkaline affinity in the Sunda Arc, Indonesia. The Sunda arc data is from Whitford et al. (1979). See text for discussion.*

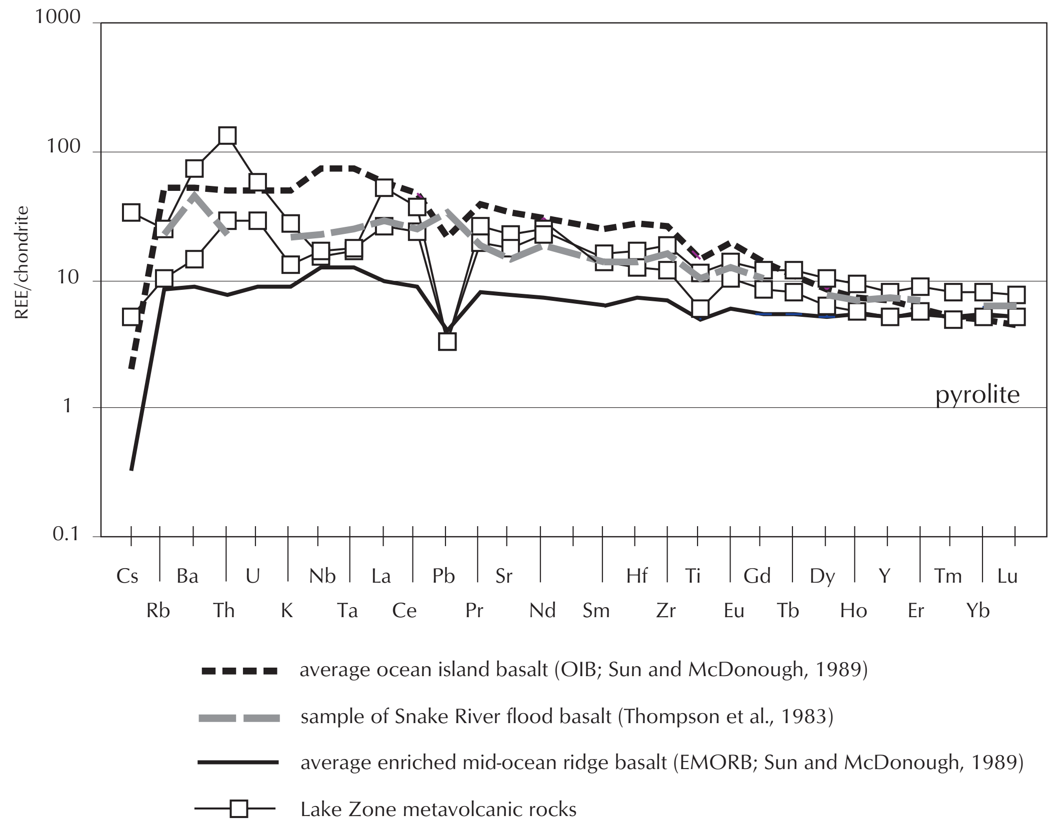


Figure 12. *A comparison of Lake Zone metavolcanic rocks to average EMORB, average ocean island basalt (OIB) and a sample of Snake River continental flood basalt. See text for discussion.*

(Fig. 7c). These chemical features are typical of arc-related magmas. Zr/Y ratios of the two meta-flow rock samples are 2.5 and 3.1, commensurate with those found in tholeiitic volcanic rocks (Fig. 10). The levels of LREE enrichment in the Outfitter's Creek metavolcanic rocks range from less than in the Sunda Arc tholeiites to just under that found in the Sunda calc-alkaline rocks (Fig. 11b). Like the Lake Zone, the metavolcanic rocks in the Outfitter's Creek area can be classed as transitional volcanic rocks. The Ti/V ratios of the two basaltic meta-flow rock samples from Outfitter's Creek are >20 and fall within the range for rift-related backarc basalts (Fig. 13).

The sample of green metavolcanic rocks from Kona Bowl is of intermediate composition and LREE-enriched. Zr/Y ratios are similar to those found in transitional volcanic rocks (Fig. 10). Like the Outfitter's Creek metavolcanic rocks, it displays depletion of Nb and Ta relative to LREE (Fig. 7d), which suggests it was derived in an arc setting.

Generally, the chemistry of the Transition Zone metasandstone is similar to sediments deposited in a mature tectonic setting. The TiO_2 content is lower than that generally found in modern oceanic arc settings and is more

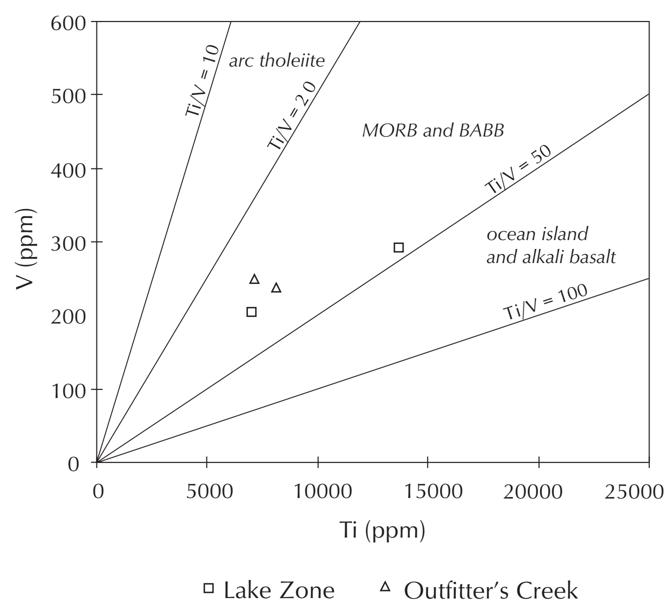


Figure 13. *V versus Ti discrimination diagram (after Shervais, 1982). Samples from the Lake Zone volcaniclastic rocks and mafic samples from Outfitter's Creek have Ti/V ratios commensurate with those of rift-related back-arc basalt (BABB).*

similar to that found in sediments at a continental margin (Fig. 14a). Al_2O_3/SiO_2 ratios are also similar to those found in continental arcs or margins (Fig. 14b). In contrast, the combined Fe_2O_3 and MgO content is elevated and somewhat similar to that found in some oceanic arcs (Fig. 14). However, it must be considered that these elements were enriched in the rocks by hydrothermal processes related to the West Kona mineralization lying below.

The sample of felsic metavolcanic or metaplutonic rock (Kudz Ze Kayah formation, or unit 3f) has an LREE-enriched pattern similar to that displayed by other Kudz Ze Kayah formation felsic metavolcanic rocks and to Simpson Range metaplutonic rocks sampled regionally by Piercey et al. (1999). The high Th (15 ppm) and low TiO_2 content (0.18%), and LREE enrichment in the felsic metavolcanic rock is suggestive of derivation in an evolved tectonic setting and/or melting of crustal material. Piercey et al. (1999) have suggested that the Kudz Ze Kayah formation felsic metavolcanic rocks mapped regionally are chemically similar to calc-alkaline felsic rocks erupted in a continental-arc setting.

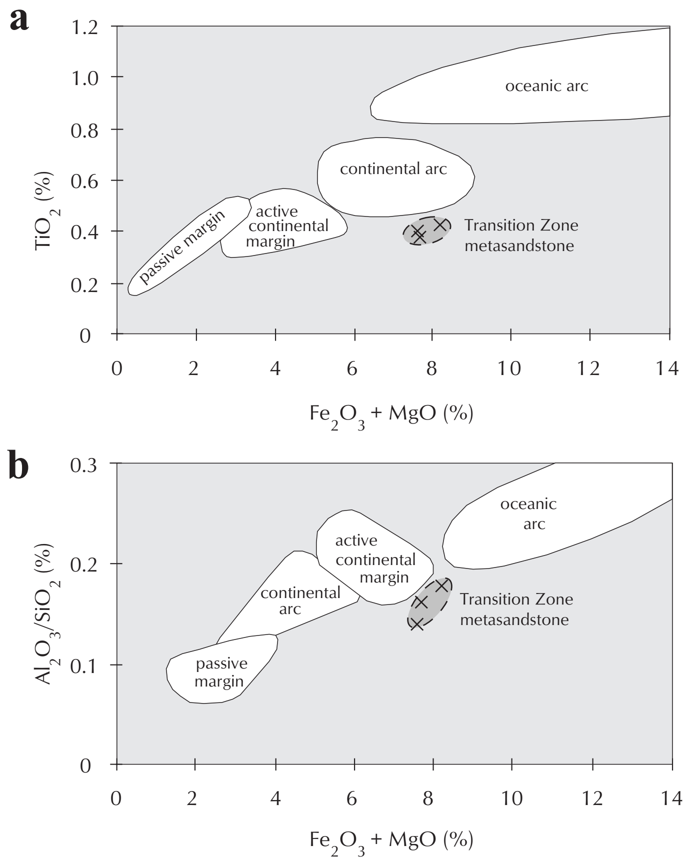


Figure 14. *Tectonic discrimination diagrams for sandstones (from Bhatia, 1983).* ***(a)*** *TiO_2 versus Fe_2O_3+MgO plot;* ***(b)*** *Al_2O_3 versus Fe_2O_3+MgO plot. Three samples from the Transition Zone metasandstones (unit 2) plot close to the field of sandstones derived from a continental arc.*

ARCHITECTURE OF THE FYRE LAKE DEPOSIT

DEPOSIT MORPHOLOGY AND STRUCTURE

Mineralization within the Fyre Lake deposit occurs in two zones, labeled the East and West Kona (Deighton et al., 1997; Foreman, 1998). Two stacked lenses of stratiform massive and semi-massive sulphide minerals and magnetite — the Upper and Lower horizons — form the East Kona Zone (Figs. 15, 16, 17 and 18). Both lenses have been drill tested for a strike length of at least 1000 m and a width of 100 to 200 m. The Upper Horizon is up to 12 m thick and is located immediately below the contact between metasedimentary and metavolcanic strata. Locally, at the western periphery, the Upper Horizon overlies metasiltstone and metasandstone layers. The Lower Horizon is up to 16 m thick and lies about 40 to 80 m below the Upper Horizon. The West Kona Zone consists of one stratiform massive to semimassive sulphide-magnetite-rich lens located at the metasedimentary to metavolcanic contact (Fig. 15 and 16). It is up to 44 m thick on its northeastern edge, and has been drill-tested over a strike length of 1420 m, and a width of 75 to 125 m (Foreman, 1998). All three mineralized lenses dip moderately (20–40°) to the east and plunge shallowly (5–15°) to the south (Foreman, 1998). The 1160 cross-fault offsets the lenses at the mouth of Kona Cirque.

The sulphide mineral and magnetite lenses are elongated in a northwest to southeast direction parallel to the L_1 lineation and to an inferred step fault, which appears to separate the East and West Kona zones (Fig. 15 and 16). The step fault is inferred from the >100 m down-drop of the western side of the deposit with respect to the eastern side, based on the different relative elevations of the metasedimentary/metavolcanic contact (Foreman, 1998; Fig. 16). The Transition Zone metasedimentary rocks also thicken abruptly to the west across this step structure. The presence of metasandstone layers within the Kona Cirque mafic schist located between the Upper and Lower horizons, and of green metavolcanic rocks chemically similar to the Kona Cirque mafic schist in the Transition Zone suggests that there also is a facies change across the step fault. Overall, the geologic data implies that the stepped offset of the underlying Kona Cirque mafic schist is an older, syngenetic fault.

A similar step fault appears to down-drop the stratigraphy to the west of Holes 96-49 and 96-69 on section 111600 and 111700 (Fig. 15). The area to the west of this structure remains to be explored for additional sulphide mineral-magnetite mineralization. Another step fault offsets the contact between metavolcanic and metasedimentary rocks in the east between Holes 61 and 62 (Fig. 15). However, there is no change in thickness of the metasedimentary rocks across this eastern structure. It may be a post-depositional reverse fault related to the Money Creek thrust.

MINERALOGY, TEXTURE AND STRUCTURE OF THE SULPHIDE LENSES

The mineralized lenses consist of single and multiple layers of semi-massive (<50%) and massive (>50%) sulphide minerals and magnetite. At Fyre Lake, pyrite is the dominant sulphide mineral (e.g., Photo 6), with lesser, but locally significant, amounts of pyrrhotite and chalcopyrite. The sulphide minerals occur as heavy disseminations, patchy bands or massive layers. Finely banded/layered sulphide beds are rare. Chalcopyrite and pyrrhotite commonly occur together and may be intergrown with pyrite or occur in gangue minerals as patches and small discontinuous bands. Sphalerite is a relatively minor phase that occurs locally.

Fine-grained magnetite is intimately intergrown and intercalated with sulphide minerals over large sections of the deposit and is disseminated or occurs in patches and conformable layers (Photo 7 and Figs. 19 to 22). Magnetite is dominant locally, and sections of the mineralized lenses consist almost entirely of finely banded magnetite iron formation up to 6 m thick. The beds of magnetite iron formation contain variable amounts of quartz bands, and minor sulphide minerals, carbonate and chlorite bands. Minor hematite occurs locally with the magnetite, and the magnetite iron formation is generally free of lithic detritus or relics.

The mixed banded magnetite-sulphide mineralization in the mineralized lenses sometimes displays discontinuous patchy to fragmental textures (Photo 7, lower). In places, it appears that fragmental magnetite, and also clastic quartz and sulphide minerals, were cemented and partially replaced by later sulphide minerals; a good example of such textures is contained in the intersection of Hole 97-95 (Photo 8) and 97-100 (Fig. 21).

Quartz is the dominant gangue mineral in the mineralized lenses. It forms the matrix to the sulphide minerals, but also occurs as discreet bands and patches. Trace amounts of carbonate minerals are present throughout the lenses, and significant amounts of chlorite are present locally in

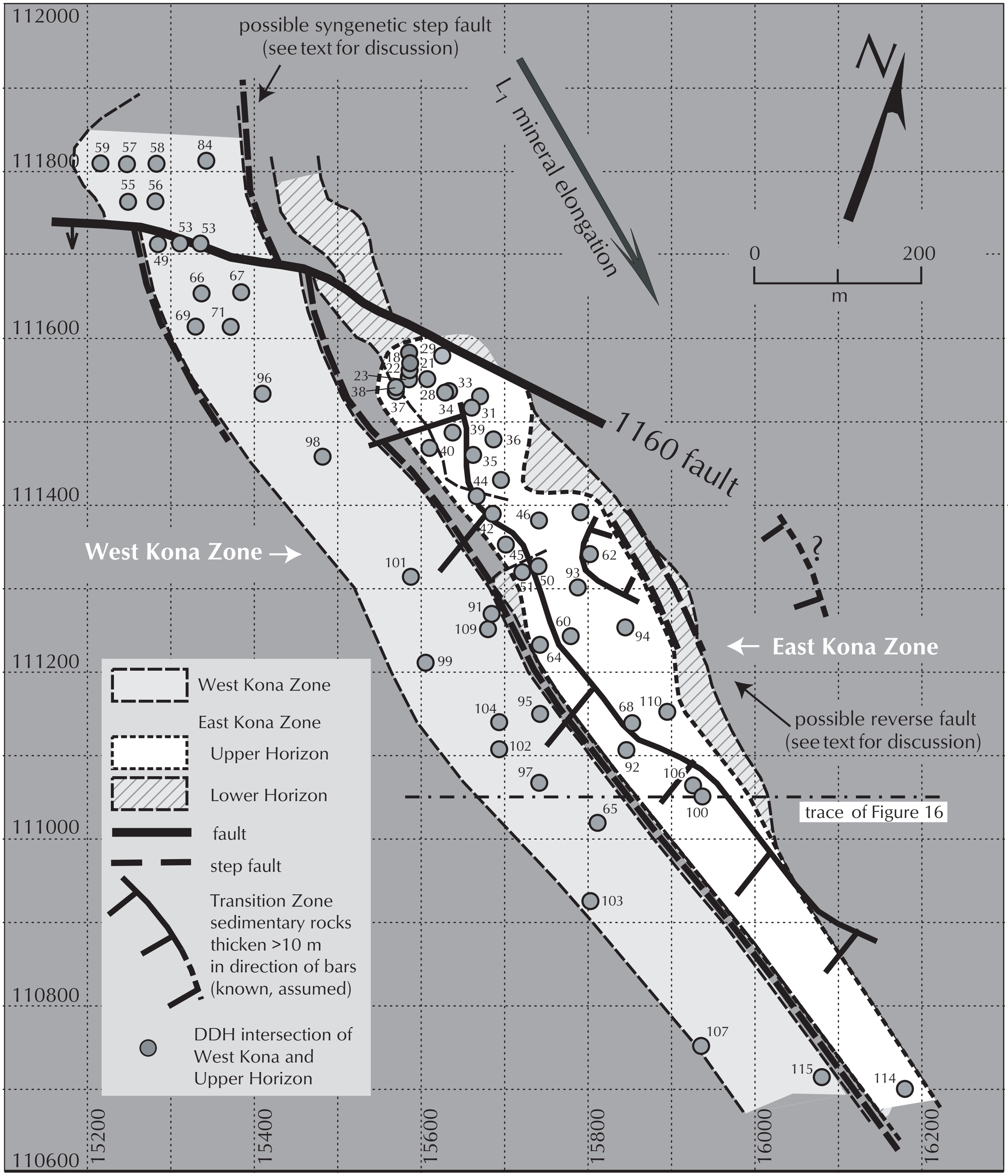


Figure 15. Plan view of the magnetite-sulphide zones of the Fyre Lake deposit. The West Kona Zone occurs to the west of an interpreted step fault, which separates it from the East Kona Zone (see text for discussion). The East Kona Zone is made up of two distinct stacked magnetite-sulphide-rich lenses termed the Upper and Lower horizons. The grid lines in the figure are local coordinates, which were used as a basis to interpret geology and construct drill sections.

semimassive mineralization, which may represent altered intercalated lithic material.

From a structural perspective, thicker drill intersections (>2 m) of the mineralized rock in the three lenses to the southeast of the 1160 fault are typically multilayered or composite in nature (Fig. 17 and 18). Graphic logs of Holes 96-37, 96-18, 97-100 and 97-97 (Figs. 19 to 22) provide examples of composite-style intersections in the East and West Kona zones.

A general description of composite mineralization is as follows. Quartz-rich layers containing sulphide minerals and/or magnetite locally mark the top of the lens (e.g., Hole 97-97: Fig. 22). These likely represent cherty exhalites. Generally, the upper part of the composite mineralization consists of fine-grained pyrite-rich sulphide minerals (Photo 6, upper) with a quartz-rich matrix. This upper pyritic sulphide lens may be up to 10 m thick, and locally contains pyrrhotite and significant quantities (up

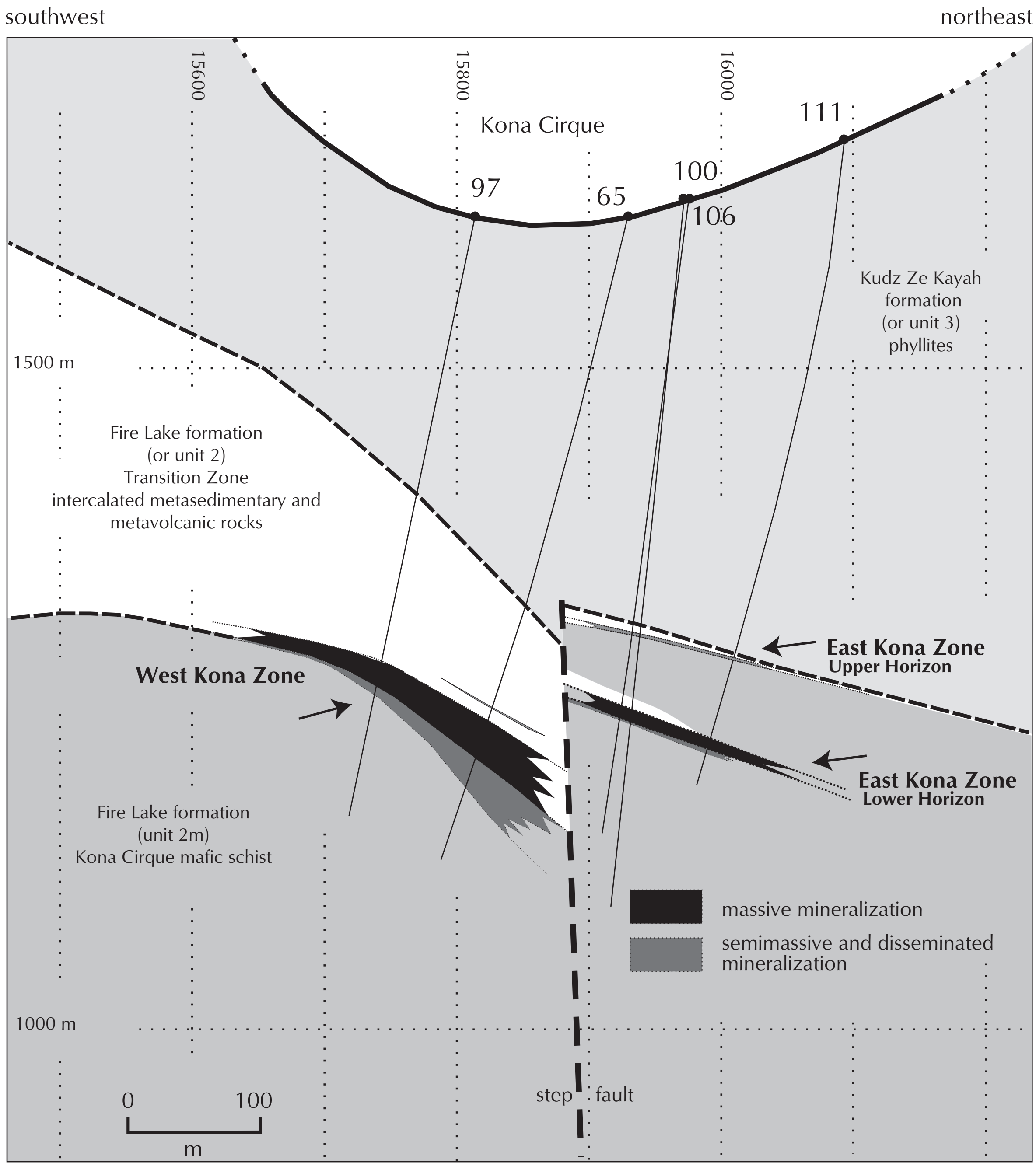


Figure 16. *Simplified geologic section through the East and West Kona zones. Trace of section is shown on Figure 15.*

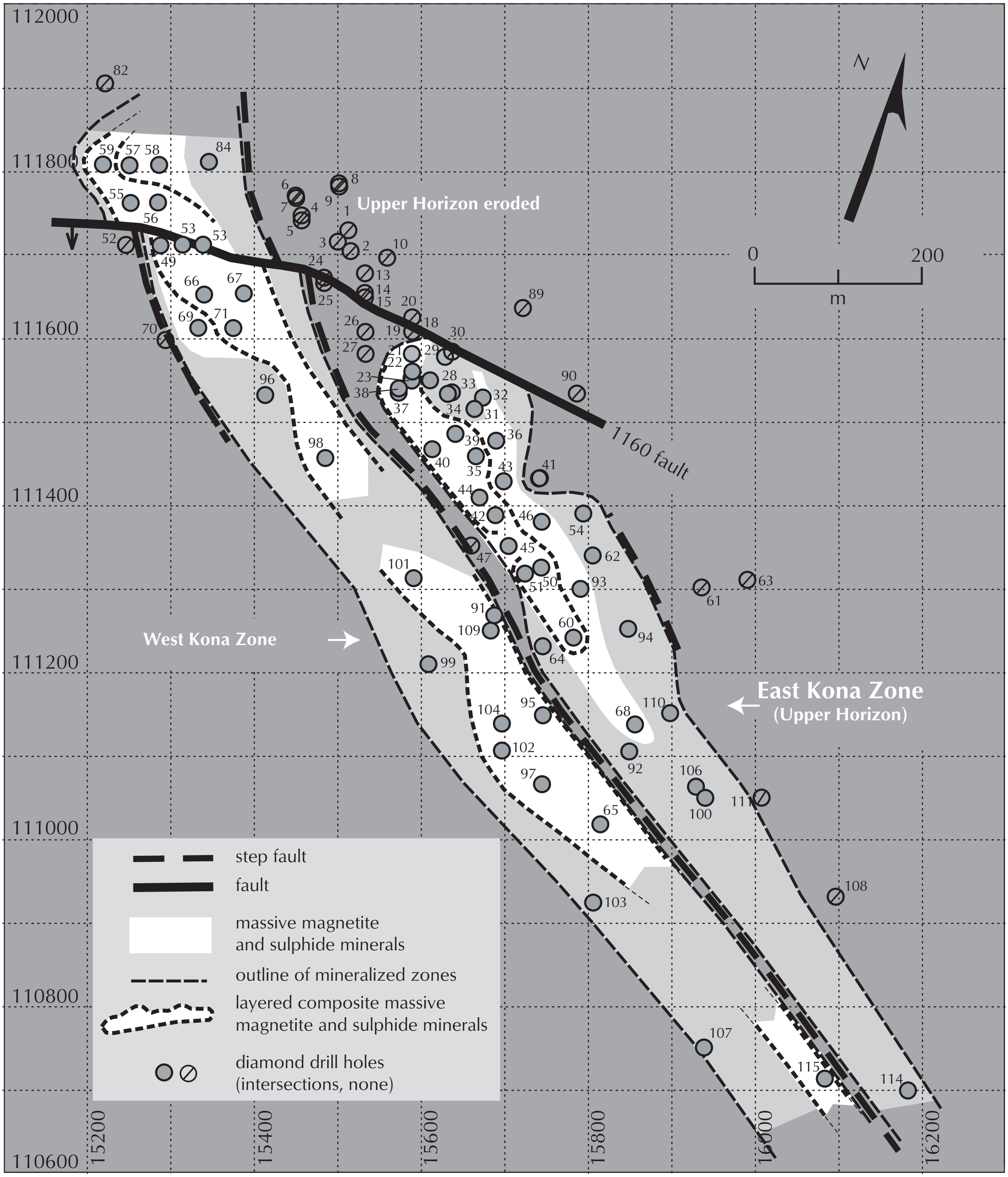


Figure 17. Plan view of the West Kona Zone and Upper Horizon, East Kona Zone. Massive (>50%) sulphide-magnetite mineralization occurs in the light areas. Composite, layered massive mineralization is outlined by the dashed line. Semimassive to disseminated mineralization, much of it hosted in chlorite-rich schist, forms the balance of the two mineralized lenses.

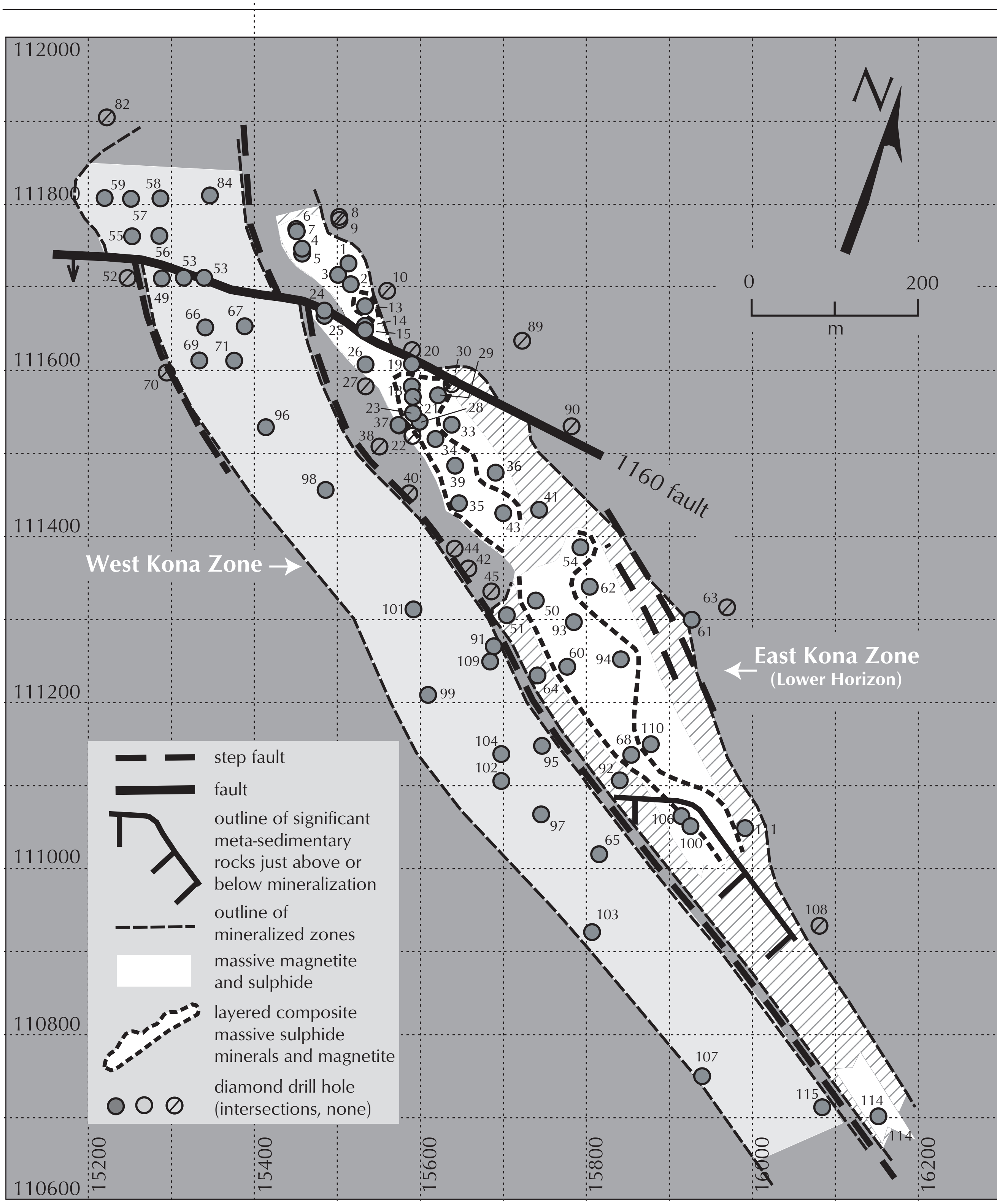


Figure 18. *Plan view location of massive (>50%) sulphide and magnetite in the Lower Horizon, East Kona Zone is marked by the light areas. Composite, layered massive mineralization is outlined by the dashed line. The balance of the Lower Horizon (hatched) is made up of semi-massive and disseminated mineralization. Biotite-quartz-rich metasandstones are contained in the chlorite-rich schists in the hanging wall and footwall of the mineralization in the southern portion of the zone.*

to 7%) of disseminated and patchy chalcopyrite (Photo 6, lower). Also locally, up to 6% sphalerite occurs in bands and patches in the upper pyritic sections of the Lower Horizon and West Kona Zone.

The lower part of the composite sulphide-magnetite mineralization consists of a combination of one or more layers of massive to weakly banded sulphide minerals, banded-intercalated massive sulphide minerals, and magnetite, foliated quartz-chlorite-rich metavolcanic rock and/or quartz-chlorite-rich semimassive-banded sulphide minerals and magnetite. A layer of weakly banded to massive pyrite-rich sulphide or quartz-dominated semimassive pyritic sulphide minerals forms the basal portion of the lenses in places (e.g., Hole 97-97: Fig. 22). Pyrrhotite is generally more abundant in the lower sections of the lenses than in the upper sections. Chalcopyrite concentrations also tend to be higher than in the upper part of the lenses and may be as high as 30% locally.

Semi-massive and disseminated (<50%) sulphide mineral- and magnetite-rich mineralization (Photo 9) is located within, peripherally, and below massive mineralization. Present drill information suggests that much of the semimassive mineralized rock is conformable with the massive mineralized rock. It contains significant chalcopyrite and is included as part of the mineral resource of the deposit (e.g., Figs. 20 and 21). The contacts between massive mineralization and semimassive mineralization may be sharp as in Hole 97-97 (Fig. 22), but gradational contacts are also common. Texturally, the semimassive mineralization consists of bands, patches or heavy disseminations of pyrite, pyrrhotite, chalcopyrite and magnetite in a schistose, friable chloritic matrix. Significant quartz is contained in the semimassive mineralization as discreet foliation-parallel bands or patches 2 to 20 mm thick (Photo 9, upper), which locally contain a large part of the sulphide minerals and magnetite. Pyrrhotite is generally more abundant in the semimassive than in the massive mineralized rock.

The semimassive mineralization is generally gradational into disseminated mineralization (e.g., Photo 9, lower left) and chlorite-rich mafic schist downward and laterally. Magnetite generally becomes relatively more abundant with respect to sulphide minerals in the disseminated versus the semimassive mineralization.

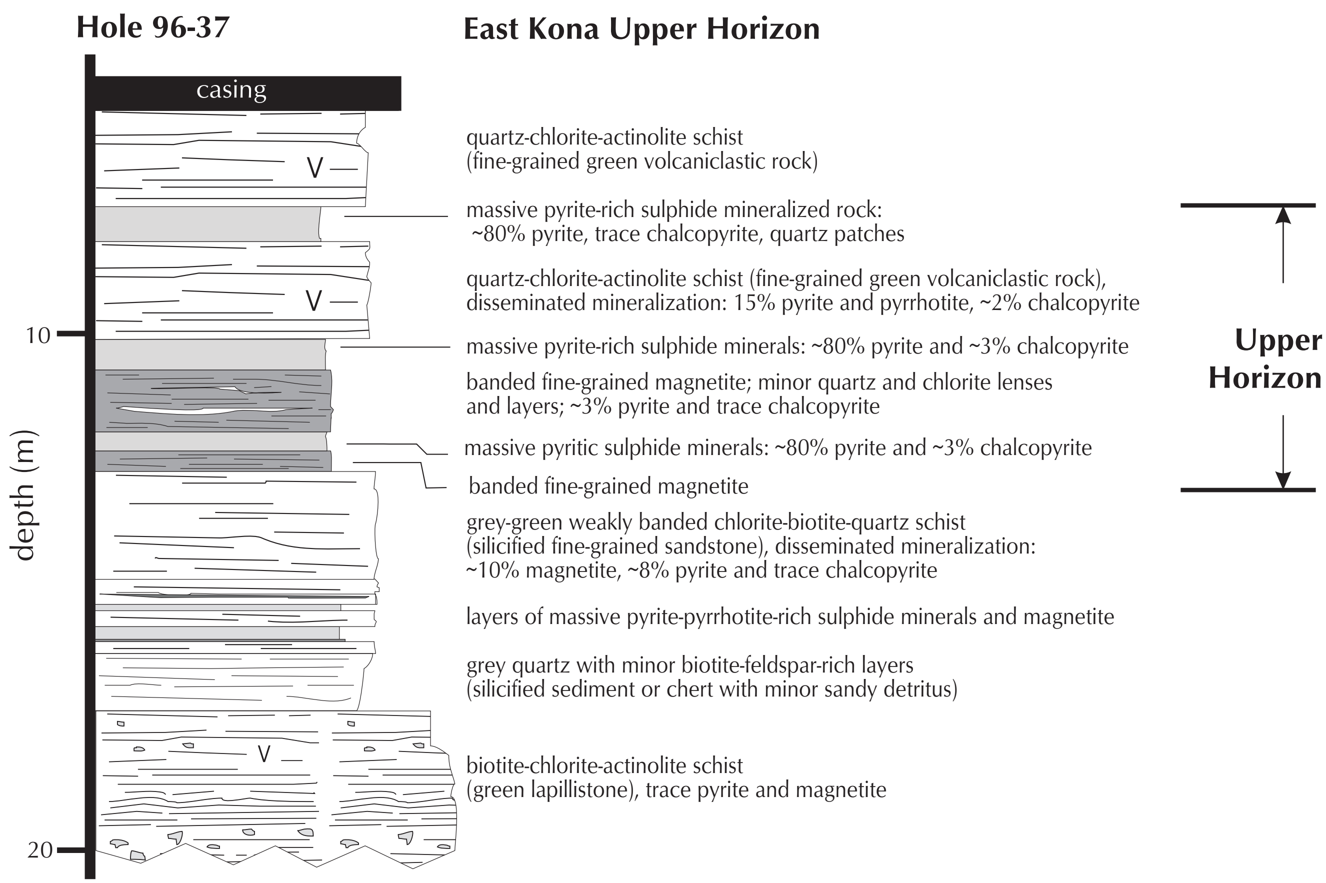


Figure 19. *A graphic drill log of the East Kona Upper Horizon intersection in Hole 96-37.*

CHEMISTRY OF THE MINERALIZED ROCK

Copper is the major economic element in the Fyre Lake deposit and chalcopyrite is the dominant copper mineral. Rare bornite occurs in some of the semimassive and disseminated mineralized rock, and trace chalcocite was noted in a metallurgical sample (Lakefield Research Ltd.).

At Fyre Lake, higher gold concentrations are commonly found in chalcopyrite-rich samples of massive or semimassive mineralized rocks. Assay data indicates that precious metal concentrations tend to correlate with copper grade (Figs. 23a and 23b).

Electron microprobe analyses done at the University of Toronto as part of metallurgical testing (Lakefield Research Ltd.) indicate that ~90% of the cobalt at Fyre Lake is contained within pyrite. More than 30 grains of pyrite were probed and the cobalt concentration ranged between 800 ppm and 4.9%. Minor cobalt (~0.2% average) occurs in

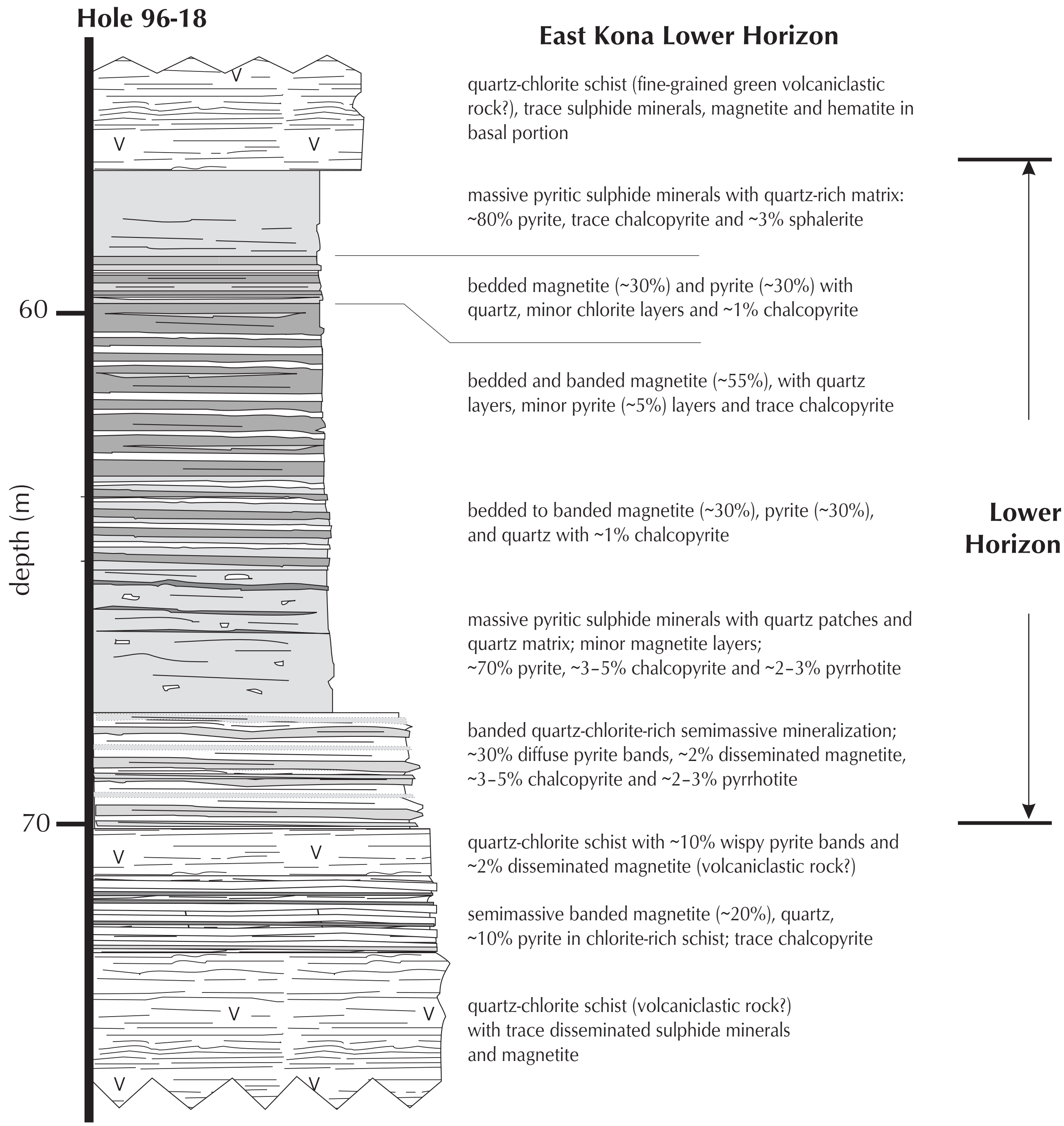


Figure 20. *A graphic drill log of the East Kona Lower Horizon intersection in Hole 96-18.*

sphalerite, and none was detected in chalcopyrite (Lakefield Research Ltd.).

The zinc grades of the sulphide minerals at Fyre Lake are generally below 0.5%. On average, the East Kona Zone Lower Horizon contains more zinc than the other mineralized lenses. Localized higher zinc values (>1%) occur in the upper part of the Lower Horizon and in its northern section where it consists of one pyrite-rich layer. Sporadic, anomalous zinc concentrations exceeding 1% are also present in the upper portions of the West Kona Zone.

In general, the sulphide mineralized rock at Fyre Lake is copper-rich and zinc-poor (Table 3) and contains elevated levels of cobalt and nickel when compared to other massive sulphide deposits. Despite that, the mineralization at Fyre Lake occurs in a sediment-rich setting, it contains less silver, arsenic, barium, lead, antimony and selenium compared to modern sulphide deposits found at sediment-rich spreading centres such as those in the Escanaba trough (Table 3). Instead, the concentrations of these elements at Fyre Lake are similar to or lower than those found at sediment-free ridges or ancient mafic-hosted deposits (Table 3).

ALTERATION

Alteration is present in the Kona Cirque mafic schist lying beneath and peripherally to the massive sulphide-magnetite mineralization. Alteration is made up of uneconomic, disseminated to semimassive sulphide minerals and magnetite, and chlorite- and quartz-rich metavolcanic rock. The alteration is generally gradational into the semimassive and massive mineralization in the mineralized lenses. It declines in intensity downward and laterally, where the host rocks become more amphibole- and epidote-rich, and

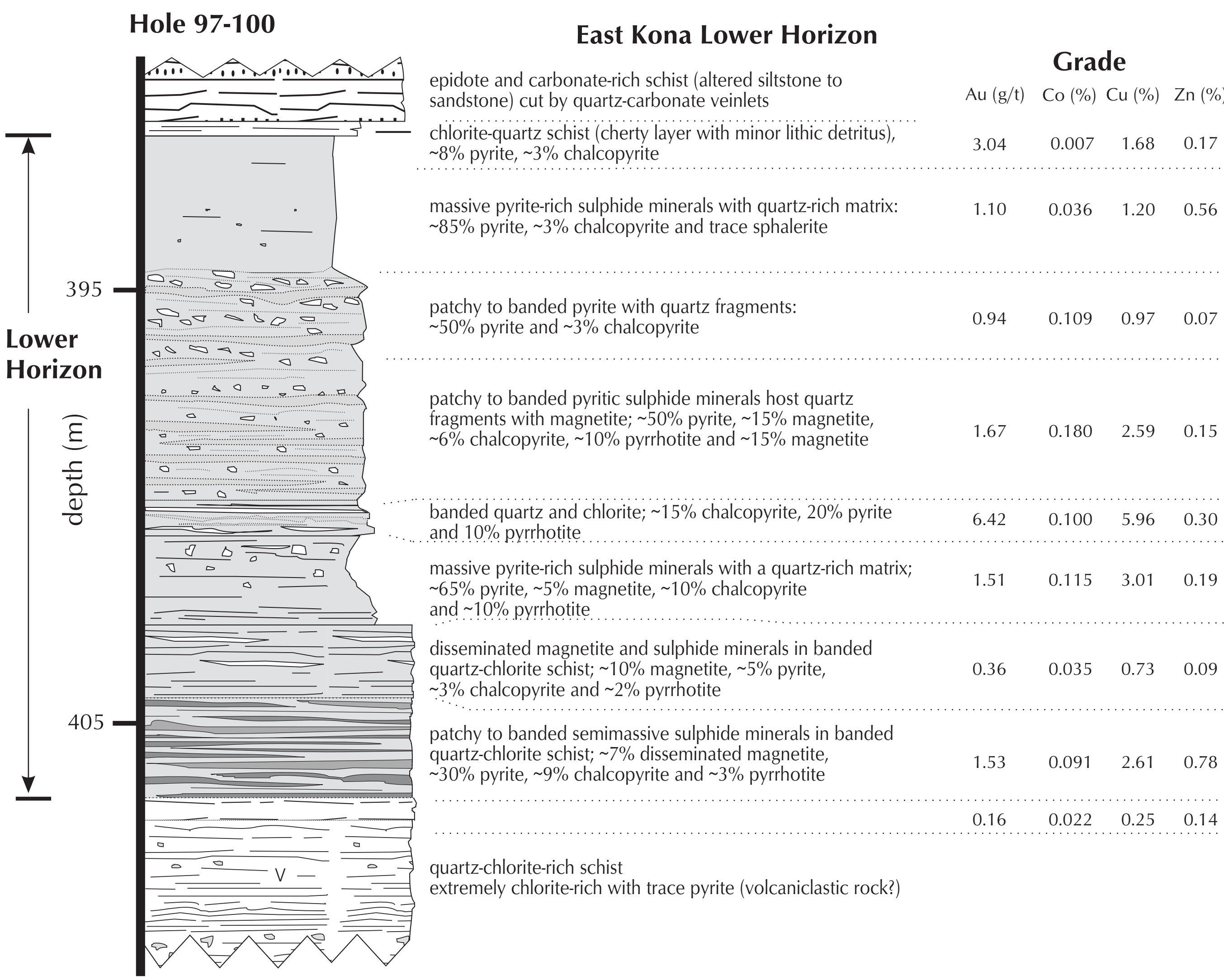


Figure 21. *A graphic drill log of the East Kona Lower Horizon intersection in Hole 97-100.*

chlorite is less dominant. Alteration in the metavolcanic hanging wall rocks of the Lower Horizon is generally weaker compared to that in the footwall. The hanging wall rocks of the Lower Horizon tend to be chlorite-rich with local occurrences of disseminated to semimassive sulphide minerals.

Nine samples of Kona Cirque mafic schist were taken below the West Kona Zone in Hole 97-115 for the purpose of chemically defining the alteration. They include chlorite schist, banded semimassive, and disseminated mineralization. A ternary Al_2O_3-CaO+Na_2O+K_2O-MgO molar proportion plot (after MacDonald et al., 1996) of least-altered and altered samples was plotted (Fig. 24). The nine samples define a discernible trend from a more plagioclase (albite)-tremolite-epidote-rich (least-altered) composition away from the mineralization, to a more chlorite (+phlogopite) -rich (altered) composition closer to the mineralization. The altered samples contain proportionally more MgO than CaO+Na_2O+K_2O.

The Transition Zone above the Fyre Lake deposit displays signs of potential hydrothermal alteration. Anomalous barium concentrations ranging from 1600 to >6000 ppm are contained in metasandstone and green metavolcanic rock above the West Kona Zone (Table 1). Also, locally, the metasedimentary rocks in the Transition Zone are siliceous and hematite-stained.

Table 3. *Comparison of sulphide mineral chemistry of Fyre Lake mineralized rock to some modern and ancient mineral deposits.*

		Fyre Lake	Escanaba trough	sediment-free ridges	Skouriotissa	Cyprus Sha	Agrokipia
		(metallurgical composite)	(pyrrhotite-rich n = 22)	(n = 9 and 172)	n = 8	n = 1	n = 87
Al	%	1.50			0.35	0.16	
As	ppm	340 (0.034%)	2700	300	74	657	89
Ag	ppm	3.7	46	79	5	10	
Au	ppm	0.98	1.39	1.05	0.5	1	
Ba	ppm	130	14 334				367
Bi	ppm	<10	79	0.75			
Ca	%	0.34	0.06		0.16	0.03	
Cd	ppm	33	52			27	
Co	ppm	1600 (0.16%)	539		359	20	32
Cu	%	2.07	2.2	4.4	2.78	1.90	327 ppm (1.52% max)
Fe	%	26.1	39.3		45.4	29.4	
Mg	%	1.30	0.09				
Mn	%	0.02					
Mo	ppm	<10	36		62	32	
Ni	ppm	130 (0.013%)	10		20	<10	32
Pb	ppm	40 (0.004%)	2300	1000	<100	94	
S	%	20.5	35.6				
Sb	ppm	10 (0.001%)	160	55	3	20	
Se	ppm	<50	130	85	296	26	
Si	%	15.8	0.46		1.77	11.69	
Sn	ppm	<20	120	<1			
Zn	%	0.99	1.4	9.6	0.02	1.20	2561 ppm (11.04% max)

Fyre Lake results are of a metallurgical composite sample reported by Mellis Engineering Ltd.
Escanaba trough results are from Koski et al. (1988), Zierenberg et al. (1993) and Koski et al. (1994) and compiled by Goodfellow and Zierenberg (1999).
Sediment-free data was reported by Bischoff et al. (1983) and Hannington et al. (1991) and compiled by Goodfellow and Zierenberg (1999).
Data from Cyprus was compiled by Hannington et al. (1998) and includes results from Kortan (1970).
The data for Agrokipia is from Herzig and Friederich (1987).

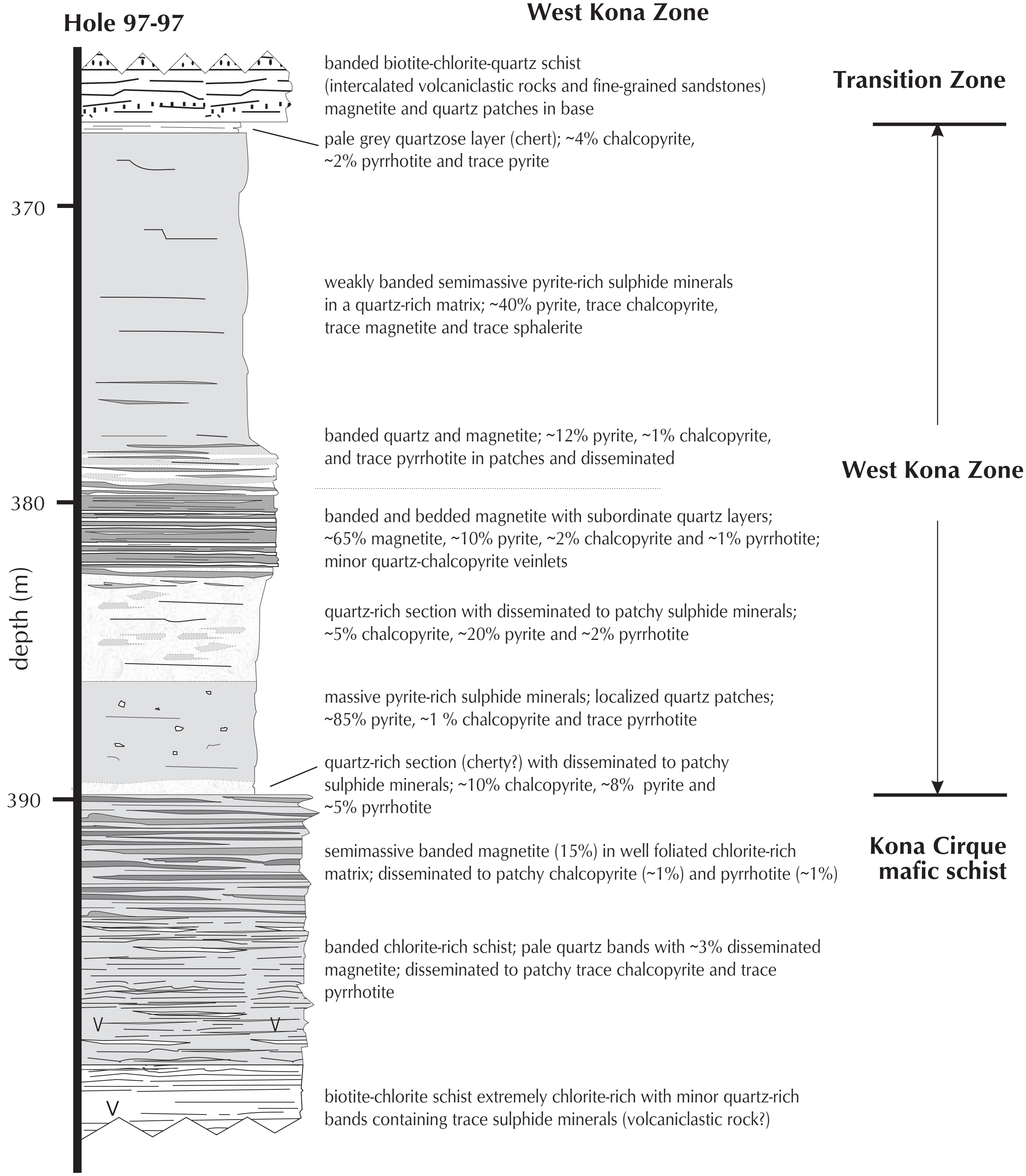


Figure 22. *A graphic drill log of the West Kona Zone intersection in Hole 97-97.*

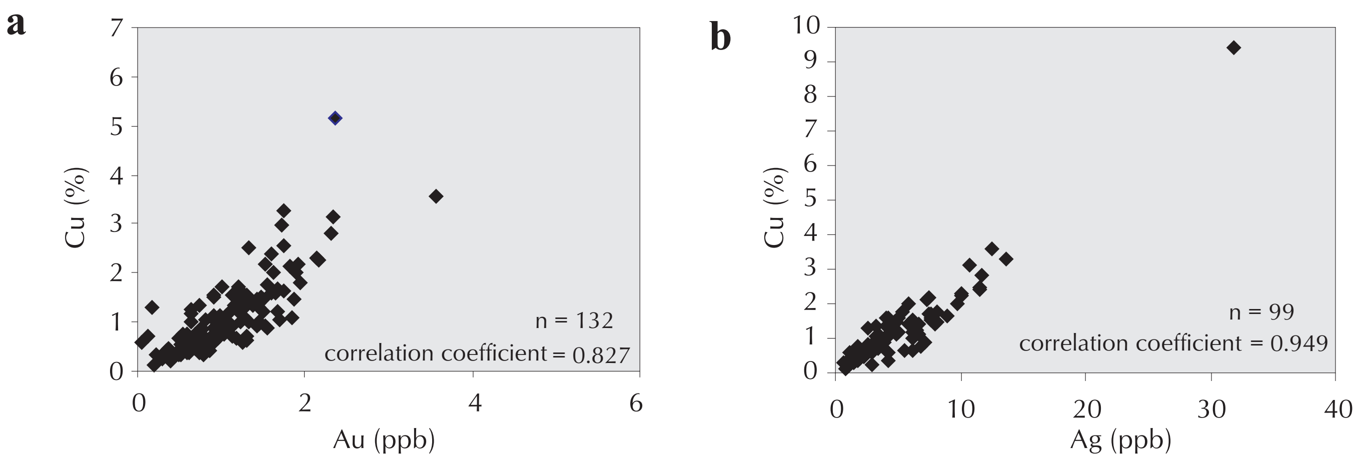


Figure 23. *Binary scatter plots:* ***(a)*** *Cu versus Au,* ***(b)*** *Cu versus Ag. The plots are based on assay data from the Lower and Upper horizon and East Kona Zone. The analyses were performed by Min En Laboratories Ltd., Vancouver, B.C.*

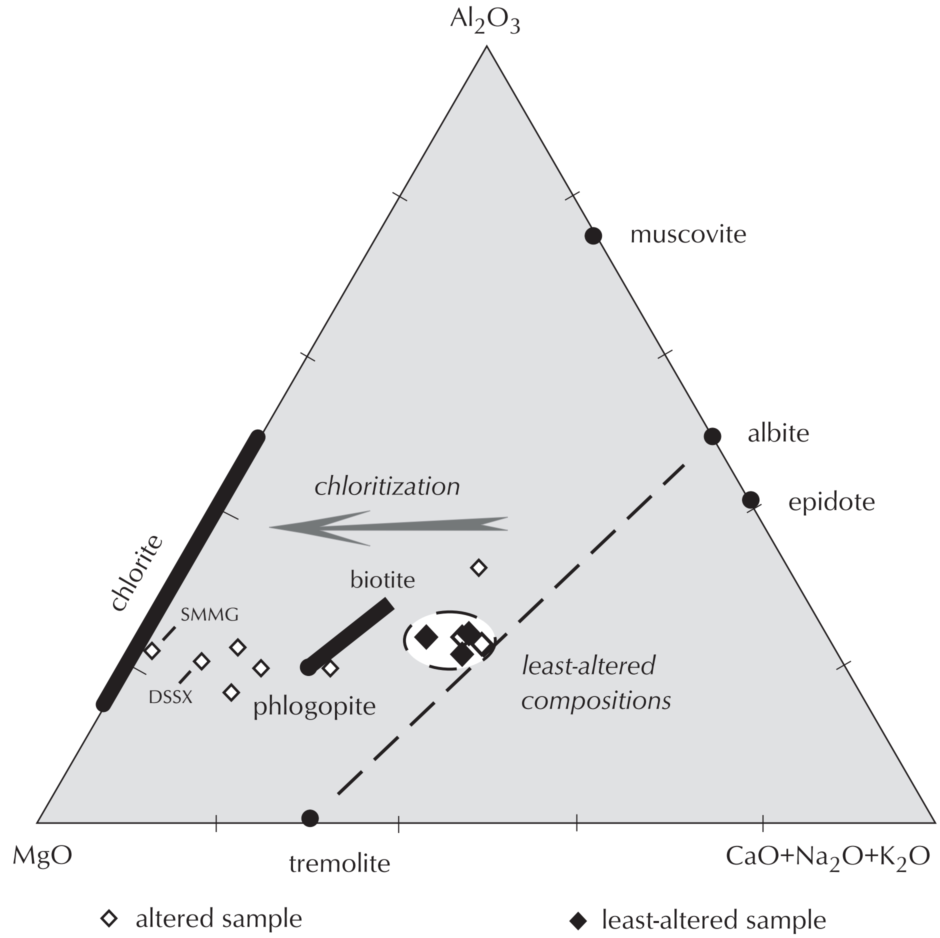


Figure 24. *Ternary molar proportion diagram of Al_2O_3 vs. $CaO+Na_2O+K_2O$ vs. MgO (after MacDonald et al., 1996). Three least-altered samples of Kona Cirque mafic schist (unit 2m) from Holes 97-97 and 97-115 (solid diamonds) are circled. The tie line from albite to tremolite provides a reference to the mineral assemblage observed in least-altered samples. The two samples plotting closest to a chlorite composition are from schists containing ~14% semimassive magnetite (SMMG; at 739.0 m) and >10% disseminated to banded magnetite and sulphide minerals (DSSX; at 761.0 m). Both these samples contained between 15 and 25% quartz bands.*

DISCUSSION

DEPOSIT CLASSIFICATION

The mineralization at Fyre Lake consists of stratiform lenses of semimassive to massive magnetite and sulphide minerals made up of mostly pyrite, pyrrhotite and chalcopyrite. Chemically, the mineralization is copper-rich and zinc-poor (Table 3); the Cu/Zn ratio in a metallurgical composite sample is >2. Concentrations of copper and nickel at Fyre Lake are elevated compared to modern and ancient mafic-associated massive sulphide deposits (Table 3). Generally the mineralization at Fyre Lake is similar to that of Besshi-style deposits (Blanchflower, 1997). Besshi mineralization is typically copper ± cobalt-rich, commonly contains minimal amounts of barium and lead, and can be associated with magnetite iron formation (Slack, 1993). Zinc contents in Besshi deposits are variable and, like Fyre Lake, many deposits contain uneconomic concentrations (Slack, 1993). The host stratigraphy of many Besshi deposits is also similar to that at Fyre Lake and consists of sedimentary successions with intercalated mafic volcanic rocks (Slack, 1993).

DEPOSIT MORPHOLOGY AND STRUCTURE

The sulphide-magnetite zones at Fyre Lake are elongated parallel to the L_1 mineral elongation (Fig. 15) and are locally affected by reverse faults possibly related to the Money Creek thrust. However, the present morphology of the deposit may partially reflect original, syngenetic structural control. Murphy (1997a), and Hunt and Murphy (1998) have proposed that mafic and ultramafic intrusive rocks exposed to the north of Fyre Lake were emplaced along a synvolcanic, basin-bounding fault, and that this structure may have also acted as a conduit for mineralizing fluids which formed the Fyre Lake deposit. The stepped offset between the East and West Kona zones (Fig. 16) may represent such a syngenetic fault, possibly related to rifting. This structure may have focused hydrothermal fluids and partially controlled the geometry of the sulphide-magnetite lenses, which are elongated parallel to it. The presence of metasandstone layers within the Kona Cirque mafic schist between the Upper and Lower horizons, and of green metavolcanic rocks chemically similar to the Kona Cirque mafic schist in the Transition Zone, suggest that both the Transition Zone and Kona Cirque mafic schist are at least partially coeval. The mineralization and sedimentary and volcanic rock units may have been deposited in response to the same extensional event.

ZONATION OF MINERALIZATION

Although not always consistent, the mineralized lenses of the Fyre Lake deposit possess a vertical and lateral mineralogical zonation. Pyritic sulphide minerals commonly occur in the top portion of the lenses. Pyrrhotite and chalcopyrite are more common in the lower sections of the lenses and are significant components of the semimassive mineralized rock. Sphalerite is a minor phase but localized concentrations are contained in the upper pyrite-rich sections of the East Kona Zone–Lower Horizon and the West Kona Zone.

Composite massive to banded sulphide minerals form the core of the lenses, while single layers of magnetite, pyritic sulphide minerals, or semimassive mineralized rock occur at the edges. Semimassive mineralized rock is also common in the footwall of the lenses. This grades into disseminated sulphide minerals downward and laterally. Disseminated mineralization is poorer in sulphide minerals and quartz, and contains a greater proportion of magnetite versus sulphide minerals.

POTENTIAL STOCKWORK ZONE AND CHARACTER OF ALTERATION

The Fyre Lake deposit contains extensive conformable semimassive banded to patchy chlorite-quartz-rich sulphide minerals and magnetite within, below and peripherally to massive mineralization. The foliation-parallel quartz ± sulphide mineral ± magnetite bands and patches in the semimassive mineralization are strongly suggestive of structurally transposed veinlets (Photo 9, upper). Therefore, it is possible that the banded semimassive quartz-sulphide mineral-magnetite mineralization constitutes a deformed stockwork-type mineralization.

In general, footwall alteration in the Kona Cirque mafic schist consists of increasing amounts of sulphide minerals, magnetite, chlorite and quartz, and a decrease in amphibole and epidote closer to the mineralized lenses. The alteration is commonly gradational to semimassive sulphide-magnetite mineralization, and chemically, there is a trend towards a greater proportion of magnesium in the rock in altered sections.

POSSIBLE DEPOSITIONAL MECHANISMS AND PARAGENESIS

The low arsenic, antimony, barium, lead, selenium and zinc content of the mineralization at Fyre Lake suggests that the hydrothermal fluids at Fyre Lake did not extensively react with overlying or underlying felsic sediments, or with sialic crust. Instead, the hydrothermal fluids may have been largely confined within the mafic metavolcanic rocks, and could have originated from the gabbroic and ultramafic intrusive rocks underlying the Kona Cirque mafic schist.

The high copper and low zinc, lead and barium content of the sulphide mineralization at Fyre Lake implies that higher temperature hydrothermal fluids (>250° C) deposited the sulphide minerals (e.g., Franklin, 1993). Locally, the massive and semimassive mineralized rock at Fyre Lake is extremely quartz-rich. The abundant quartz may have been deposited from hydrothermal fluids just below the sea floor, with, and within the sulphide minerals and clastic rocks as the fluids mixed with seawater and were cooled (e.g., Rimstidt and Barnes, 1980; Ohmoto, 1996).

Textural evidence suggests that both exhalation and replacement/infilling were responsible for the deposition of the mineralization at Fyre Lake. Features suggestive of exhalative processes are the finely banded and conformable nature of the magnetite iron formation, which is generally free of lithic relics. Also, quartzose sulphide mineral-bearing layers locally overlie the West Kona Zone and the Lower Horizon of the East Kona Zone, and these may constitute metamorphosed siliceous hydrothermal cherts.

In contrast to the magnetite and chert, much of the sulphide-mineralized rock at Fyre Lake displays features that suggest it was the product of replacement or infilling processes. Both the massive (>50%) and semimassive sulphide minerals at Fyre Lake display disseminated, patchy and massive homogeneous textures. Finely banded sulphide minerals are generally rare. For example, massive (>50%) sulphide minerals of the West Kona Zone cored in Hole 97-115 are not bedded. Instead they display patchy, fragmental to heavily disseminated textures and grade downwards into sulphide-poor quartz-chlorite-rich semimassive mineralization (with a similar texture; Photo 10). Protolith textures in the Kona Cirque mafic schist suggest that a large portion of it was clastic in nature. The permeability of a clastic host would have facilitated deposition by infilling and replacement and the formation of the extensive semimassive and disseminated sulphide-magnetite mineralization. Other evidence for replacement processes in the mineralization at Fyre Lake includes local examples of fragmental magnetite, quartz or sulphide minerals cemented by later sulphide minerals.

The intercalated magnetite and sulphide mineral layers in the West and East Kona zones suggest that there were changes in the fluid chemistry, temperature, or redox conditions during deposition. However, the origin of the large amounts of magnetite at Fyre Lake and its paragenetic relation to the sulphide minerals remain unclear. Thin section studies of banded magnetite in the Lower Horizon by Leitch (1998) and Deighton et al. (1997) have not provided any definitive clues as to its origin. The magnetite is generally euhedral and no examples of colloform or acicular textures, which would indicate a hydrothermal origin, were found. However, it is unlikely that all the magnetite at Fyre Lake, especially the banded iron formation, is simply a product of regional metamorphism of hematite or previous iron hydroxides. There are no remnants of these latter phases; only minor hematite and limonite occur with magnetite at Fyre Lake and these phases are probably secondary given that they rim the magnetite in thin section.

Other workers have proposed a diagenetic or late syngenetic origin for magnetite found at other massive sulphide deposits and this may be considered for Fyre Lake. For example, magnetite-rich lenses occur with massive sulphide mineralization at Golden Grove, Australia (Frater, 1983). Frater has proposed that the magnetite at Golden Grove may be a product of partial reduction of previously deposited hematite and hydroxides by oxygen-poor and Fe^{2+}-rich hydrothermal fluids after burial. A similar reduction mechanism has been proposed by Hackett and Bischoff (1973) who suggest that hydrothermal fluids reduced goethite to a hematite, magnetite and pyroxene assemblage in a portion of the Central Oxide Zone of the Atlantis II Deep, Red Sea. More recently, Ohmoto (2003) has proposed that earlier iron hydroxides and hematite may be converted to magnetite by the addition of ferrous iron contained in hydrothermal fluids. This latter process is not a redox reaction but is an acid-base reaction and would also be facilitated by burial.

There is some implicit evidence for burial and a change to reducing conditions during deposition at Fyre Lake. Altered, chlorite-rich mafic schist and local semimassive to disseminated sulphide-mineralized rock locally overlie some sections of the sulphide-magnetite zones, and these may have been altered after they covered a part of the hydrothermal field. Similarly, there is suggestion of weak alteration in Transition Zone metasedimentary rocks overlying the West Kona Zone, and the Transition Zone contains small disseminated to patchy pyrrhotite-rich layers in places. Locally, within the mineralized lenses, fragmental magnetite appears to be cemented by sulphide minerals and quartz (Photo 8). The sulphide minerals at Fyre Lake generally display disseminated, patchy and massive homogeneous textures. While these textures may be partially due to metamorphic recrystallization, the possibility remains that they are primary and were produced by replacement/infilling and/or hydrothermal recrystallization after deposition. Such processes would have taken place below the seafloor under more reducing conditions.

Therefore, deposition at Fyre Lake may have started with precipitation of hematite or iron hydroxide-rich layers and veinlets under oxidizing conditions near and at the seafloor. Subsequently, a combination of partial burial and/or increased hydrothermal discharge may have served to create more reduced conditions and possibly also higher temperatures in sections of the deposit. This change would have caused metals to be deposited as sulphide minerals, partially replacing and cementing earlier iron-oxide mineralization, and converting previously deposited iron oxy-hydroxides, hydroxides and hematite to magnetite.

The presence of intercalated magnetite and sulphide minerals in the deposit could have (in part) been produced by local repetition of an oxidizing to reducing cycle caused by volume and temperature changes in the hydrothermal discharge of the system. Some of the iron formation in the deposit could also have been deposited in the waning stages of the hydrothermal field or under more oxidizing conditions at its periphery.

Overall, given the textural and structural features of the deposit, one may suggest that a portion of the Lower Horizon (East Kona Zone) and the West Kona Zone were probably deposited near or at the seafloor and then buried. The alteration and sulphide layers in the overlying metavolcanic and metasedimentary rocks suggest that hydrothermal activity continued after the burial of the West Kona Zone. The Upper Horizon (East Kona Zone) was probably deposited subsequently to the emplacement of the Lower Horizon and West Kona Zone.

TECTONIC SETTING OF THE METAVOLCANIC ROCKS AND THE FYRE LAKE DEPOSIT

The exact location of the Lake Zone metavolcanic rocks in the stratigraphy is not certain. Field mapping indicates that they are below the Kona Cirque metavolcanic rocks. However, the biotite-quartz-rich metasedimentary rocks lying below and above the Lake Zone are outwardly very similar and there are sheared zones, possibly representing shallow thrusts, lying between the Lake Zone and other metavolcanic rocks of Fire Lake formation. This leaves the possibility that the Lake Zone metavolcanic rocks are contained in the upper section of North River formation.

Lithogeochemical results allow that the Lake Zone metavolcanic rocks were derived from transitional rift-related basaltic volcanic rocks with a LREE and HFSE-enriched (light-rare-earth and high-field-strength elements) chemical signature. Their chemistry is somewhat similar to volcanic rocks erupted in within-plate settings such as EMORB (enriched mid-oceanic ridge basalt), OIB (oceanic island basalt) and some continental flood basalts (Fig. 12). The Lake Zone metavolcanic rocks may have been erupted in a continental or mature arc setting.

Field mapping indicates that the metavolcanic rocks of the Outfitter's Creek area and Kona Bowl are laterally discontinuous and partially interbedded with the phyllites of Kudz Ze Kayah formation. They lie above the Kona Cirque mafic schist in the stratigraphy, and chemically bear a resemblance to rift-related transitional mafic to intermediate volcanic rocks erupted in an evolved, mature island arc or continental arc setting. The felsic metavolcanic rocks in Kudz Ze Kayah formation also display chemical features of volcanic rocks erupted in a continental-arc setting (Piercey et al., 1999).

Geochemistry suggests that the Kona Cirque mafic schist formed from a volcanic protolith of boninitic affinity. Geochemically similar mafic volcanic rocks have been mapped, analysed and reported within the Fire Lake formation regionally and in proximity to Fyre Lake by Murphy (1997a,b), Hunt and Murphy (1998) and Piercey et al. (1999 and 2001).

Previously documented occurrences of rocks of boninitic affinity indicate that they are erupted in extensional regimes in the forearc of primitive oceanic arcs (e.g., Bloomer and Hawkins, 1983 and 1987; Bloomer et al., 1995). Boninite-like lavas are also reported from nascent backarc settings such as the North Tonga Trench (e.g., Falloon et al., 1987). Others are found in ophiolites formed in rifted oceanic environments, such as Troodos, Cyprus (Cameron, 1985). Therefore the boninitic chemistry of the Kona Cirque mafic schist implies a rifted setting for the Fyre Lake deposit.

Regional and local mapping by Murphy (1997a,b), Hunt and Murphy, (1998), Murphy and Piercey (1999), and Murphy (2004a) suggests that the mafic and ultramafic rocks of the Fire Lake formation (units 2m, 2mum and 2um) overlie, and locally intrude older metasedimentary rocks of North River formation. North River formation rocks are rich in quartz and feldspar, and they contain a lower felsic volcanic member (Murphy, 1997a,b). It has been suggested that North River formation metasedimentary rocks represent a passive continental margin assemblage (e.g., Wheeler et al., 1988; Mortensen, 1992). The metasandstones from the Transition Zone (Fire Lake formation), which overlie and interfinger with the Kona Cirque mafic schist, also bear mineralogical and chemical features similar to sediments derived in a continental setting.

This is an unusual environment for boninitic rocks, which are generally associated with more primitive arc and oceanic settings. Documented examples of boninites and high-Mg andesite lavas contained in continental-type sequences occur in Baja, California (Saunders et al., 1987 and Rogers and Saunders, 1989), the Setouchi Belt, Japan (Tatsumi and Ishizaka, 1982), the North Island of New Zealand (Wood, 1980) and in western Tasmania (Brown and Jenner, 1989). Compared to the Kona Cirque mafic schist, the high-Mg andesites in Baja, California and the Setouchi Belt contain more TiO_2 and Zr, and are strongly LREE enriched. However, the Kopi boninite on the North Island of New Zealand is high in MgO, CaO, Cr and Ni and contains extremely low amounts of TiO_2, Zr, and Nb and is chemically very similar to the Kona Cirque mafic schist (see Table 2). The Kopi boninite is composed of flow rocks and hyaloclastites but as exposed is only about 10 m thick. However, like the Kona Cirque mafic schist, the Kopi boninite is contained in a sediment-rich setting in eastern Wairarapa within the Pahaoa Group — a sequence of quartzo-feldspathic siltstones and sandstones of Cretaceous age (Wood, 1980; Moore and Speden, 1984). These sediments are part of a 1500-metre-thick accumulation interpreted as submarine fans or fan-delta deposits accumulated in a fault-controlled basin at the continental margin of New Zealand (Moore and Speden, 1984). Syngenetic and post-depositional faults deform the sediments but there is no evidence for an allochthonous origin for the boninitic rocks. Also interesting, is that the Kopi boninite occurs near alkalic basaltic flows and sills contained in the same quartzo-feldspathic sedimentary rocks (Wood, 1980).

In western Tasmania, volcanic rocks of boninitic affinity and associated mafic and ultramafic intrusive rocks are contained in a sediment-rich sequence within the Dundas Trough (Brown and Jenner, 1989). The chemistry of some of these volcanic rocks is very similar to the Kona Cirque mafic schist (see Table 3). However, some workers interpret the boninitic rocks of the Dundas Trough as a structural artifact. They are seen as originally erupting in a primitive oceanic arc, which was subsequently accreted onto a continental margin (Berry and Crawford, 1988; Crawford and Berry, 1992). This is an unlikely scenario for the Kona Cirque mafic schist as present geological evidence suggests that it and Fire Lake formation ultramafic rocks display non-faulted contacts with older metasedimentary rocks of North River formation.

Piercey et al. (2001) have also concluded that the boninitic rocks contained in the Fire Lake formation were emplaced in a continental arc–backarc setting. Given the low concentrations of Th, HFSE and LREE in the boninites of the Fire Lake formation, Piercey et al. (2001) have suggested that the generation of these rocks may have been in response to the propagation of a spreading ridge into a composite basement of continental and oceanic crust. This would have resulted in high heat flux and rapid rifting with generation of boninitic magmas from a refractory mantle wedge and rapid transport from mantle source to surface, minimizing crustal contamination.

In conclusion, the Fyre Lake sulphide mineral-magnetite deposit represents a Besshi-style deposit, which was emplaced in volcanic rocks of boninitic affinity. The Kona Cirque mafic schist is chemically similar to primitive mafic volcanic rocks found in some supra-subduction zone ophiolites such as the Troodos Ophiolite, Cyprus. The Kona Cirque mafic schist lies in a metasedimentary-rich stratigraphic sequence. The metasedimentary rocks are compositionally and texturally similar to sediments found in continental settings — an unusual one for boninitic rocks. Other metavolcanic rocks in the stratigraphy possess chemical features suggesting they were erupted in or near a mature island arc or continental arc setting. Therefore, the Kona Cirque mafic schist may also have been erupted in response to rifting in or near an evolved tectonic setting, possibly a continental-arc or a mature island arc with continental-style crust.

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Plates

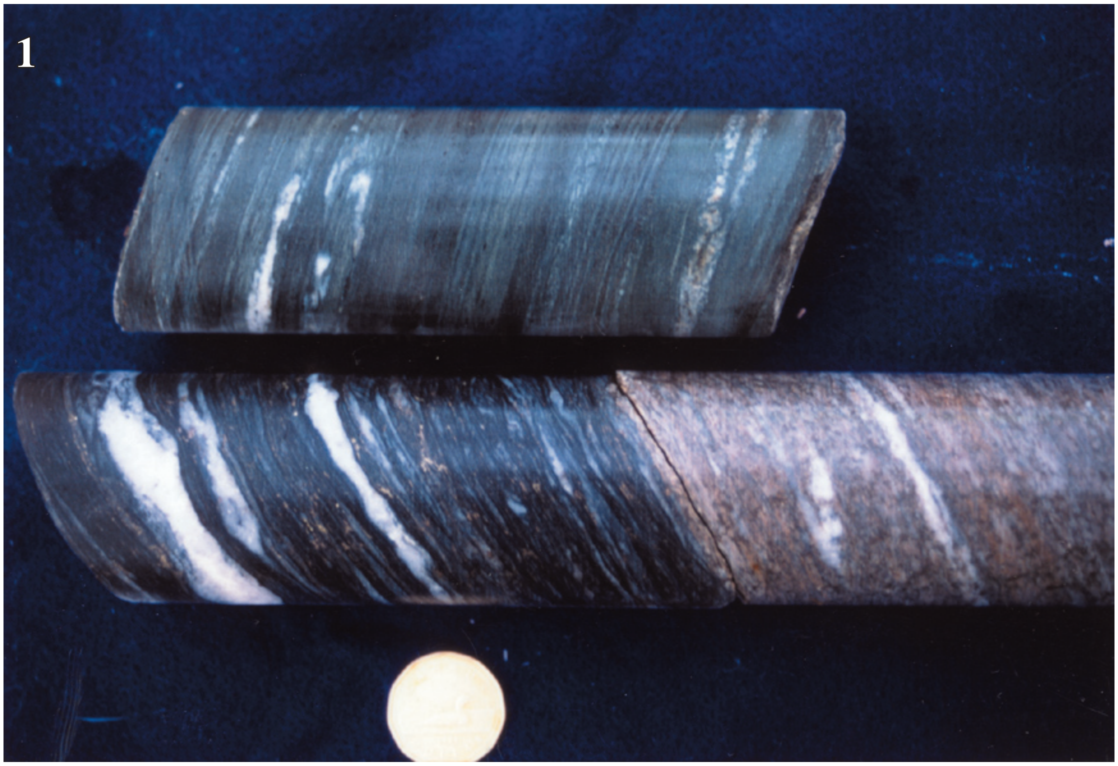

Photo 1. *The upper shorter core is of green laminated fine-grained mafic volcaniclastic rock from the Lake Zone metavolcanic rocks (unit 2) cored in Hole 97-76 (15.2 m). The lower core (from Hole 97-76, 71.3 m) contains dark carbonaceous biotite-muscovite quartz-rich phyllite overlying brown quartz-biotite schist and comes from a sequence of intercalated metamorphosed mudstones and sandstones included in unit 1, which underlie the Lake Zone metavolcanic rocks. Looney for scale.*

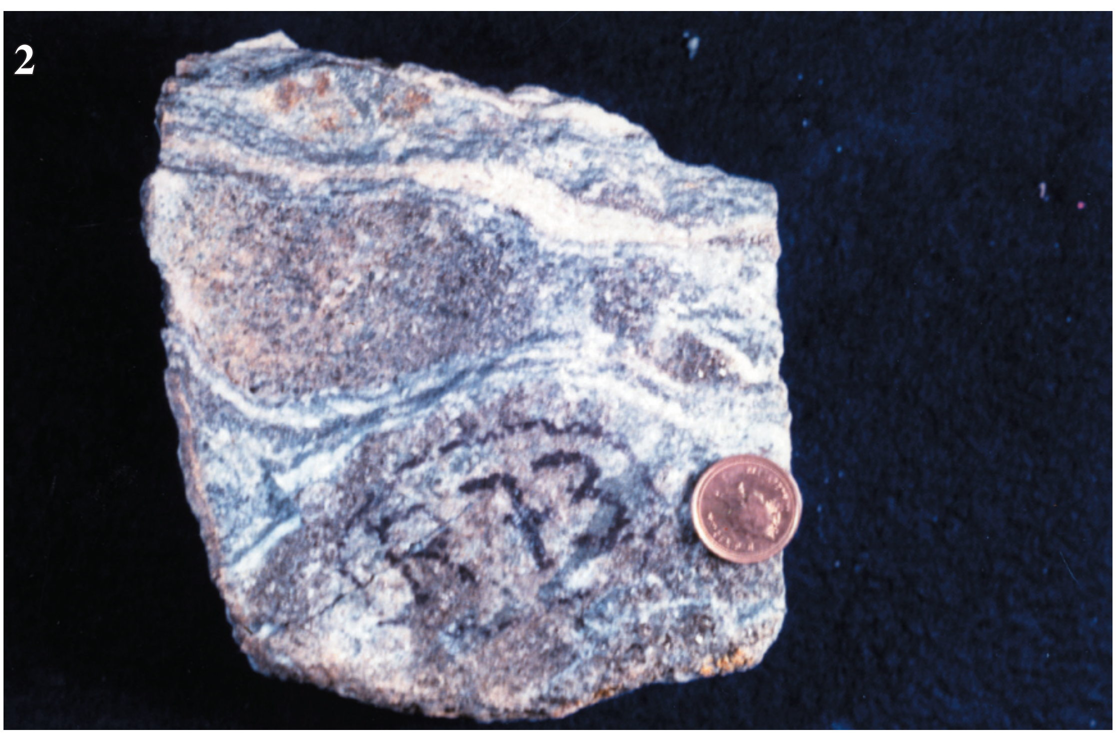

Photo 2. *A hand sample of well foliated, calcareous, biotite-quartz-rich schist from North River formation (unit 1). This sample, RO Stn73, was collected from outcrop lying below the Lake Zone. The protolith is interpreted as a siltstone or sandstone, largely of felsic derivation. Quarter for scale.*

Photo 3. *Example in outcrop of tight interfolial folds in a micaceous quartzite bed contained in phyllites (of Kudz Ze Kayah formation, unit 3) above the mineralization in Kona Cirque. Hammer in centre for scale. The fold axes plunge southeast and are parallel to the strong mineral elongation (L_1) and to the long axis of the sulphide mineral-magnetite lenses forming the Fyre Lake deposit.*

Photo 4. *Core samples of the Kona Cirque mafic schist (unit 2 m) taken well below the West Kona mineralization. The top specimen is from Hole 97-97 (442.8 m) and is largely composed of a clast-supported breccia; fragment outlines are visible in the lower half of the sample. The lower core is from Hole 97-115 (812.9 m) and contains an epidote-rich lobate-shaped lava block. The lower half of the sample is a banded mafic volcaniclastic rock. Arrow indicates direction to top of the hole.*

Photo 5. *Core samples of the Transition Zone metasedimentary rocks (unit 2). Top core is from Hole 97-97 (255.6 m); the lower core is from Hole 97-115 (617.9 m). Both samples are of intercalated brown biotite-rich schist (after fine-grained felsic metasandstones) and green chlorite-actinolite schist (after fine-grained mafic metavolcaniclastic rocks). Pale carbonate is contained in the mafic volcaniclastic layers in the lower core. Both cores contain syndepositional features. The upper core displays lensey discontinuous green volcaniclastic beds, and displays possible scouring of an upper contact of green volcaniclastic by brown metasandstone just below the crack in the upper section of the core sample. Alternating finer grained dark brown vesus lighter relatively coarser grained bands make-up the metasandstones of the lower core and these may be the product of small turbidites. The bedding displays angular contact relationships, which are possibly the product of cross-bedding.*

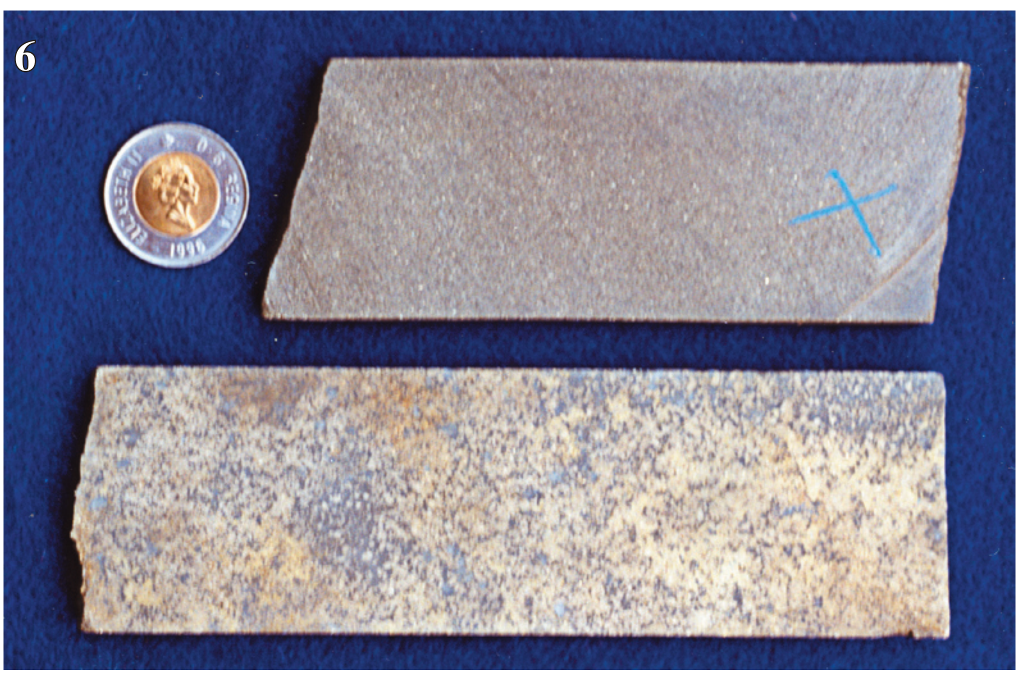

Photo 6. *Samples of pyrite-rich mineralization. The upper core slice is from the upper portion of the Lower Horizon in Hole 96-35 (108.8 m). It is made-up of fine-grained massive pyrite with trace quantities of chalcopyrite, sphalerite and quartz. The lower core slice is from the West Kona Zone as sampled in Hole 97-102 (349.5 m). Fine- to medium-grained patchy to disseminated pyrite with interstitial chalcopyrite is contained in a grey quartz matrix.*

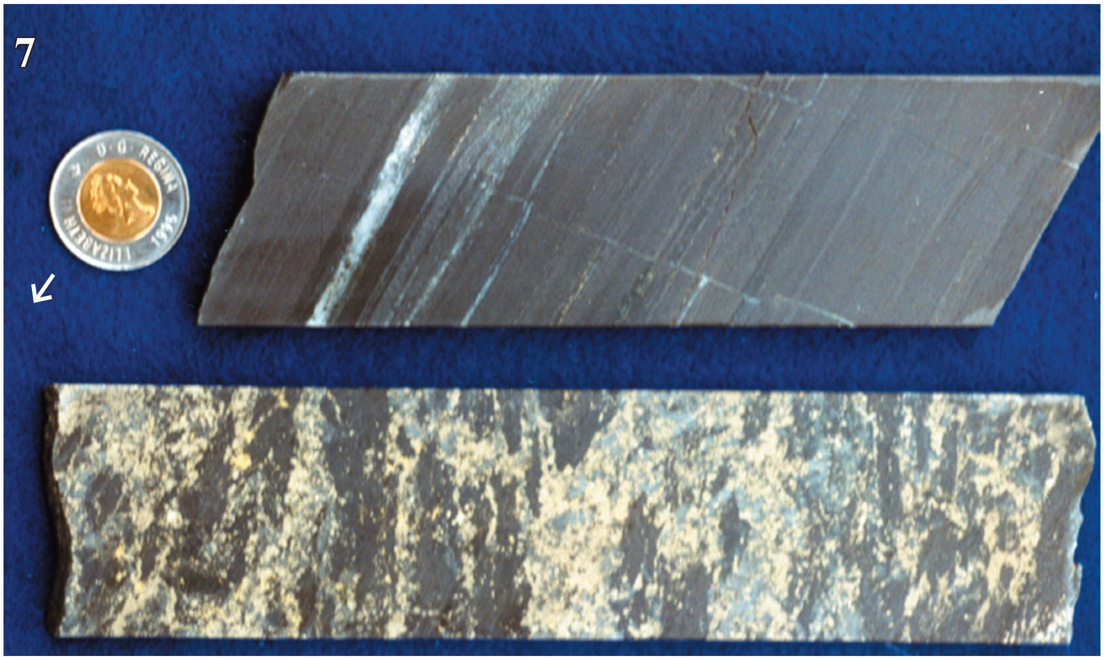

Photo 7. *The upper core slice is an example of banded magnetite iron formation contained in banded massive sulphide and magnetite mineralization of the Lower Horizon from Hole 96-34 (72.3 m). The lower core slice is from the West Kona Zone as sampled in Hole 97-95 (341.8 m). It contains a mixture of patchy to discontinuously banded pyrite-rich sulphide minerals intimately intergrown with fine-grained magnetite (dark patches). Quartz accompanies the sulphide minerals and makes up about 25% of the core. The magnetite appears to have a fragmental texture and may be replaced or was fractured and then cemented by sulphide minerals and quartz.*

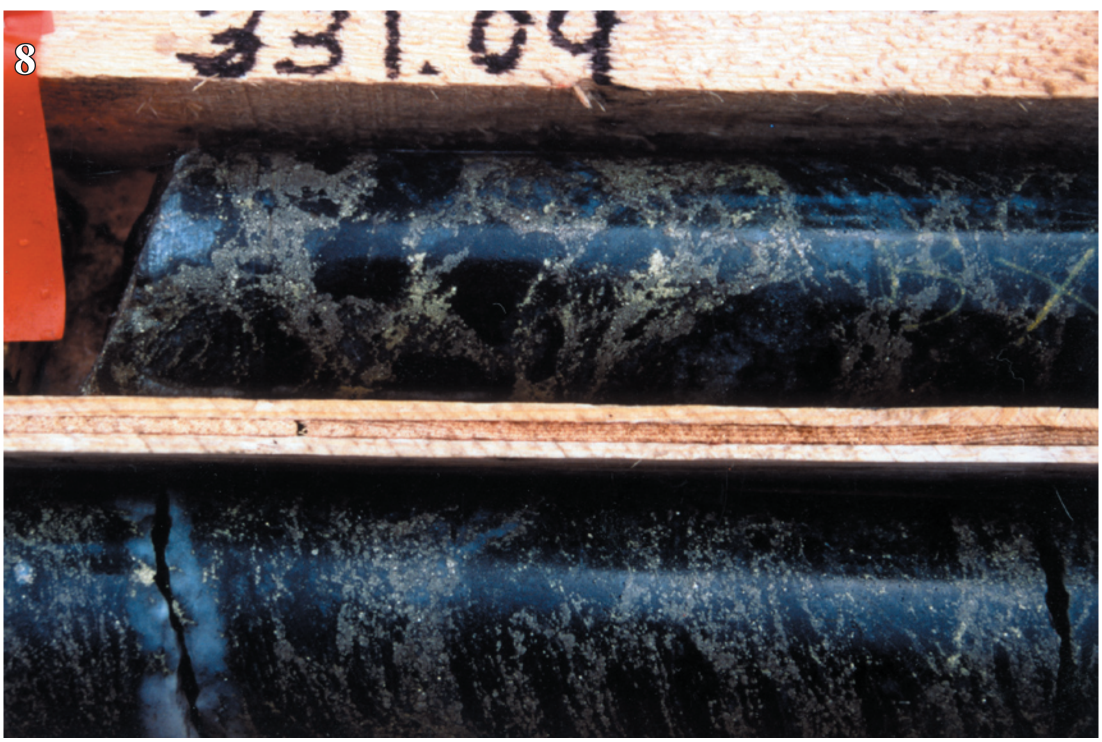

Photo 8. *Close-up photo of fragmental-textured fine-grained magnetite cemented by pyrite, pyrrhotite, chalcopyrite and quartz. A quartz veinlet with chalcopyrite patches cuts the lower core at left. The core is from the West Kona Zone cored in Hole 97-95 (331 m).*

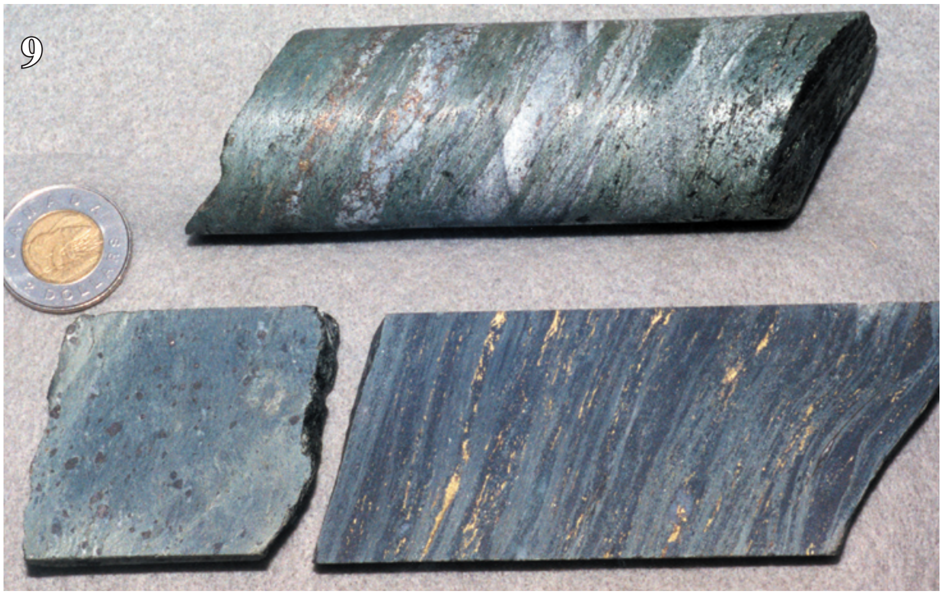

Photo 9. *Core samples of semimassive and disseminated magnetite and sulphide minerals. The upper core is from below the West Kona Zone in Hole 97-115 (746.8 m) and contains foliation-parallel quartz bands with sulphide minerals and magnetite. The matrix is chlorite-rich and contains disseminated magnetite. The quartz bands may represent stringers of a footwall feeder zone that were tectonically transposed parallel to the foliation (F_1). The core slice at lower right contains a quartz-poor example of semimassive sulphide minerals and magnetite taken just below the Upper Horizon in Hole 96-35 (67.8 m). Magnetite bands (dark) are contained in a chlorite-rich schist matrix after altered volcanic rocks. Patches and discontinuous bands of pyrite-chalcopyrite-rich sulphide minerals parallel the magnetite bands. The core slice at lower left is from disseminated magnetite mineralization below the Lower Horizon in Hole 96-33 (75.0 m). It consists of a chlorite-rich schist matrix with disseminated magnetite crystals up to 4 mm across.*

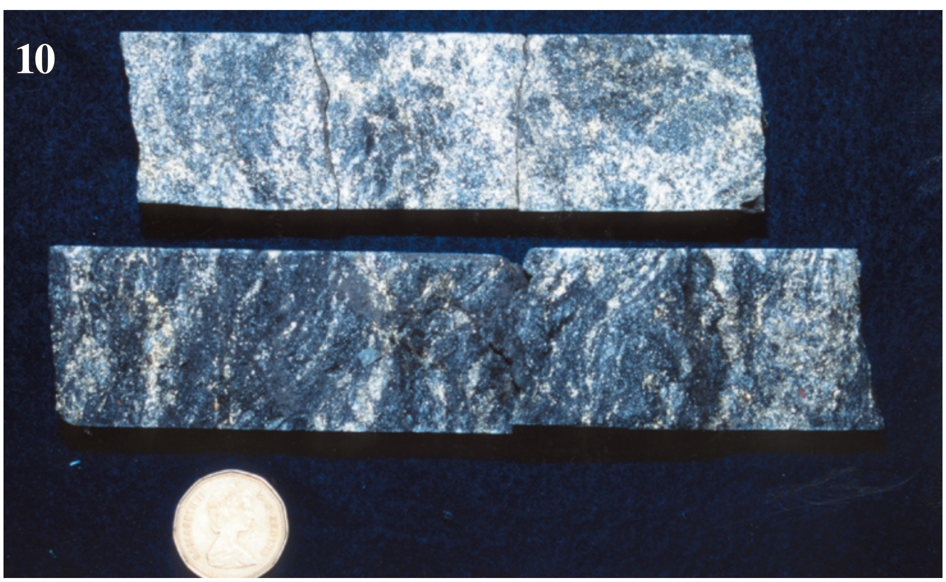

Photo 10. *Examples of semimassive sulphide mineral-magnetite in the lower section of the West Kona Zone in Hole 97-115. The upper core contains ~40% pyrite and 10% magnetite, with quartz as matrix and in patches. It was taken at 713.8 m depth right at the base of massive (>50% sulphide mineral) quartz-pyrite-rich mineralized rock, which is gradational to the semimassive mineralization lying below. The lower core (719.6 m) contains ~20% sulphide minerals in wispy bands and disseminations with ~25% magnetite, quartz and minor chlorite. The chlorite likely represents altered wallrock. The sulphide mineral textures in these specimens are interpreted to be the result of replacement or infilling processes in the Kona Cirque mafic schist (unit 2m).*