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EXPLORATION FOR IRON OXIDE COPPER GOLD DEPOSITS IN ZAMBIA AND SWEDEN: COMPARISON WITH THE AUSTRALIAN EXPERIENCE

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Abstract - The major iron oxide copper-gold (IOCG) deposits in Australia (Olympic Dam, Ernest Henry) are 'blind', and were discovered under younger cover. Exploration for this style of mineralisation presents a new set of problems to the explorationist, and involves target definition applying criteria gleaned from work in known terranes, extrapolated into new areas.

Equinox applies a model for IOCG mineralisation principally derived from studies of known mineralisation in the Cloncurry region and the Stuart Shelf/Gawler Craton of South Australia. This model was initially applied in Australia, and was later extrapolated to Zambia in Central Africa and the Norrbotten region in Sweden.

Key features of the model for IOCG mineralisation used by Equinox in the early 1990's were: (1) IOCG deposits are essentially iron deposits with variable concentrations of copper, gold, uranium, REE and other metals; (2) The country/host rocks of significant deposits are typically feldspathic rocks such as felsic to intermediate volcanics, granitoids and psammites; (3) Host rocks are strongly brecciated where mineralised and are commonly intensely altered by iron oxide-potassic alteration proximal to mineralisation and extensive sodic-calcsilicate alteration on a regional scale; (4) Deposits are associated with radioactively anomalous A-type granitoids, typically fractionated and multi-stage, commonly in the roof zone or carapace of such granites; (5) Structures active contemporaneously with granite emplacement provide the conduits for the flow of mineralising fluids, which focus into zones of structural dilation; and (6) Fluids involved have a high magmatic component, and are generally oxidising and highly saline.

IOCG mineralisation in Zambia is related to the Cambrian age Hook Granitoid suite, a late tectonic A-type suite associated with regional iron-copper-gold-uranium mineralisation. There is evidence that classic Copperbelt mineralisation may also be of this age and genesis. In Norrbotten, IOCG mineralisation is associated with alkalic to A-type granitoids of 1895 to 1790 Ma age.

Experience in these countries and Australia, combined with current field research, suggests IOCG mineralisation can range from Early Proterozoic to Mesozoic in age, with examples recognised worldwide. The evolution of Equinox's model for IOCG mineralisation also is discussed.

Introduction

In the early 1990's several authors of this paper, through Hunter Resources Limited, were directly involved in the discovery of the Ernest Henry Iron Oxide Copper Gold deposit near Cloncurry in northwest Queensland. Subsequent to this discovery, those authors formed Equinox Resources Limited (Equinox), which listed on the Australian Stock Exchange in 1994. Since listing, Equinox has focussed its exploration effort on IOCG style mineralisation, initially in the Gawler Craton of South Australia when the SAEI aeromagnetic surveys were released, and latterly in the Cloncurry District of northwest Queensland and the Curnamona region of South Australia.

In 1996 Equinox expanded its exploration for IOCG mineralisation into Zambia, through a joint venture with Anglo American Corporation, and in 1997 the Company initiated its activities in the Norrbotten Region of northern Sweden. An alliance has recently been formed between Equinox and Billiton to explore the Norrbotten Project.

The major IOCG deposits in Australia, Olympic Dam and Ernest Henry, are 'blind' deposits discovered under cover using primarily geophysical techniques, in particular good quality aeromagnetic data. Equinox's philosophy has been to focus on highly prospective, but unfashionable and poorly explored terranes, where large ground positions can be easily established. This usually means the geology in these terranes is poorly understood, with little geophysical and other regional data available. After a country or region is selected, a number of steps have to be undertaken in order to define targets, namely:

- Review and compilation of all relevant previous exploration and research work in the region;

- Acquisition of suitable aeromagnetic, gravity and remote sensing data, (in some cases acquired at considerable cost);
- Construction of a geological framework for mineralisation based on (1) and (2); and,
- Target selection, followed by drill testing of targets.

The Equinox targeting process applies a model for IOCG mineralisation constructed principally from studies of known mineralisation, in particular the Ernest Henry deposit and other mineralisation in the Cloncurry region, as well as the Olympic Dam copper-uranium-gold deposit on the Stuart Shelf/Gawler Craton of South Australia. This model is constantly refined and updated as new information becomes available. This paper presents a model for IOCG mineralisation, which was developed in the late 1980's and early 1990's by the Equinox team and then shows how it has been subsequently modified by the Company's experience in Australia, Zambia, Sweden and recent research work.

When the Equinox team initially commenced IOCG exploration in the late 1980's, only limited research on IOCG mineralisation was available. Consequently the team relied heavily on geological work by companies and AGSO in the Eastern Succession of the Mt Isa Belt. In particular, work on Starra, Mt Dore, Mt Elliott, and the SWAN deposit (Nisbet and Joyce, 1980; Nisbet, 1983; Nisbet, *et al.*, 1983), input by Mike Etheridge (SRK Consulting), and published material (Reeve *et al.*, 1990; Kary and Harley, 1990; Davidson *et al.*, 1989; Wyborn, 1992). This model is quite empirical in nature and not totally dependent upon interpretation of the genesis of specific deposits.

Equinox's Early - 1990's Exploration Model

IOCG deposits are essentially iron deposits with variable concentrations of principally Cu, Au, U, REE, Co, Ag, (Hitzman *et al.*, 1992; Reeve *et al.*, 1990). In the Cloncurry district, this metal associations is illustrated at Ernest Henry and at many smaller deposits such as Osborne (Davidson *et al.*, 1989), Starra (Kary and Harley, 1990), Mt Elliott (Nisbet, 1983), SWAN (Nyvult, 1980), Mary Kathleen (Derrick, 1977), and Mt Cobalt (Nisbet *et al.*, 1983).

The mineralisation constitutes the matrix to brecciated feldspathic rocks, with breccia textures showing a gradation from incipient crackle breccia to pervasively altered and rounded clasts that are matrix supported. The extreme alteration is an *in-situ* chemical digestion event and not necessarily due to tectonic milling.

Associated regional alteration is usually widespread and intense, and consists of sodic, calcsilicate, potassic, silicic, carbonate, scapolite, and tourmaline alteration. Oreskes and Hitzman (1993), present a cross section showing the relationship of alteration style to depth, with:

- magnetite-albite-actinolite at deep crustal levels;
- magnetite-K-feldspar-actinolite-biotite-sericite-chlorite at intermediate levels, and;
- hematite-sericite-carbonate-chlorite at the shallowest levels.
- Sericite-hematite-quartz alteration overprints all of these styles.

Note: magnetite bodies are commonly associated with the deeper and intermediate level alteration systems, and hematite with the shallower sericitic domains.

By inference, this depth zonation appears to correspond to a time zonation as well, with potassic alteration typically later than sodic alteration, and sericitic-silicic alteration typically the last event. Sulphide/Cu-Au-Ag-U-REE/apatite mineralisation seems to be enriched in the last phase of potassic alteration. Regional scapolite and tourmaline alteration is very common in the Cloncurry district and the Stuart Shelf, and to a lesser extent in the Kiruna region.

Alteration proximal to mineralisation is dominated by potassic phases, usually in the form of biotite and/or K feldspar (Cloncurry) or sericite (Olympic Dam). Associated products are magnetite/hematite, carbonate, amphibole and/or clinopyroxene/epidote.

The iron oxide occurs as dominantly magnetite at Ernest Henry and hematite at Olympic Dam, and both deposits are associated with intense magnetic anomalies. It is significant that within both the Cloncurry region and the Stuart Shelf (Gow *et al.*, 1994), there exist many other similarly intense magnetic anomalies resulting from extensive development of magnetite-hematite in highly altered breccia, but without economic copper and gold mineralisation. The explorationist may need to test numerous magnetic targets to find one with associated sulphides.

Mineralisation is considered to be epigenetic, and spatially related to the Williams-Naraku (Ernest Henry) and Hiltaba (Olympic Dam) suite A-type granitoids (Wyborn, 1992). These granitoids are high temperature, highly fractionated and enriched in Cu, K, U, Th, and silica, with ages around 1480 to 1590 Ma. This Mesoproterozoic age was considered to be an important, but not necessarily critical factor in area selection. Regional-scale aeromagnetics and gravity suggest that mineralisation is usually localised in proximity to the roof zones of these large granite bodies.

Mineralisation was precipitated from saline, oxidising fluids circulating at the time of granite intrusion. These fluids resulted from the mixing of magmatic fluids with supracrustal fluids, possibly including fluids derived from evaporites. The fluids were funnelled into structures active at the time of granite intrusion, and precipitated in dilational zones in or adjacent to these structures.

The country / host rocks are typically quartzo-feldspathic rocks such as felsic to intermediate volcanics, granitoids, quartzites and arkoses/psammites. Host rocks to the large deposits (Ernest Henry, Osborne) are not the most reactive rocks in the sequence (e.g., calcsilicates or black shales), but mechanically competent quartzo-feldspathic rocks which provide competency contrasts and potential dilation/precipitation sites during deformation. This suggests that mechanical controls are more important than chemical controls in localising mineralisation, and usually deposits with calcsilicate or black shale host rocks (Mt Elliott, Mt Dore) are smaller tonnage and higher grade, with relatively low magnetite content.

Exploration in Zambia

IOCG Mineralisation

An overview of the Proterozoic geology of the African continent was carried out by Equinox from published sources, focussing on key granitoid suites and areas of regionally developed Cu-Au-U-Co-Ag mineralisation, particularly where associated with iron-rich rocks. Whereas the Proterozoic of Australia is dominated by 1900 to 1400 Ma ages, the Proterozoic of Africa is largely comprised of pre-1900 Ma, and post-1400 Ma sequences. Despite the significant differences in the overall character and age of the Proterozoic sequences between the two continents, there is widespread evidence of Proterozoic IOCG deposits in Africa.

The initial research phase identified Zambia as a country with outstanding IOCG potential. Regional target identification in Zambia used a number of datasets, including:

- the SANABOZI (Southern Africa) regional aeromagnetic dataset;
- a 1:1 million scale Landsat MSS Image;
- the Zambian Geological Survey (ZGS) 1:1million scale Geological Map of Zambia (4 sheets);
- 1:2 million scale ZGS Geological and Mineral Occurrence Map of Zambia;
- a report by Watts, Griffis and McOuat, 1991 commissioned by and purchased from the Zambian Government.

Most of Zambia is within a northeast-trending Proterozoic mobile belt, the 'Kibaran Mobile Belt', which was probably initiated in the Palaeoproterozoic, but is dominated by Neoproterozoic rocks and structures. Numerous granitoids have been delineated from the aeromagnetics, both outcropping and in the sub-surface (Fig. 1), and of particular significance as a source of IOCG mineralisation is the Hook Batholith.

The Hook Batholith is associated with the most intense magnetic variation of all the geological entities in Zambia. On a broad scale, the Hook Batholith can be characterised magnetically as a composite body, the older phase associated with flat aeromagnetics (Unit HG1 in Fig. 1). A younger phase, Unit HG2, truncates Unit HG1 and is associated with numerous circular, magnetically flat granitoid bodies with magnetic anomalies in their carapace. Unit HG2 thus includes late Hook Granite varieties plus all the carapace units which the late Hook Granite phase has altered, including metasediments and volcanics, felsic gneisses, and earlier Hook granite. Work by Equinox personnel has shown that Unit HG2 of the Hook Batholith is complex in detail, with numerous phases, both foliated and unfoliated, and extensive biotite-silica-K feldspar-tourmaline-epidote-magnetite-hematite-pyrite alteration.

A number of shear zones have also been identified which were active during intrusion of Unit HG2, in particular north-south shear zones, east-west shear zones, and northeast trending shear zones. These shear zones in some areas truncate Unit HG2, and elsewhere are cut by HG2 granites. These structures were clearly active during HG2 granite intrusion. Most of the large mass of Unit HG2 is in the Mumbwa area west of the Mwembeshi Shear Zone, although a lobe occurs to the east and south as well.

This main zone of Hook Batholith in the Mumbwa area contains numerous iron and copper mineral occurrences within the Hook Granite and iron, gold and copper-silver in the Katanga Supergroup (Griffiths, 1977; Watts, Griffis and McOuat, 1991; also Fig. 1). Skarn and replacement mineralisation in breccias and cross-cutting pipe-like bodies is described, often associated with fluorite, galena and sphalerite. Most copper-only mineralisation (Sable Antelope, Silver King) is hosted in argillaceous and carbonate rocks, though mineralisation within syenite is also reported. copper-gold mineralisation at Chifumpa northwest of Mumbwa (Sugarloaf, Lou-Lou) is located in brecciated Kundelungu Dolomite and 'diorite'. Gold mineralisation usually occurs in silicified breccias in a variety of rock types. Iron deposits occur as magnetite and magnetite replaced hematite skarns and breccias.

Additional areas of HG1 and HG2 phases of the Hook Granite intruding the Katangan Supergroup rocks have been delineated in a large area southwest, west and northwest of Mumbwa, as shown in Fig. 1. As well, a north-south trending zone 150 km long and 50 km wide passing through Kasempa contains iron mineralisation (229 million tonnes averaging 66% Fe in 10 deposits) hosted by brecciated Upper Katanga Supergroup rocks associated with a suite of syenites. This iron mineralisation occurs as hematite or magnetite with sulphides as veins and replacements. Extensive silicification, gold-copper sulphide mineralisation, and Fe occurrences in brecciated Upper Kundelungu Group and porphyries are described from the Kalengwa area, including the Kalengwa Deposit, from which 1.6 million tonnes grading 6.45% Cu have been mined.

Dating of some deformed and undeformed phases of the Hook Batholith produced 570 to 530 Ma ages (Hanson *et al.*, 1993), though the actual range may be larger. Hanson *et al.*, (*op. cit.*) suggest that all phases are post-Katangan, with the batholith mainly composed of older, medium grained biotite-hornblende granitoid intruded by microcline-biotite-hornblende megacrystic granitoids. Both varities vary from massive to highly foliated. Cosi *et al.*, 1992, produced a U-Pb in zircon date on a syenite from the Solwezi area of 513 Ma, and many other ages of this general range have been reported (Masters, 1998). Equinox considers that the HG2 phase of the Hook Batholith to be the most prospective phase for exploration for IOCG mineralisation in Zambia.

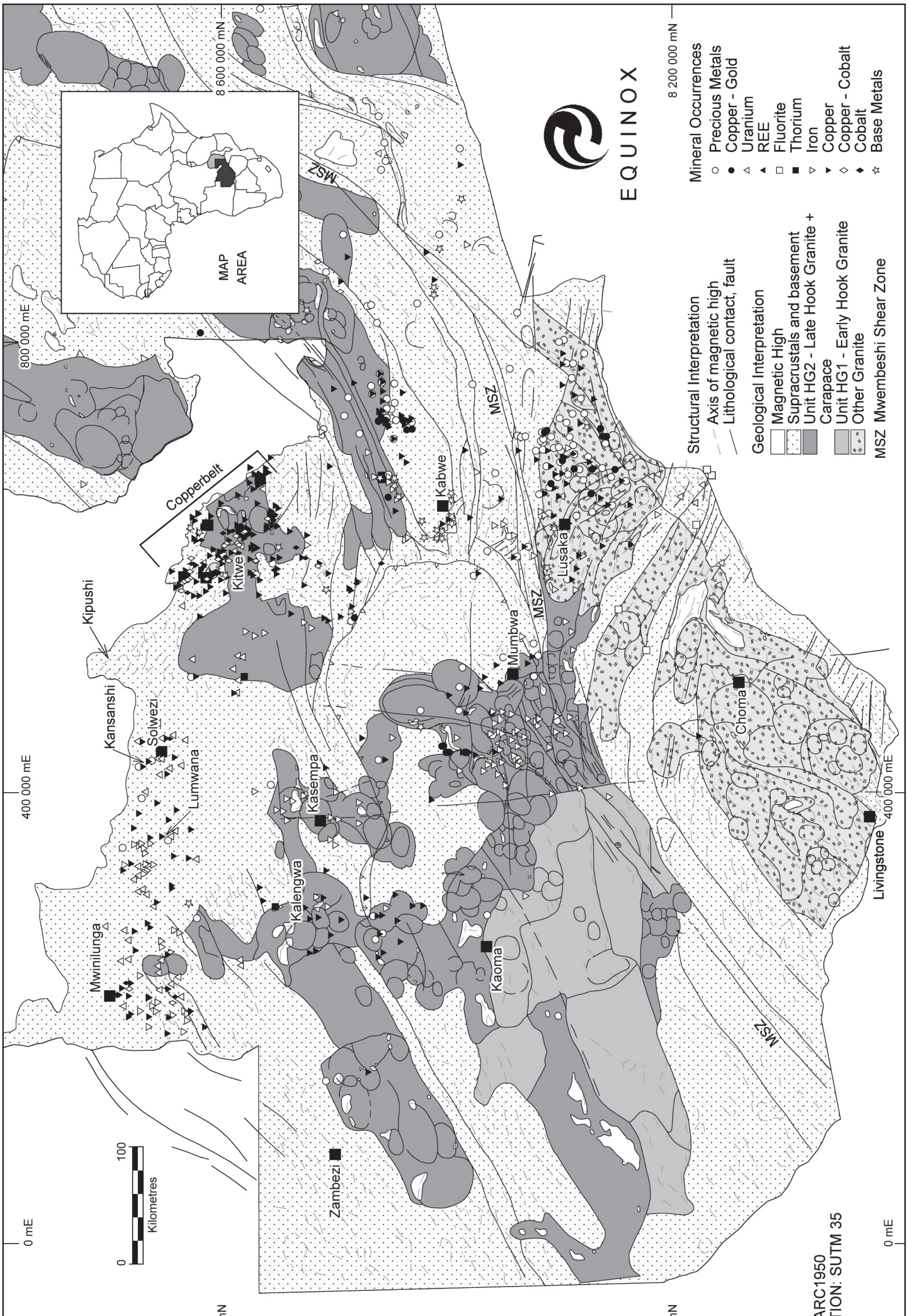

Figure 1: Aeromagnetic interpretation of Zambia showing the distribution of granitoids, structure and minerals occurences.

Copperbelt Mineralisation

Copperbelt mineralisation has previously been described as stratiform and stratabound, and is widely interpreted to be either syngenetic (Fleischer *et al.*, 1976), or diagenetic (Cailteux *et al.*, 1994a,b) by most workers. However, more recent research is favouring a structurally controlled epigenetic model for the Copperbelt mineralisation. While it is acknowledged that Copperbelt mineralisation does not fit the classic Proterozoic IOCG model, many deposits in the Cloncurry area were initially considered to be syngenetic (Davidson *et al.*, 1989), and Olympic Dam was originally thought to be a syngenetic-diagenetic-synrift type deposit (Roberts and Hudson, 1983).

Features suggesting some compatibility of the Copperbelt with the IOCG model are;

1. Host Rock Age and Type - Whereas most copper-cobalt mineralisation in Zambia is confined to the Roan Group, significant uranium, copper-cobalt, and lead-zinc mineralisation occurs throughout the Katanga Supergroup in the Kundelungu Group (e.g. Kipushi and Kansanshi), in the Muva Supergroup (Lumwana) and Basement Complex (Lumwana). Work by Equinox indicates that mineralisation from the above localities resembles the Copperbelt mineralisation in mineralogy and associated alteration. This setting is analagous to the Cloncurry and Stuart Shelf regions, where mineralisation is related to late granitoids, but is hosted by rocks of various ages.

2. Metal Association - Mineralisation in the Copperbelt is principally copper-cobalt-iron-rich, and in the Northwestern Province significant U and Au mineralisation and lesser F mineralisation are also described. This metal association is very similar to the IOCG metal association.

3. Alteration - Copperbelt mineralisation is hosted by rocks of lower greenschist to upper-amphibolite facies metamorphic grade, with 'metamorphic veins' of specularite-microcline-anhydrite-quartz (Fleischer *et al.*, 1976) extending for at least 100m down into the basement. The most common alteration mineral associated with copper mineralisation is carbonate, usually dolomite, but less commonly muscovite, tourmaline, tremolite and scapolite. These alteration assemblages are similar to those from Olympic Dam and Ernest Henry.

4. Granite Association - The basement in the Copperbelt is intruded by various granitoids, including the pre-Roan Nchanga Red Granite and Muliashi Porphyry. In the Copperbelt region, individual magnetic units are hard to define and harder to relate to the mapped geology, though a 150 by 100 km elongate, northwesterly trending, diffuse magnetic high visible in the SANABOZI data may represent a large Hook Granite body at depth. Detailed aeromagnetics indicates the presence of various magnetic aureoles within the basement granites, suggesting that the basement includes younger granites of various ages, possibly including Hook Batholith ages.

5. Association with Deformation - Copperbelt mineralisation is often associated with tectonic breccias (Cailteux *et al.*, 1994a,b; Master, 1998), layer-parallel veining and shear zones (authors personal observations at; Mindola, Chibiluma, Baluba, Nchanga and; Chambishi Mines; Ross McGowan, University of Southampton, *pers, comm*, 2000). Furthermore the 'ore shale' commonly displays intense and tight 'drag folding' (Fleischer *et al.*, 1976), which is particularly well developed at Mindola and Chambishi. A decollement is mapped in the sequence above the 'ore shale' at Nchanga (Fleischer *et al.*, *op. cit.*).

6. Age of Mineralisation and Host Rocks - Most mineralisation discovered to date is hosted by the Lower Roan Formation of the Katangan Super Group. These rocks unconformably overlie the Nchanga Granite in the Copperbelt, and Master (1998), dates the Lower Roan sequence at about 870 to 880 Ma, mainly based on an 879±16 Ma age from the basal Kafue Rhyolite. The immediate hangingwall of the ore at Lumwana in Northwestern Zambia has been dated by U-Pb in zircons at 1200 to 1400 Ma (Cosi *et al.*, 1992).

There has been only limited dating of Copperbelt mineralisation, but pitchblende at Lumwana gives an age of 512 Ma (Cosi *et al.*, 1992). Re-Os ages of molybdenite from the Kansanshi Deposit, hosted in Kundelungu Formation 175 km west of the Copperbelt gives a range of ages from 503 to 513 Ma, and a SHRIMP U-Pb age from monazite of 509 Ma (Torrealday, 1999). These mineralisation ages fall within the age range of the Hook Batholith described above. Consequently there is a substantial time period between deposition of host rocks and formation of mineralisation in at least two of the major Copperbelt-style deposits, with mineralisation ages compatible with the age of Hook Batholith intrusion.

Conclusions-Zambia

In summary, IOCG mineralisation has been identified in Zambia, and is associated with the Cambrian age Hook Batholith. The Hook Batholioth is syn to late Lufilian Orogeny, which is part of the Pan African deformation which affected most of the African continent. Copperbelt style mineralisation in Zambia is poorly dated, but available dates from similar deposits suggest an age for mineralisation contemporaneous with the Hook Batholith. Other features such as metal association, alteration styles, and association with deformation tend to confirm this age, suggesting that the Copperbelt copper-cobalt mineralisation may be contemporaneous with Pan-African tectonism and Hook Batholith intrusion.

Exploration in Sweden

Cliff *et al.* (1990), and Hitzman *et al.* (1993), highlighted the similarity between Olympic Dam and the iron ore deposits of the Kiruna region in northern Sweden (Norrbotten). This lead to a field visit to Sweden by Equinox in 1996, and the establishment of a Swedish exploration program by Equinox in 1997 (Fig. 2).

The Fennoscandian or Baltic Shield is composed of Archean to Mesoproterozoic rocks and outcrops in Norway, Sweden, Finland and the Kola Peninsula of Russia (Weihed and Maki, 1997; Martinsson, 1997). These rocks are bounded to the northwest and southeast by Phanerozoic and Caledonide sequences.

A complex suite of early orogenic calc-alkalic and I-type granitoids are described in northern Fennoscandia, with ages ranging between 1950 to 1860 Ma. In Finland these are represented by the Central Finland Granitoid Complex, dominated by granodiorites to tonalites, which appear co-magmatic with at least some of the volcanics (Weihed and Maki, 1997). In northern Sweden the Jörn and Haparanda Granites are part of this suite, the latter probably coeval with the Porphyrite Volcanics (Bergman, 1997). Late orogenic S-type granites of the Lina-Härnö Suite and Skellefteå Granites were emplaced around 1820 to 1790 Ma in northern Sweden, and are characterised by their migmatitic and highly deformed nature (Weihed and Maki, 1997).

Late to post-Svecokarelian A to I-type alkaline Revsund and Trans-Scandinavian Igneous Belt granitoids were emplaced between 1800 to 1780 Ma, although this intrusive phase continued intermittently until ~1650 Ma. (Weihed and Maki, 1997). The Revsund Granite Suite comprises I/A-type granitoids, which were largely intruded after the main phases of deformation, and post-date peak regional metamorphism (Billström and Weihed, 1996). Although Revsund granites are regarded as post-orogenic, numerous shear zones cut these granitoids indicating that intrusion corresponded partially with deformation (Billström and Weihed, 1996).

These granitoid ages and structural relationships suggest the Baltic Shield is geologically comparable to the highly mineralized shield areas of Australia, Canada and Africa, but substantially under-explored by comparison. Significant economic deposits are located in northern Sweden including the Kiirunavaara iron oxide deposits and the Aitik copper-gold deposit, western Europe's largest copper mine (Frietsch *et al.*, 1997). The large iron oxide deposits of northern Sweden are considered by Swedish workers to have formed as either primary magnetite-rich lava flows (Frietsch, 1978) or chemical sediments (Parak, 1975). However Blake and Williams (1997), and Cliff *et al.* (1990), consider that most of the magnetite at Kiirunavaara was precipitated from fluids of magmatic origin, and that the magnetite was emplaced between 1950 to 1880 Ma., a similar age to the enclosing felsic volcanics and granites of the Jörn -Haparanda Suite. Regional alteration comparable to that of the Cloncurry region is described from northern Sweden (Frietsch *et al.*, 1997; Blake and Williams, 1997), and can be seen at Gruvberget and Levieneimi. As well, numerous copper-gold occurrences in the region have similarities to the IOCG mineralisation, e.g. Pahtohavare, Nautanen, Bidjovagge, Liikkavaara, Svaapavaara, Stuor-Ratek (Frietsch *et al.*, 1997).

The iron oxide deposit and its associated alteration system at Kiirunavaara is similar in size to the Olympic Dam alteration system, albeit copper-uranium-gold-silver poor in comparison. As there are many sulphide-poor iron oxide alteration systems in the vicinity of both Ernest Henry and Olympic Dam, it is possible that Kirunavaara is an example of such a sulphide-poor system, and that a major copper-gold-silver-uranium deposit is yet to be discovered in the region.

Interpretation of aeromagnetics and gravity data and fieldwork by Equinox suggests there are three types of iron oxide mineralisation in the Norrbotten region:

Type 1 - Early Magnetite Ores

Early Magnetite Ores (e.g. Kiirunavaara, Luossavaara, Tuolluvaara) associated with amphibole-K-feldspar-albite-quartz-carbonate-fluorapatite-scapolite alteration assemblages. These are composed of magnetite and apatite, varying from a massive magnetite-rich core (>50% Fe) to margins of brecciated and altered felsic volcanics with the breccia matrix composed dominantly of magnetite-amphibole and /or biotite. On a regional scale these bodies are deformed and associated with reverse faulting. They are probably of 1950 to 1880 Ma age as determined by Cliff *et al.* (1990).

Type 2 - Hematite-Magnetite Ores

Hematite-Magnetite Ores (e.g., Haukivaara, Henry, Nukutus, Rektorn and Lappmalmen) associated with sericite-carbonate-K feldspar-quartz-apatite-scapolite alteration. This style overprints Type 1 mineralisation, and is probably related to later movement along northerly trending thrusts that repeat stratigraphy.

Type 3 - Late Magnetite Mineralisation

Late Magnetite Mineralisation (Mertainen, Stuor-Ratek) associated with similar alteration to the early magnetite mineralisation, but is considered by Equinox to cross cut early magnetite and early structures on a large scale. This type of mineralisation is spatially related to late felsic plutons which have been dated by Martinsson, (1997a,b) at 1800 to 1790 Ma, that is, coeval with the Revsund Suite.

Equinox considers that the iron oxide deposits at Kiruna formed within alteration systems related to structures coeval with the emplacement of fractionated granites into the felsic-intermediate host rocks. The subsequent overprinting of the magnetite orebodies by compressional structures and associated hydrothermal activity (Hauki, Henry, Nukutus) enriched in incompatibles (as evidenced by higher K, P, REE, F and Cu levels) has produced replacement of magnetite by hematite. Later magnetite alteration overprints these assemblages. Further studies are necessary to determine the ages of mineralisation, the mineralising structures, the granite phases associated with the deposits and other aspects of the mineralised system that may provide targeting criteria for exploration.

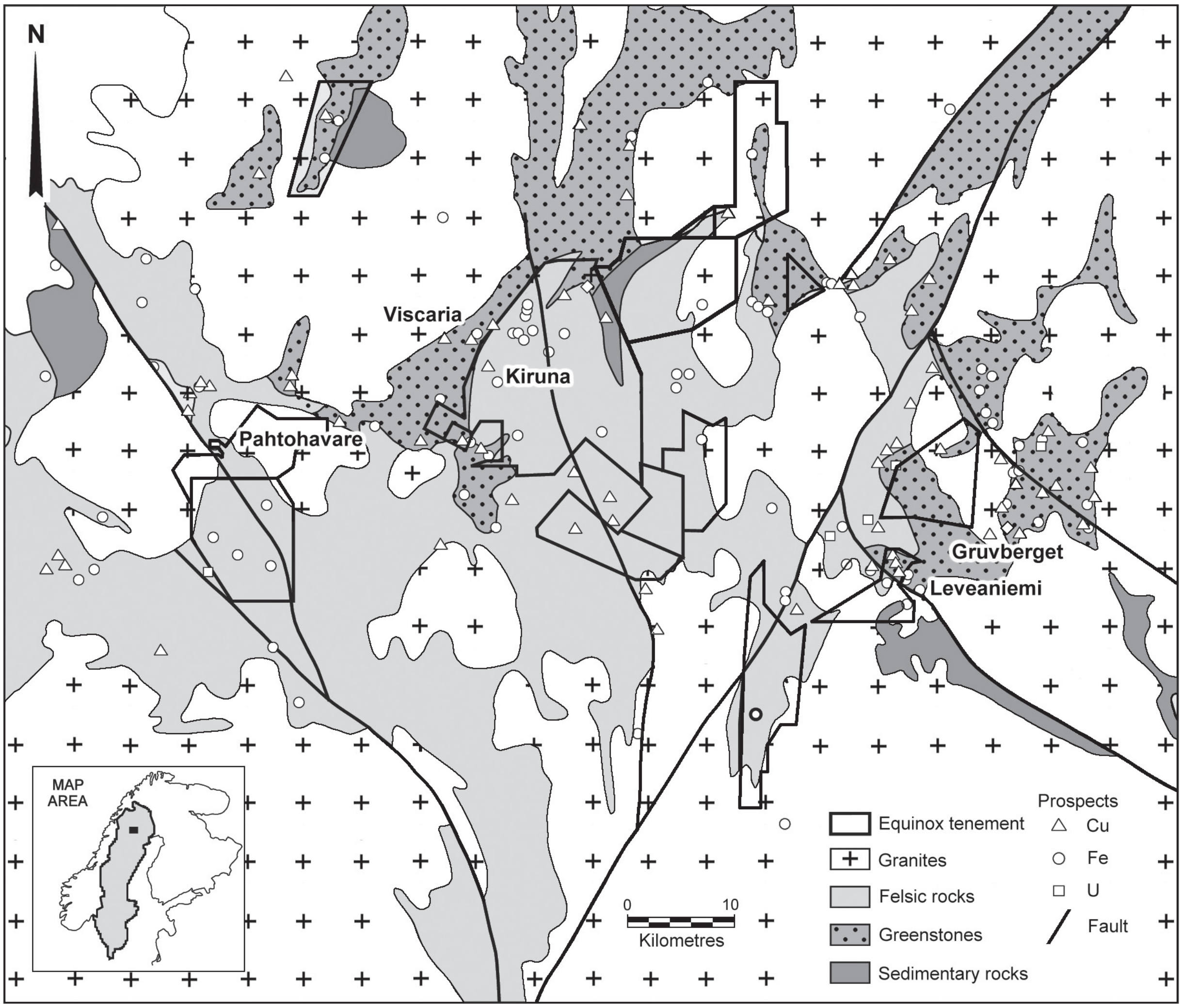

Figure 2: Geological map of the Kiruna region in northern Sweden showing the Equinox licences.

Advances in IOCG Research

Extensive research in the IOCG style of mineralisation has been conducted during the 1990's, particularly in Australia in the Cloncurry region and in the Stuart Shelf of South Australia. The following is a summary the thrust of this research, and an explanation of the modification of the Equinox model for IOCG mineralisation.

Timing of Mineralisation and Alteration

Extensive age dating, particularly Ar-Ar ages of biotite and amphibole and U/Pb in zircons (Perkins and Wyborn, 1998; Page and Sun, 1998) in the Eastern Succession at Mt Isa and of the Olympic Dam deposit (Johnson and Cross, 1995) have demonstrated that mineralisation and alteration assemblages are demonstrably very late in the structural/metamorphic sequence in both these areas. Furthermore, this work has shown that alteration ages overlap with ages of the Williams-Naraku granites (1550 to 1485 Ma) in the Eastern Succession and the Hiltaba Suite intrusives in the Stuart Shelf (1590 to 1580 Ma).

Although in Australia both the Stuart Shelf and the Cloncurry host sequences and associated granitoids are Mesoproterozoic in age, there is no convincing evidence that any particular host-stratigraphic age or granitoid age is required for IOCG mineralisation. Williams, (2000), suggests IOCG mineralisation in Australia formed in the period from 1850 to 1500 Ma. Other examples of IOCG mineralisation occur in the Punta del Cobre district, Chile (La Candelaria; Marschik *et al.*, 1997), and dating of biotite coeval with mineralisation by these authors gave a mineralisation age of 115±1.0 Ma, indicating that IOCG mineralisation is not confined to a specific time period in the Mesoproterozoic as previously thought.

Relationship of Mineralisation to Granites, Gabbros and Ultramafics.

Wyborn, (1992) was one of the first to point out the temporal and spatial proximity of A-type granitoid suites and mineralisation in the Cloncurry and Stuart Shelf regions, and the question remains as to whether the granites the source of the mineralisation or part of the mineralising process. Pollard *et al.* (1998), have divided the Williams-Naraku Batholiths into the Cloncurry Supersuite and the Eureka Supersuite. They suggest that mineralisation is likely to be related to the Shoshonitic Eureka Supersuite, probably formed by partial melting of incompatible element-enriched gabbroic rocks in the lower crust (see also Wyborn, 1998). This melting was caused by intrusion of basic magmas into the crust.

A similar proposal is made by Campbell *et al.* (1998), for the Olympic Dam area. They suggest that mineralisation was derived from oxidised alkali mafic/ultramafic bodies which fractionated to produce the metal-rich hydrothermal-magmatic fluids which gave rise to the mineralisation. These mafic magmas are similar in age to the Hiltaba Suite of granitoids. Knutson *et al.* (1992), suggest the copper mineralisation in the Stuart Shelf was leached from mafic volcanics in the Gawler Range Volcanics, a proposal also put forward by Haynes *et al.* (1995).

Skirrow (1999), reviewed exploration criteria for IOCG systems in general. He proposes that mafic rocks in the supracrustal sequence, possibly indicated by regional bouguer gravity anomalies, may be a favourable empirical criterion for mineralisation in IOCG systems. Extensive mafic volcanics are mapped in the Kiruna region (Porphyrite Group, Bergman, 1997) and these rocks are underlain by large bouguer gravity highs, suggesting widespread mafic rocks at depth in Norrbotten.

Notwithstanding these observations, when an explorationist is faced with a poorly known and unexposed region, the relevant detail may not be available to discriminate using these criteria. In many regions, significant mafic-ultramafic sequences may be present but not recognised, However, if aeromagnetic data are available, the presence of suitable A-type granitoids and associated iron oxide alteration will be relatively easy to identify, and will be the primary criterion for indicating the attractiveness of the region for IOCG mineralisation.

Nature of Fluids

Fluids described in the various deposits are usually highly saline and oxidising, but sometimes reducing (Skirrow, 1999). Various fluid sources have been proposed for IOCG mineralisation (Twyerould, 1997), namely:

- Direct crystallisation from an intrusive iron-rich melt (Frietsch, 1978);
- Exhalative-sedimentary model (Parak, 1975);
- Precipitation from iron-rich hydrothermal fluids fractionating from granitic bodies (Wyborn, 1998 and Oliver, *et al.*, 2000);
- Metal leaching of country rock by deep-circulating hydrothermal cells related to granitoid emplacement (Hitzman *et al.*, 1992). Barton and Johnson (1996), modify this model with input from evaporitic rocks in the sequence; and,
- Mixing of deeply circulating hydrothermal fluids and near-surface saline fluids (Haynes *et al.*, 1995, Gow *et al.*, 1994).

Isotope studies support these models to varying degrees in different regions (Skirrow, 1999), and a composite of models 3, 4 and 5 is favoured, with input from evaporitic horizons in the sequence considered important. However Skirrow (1999), points out that evaporites are not necessary to generate these fluids, and unequivocal identification of evaporites in the relevant sequences in Australian examples has only been made in the Cloncurry area. Identification of evaporites in a highly metamorphosed sequence may be difficult, and often the presence of widely developed scapolite alteration would be seen as very encouraging. Scapolite is widely developed in both the Norrbotten region (Frietsch *et al.*, 1997) and Zambia (Fleischer *et al.*, 1976).

Structure

Deep seated structures active around the time of granite emplacement provide the conduits for the flow of mineralizing fluids (Pollard *et al.*, 1998). Dilational sites in these faults are the proposed 'trap sites' for mineralisation (Beardsmore, 1992). In many cases these faults may be early faults which have been reactivated during later deformation. Pollard *et al.* (1998), propose that the granites cannot generate their own fluid pathways at mid-crustal depths, but must use existing faults or structures which are active when they are intruding.

The Equinox team's studies at Ernest Henry indicate that the deposit is localised by flat dipping, northeasterly trending thrust faults linking north-northwesterly and north-northeasterly-trending, steeply east-dipping reverse faults in an approximately east-west compressional regime (Fig. 3). As well, other deposits in the Cloncurry region are associated with late reverse faults (Osborne: Adshead *et al.*, 1998; Mt Elliott: Fortowski and McCracken, 1998; Mt Dore: Beardsmore, 1992; Nisbet, 1982), suggesting that favourable sites for localisation of mineralisation are dilational zones in late D_2 or D_3 reverse faults or associated structures.

The structural setting at Olympic Dam is more equivocal, but Drexel *et al.* (1993), consider that the Olympic Dam Breccia Complex is localised within a dextral dilation zone in a west-northwesterly trending wrench fault system. West-northwesterly and northwesterly faults active during granite emplacement in the Stuart Shelf have also been identified by Gow *et al.* (1994).

Nature of Host Rocks

The most favourable hosts for large deposits are quartzo-feldspathic rocks, e.g. felsic to intermediate volcanics (Ernest Henry, La Candelaria), granites (Olympic Dam) and feldspathic psammites (Osborne). Lower priority hosts are skarns, BIFs, magnetite units, or reducing units (carbonaceous shales), though deposits in these host rocks tend to be smaller (Starra, Mt Dore, Kuridala). Mafics and calcsilicates are not good hosts, though calcsilicates may be an important source of fluids for reacting with circulating metamorphic/igneous mineralising fluids.

Evolution of the Equinox IOCG Model

The Equinox IOCG model has evolved with continuing research and experience in geological terranes other than those in the Proterozoic of Australia. Significant changes to the early 1990's exploration model of Equinox include the following:

- Age of mineralisation is not critical. IOCG mineralisation worldwide has been shown to vary from 1900 to 100 Ma in age.

- A-type and related granitoids are critical in the target region, but may be simply an indicator of the tectonic process rather than the source of the fluids or metals. Close proximity to the roof zones of these granitoids is encouraging, but no longer thought to be an essential criterion.
- Magnetics is an important exploration tool, both to generate direct targets and to elucidate regional and local geology. If magnetite is a host for mineralisation rather than being coeval with it, magnetic lows or conductivity / resistivity anomalies within magnetic highs may be better targets than the magnetic peaks.
- Mafics may be an important component in the mineralising system, both for mineralising fluids and metals, and may be recognisable with regional gravity data. In a poorly explored or outcropping region, however, these rocks may not have been identified, and their presence or absence should not be seen as a negative factor.
- The presence of evaporites may be important as a source of saline fluids, but they are often difficult to recognise,

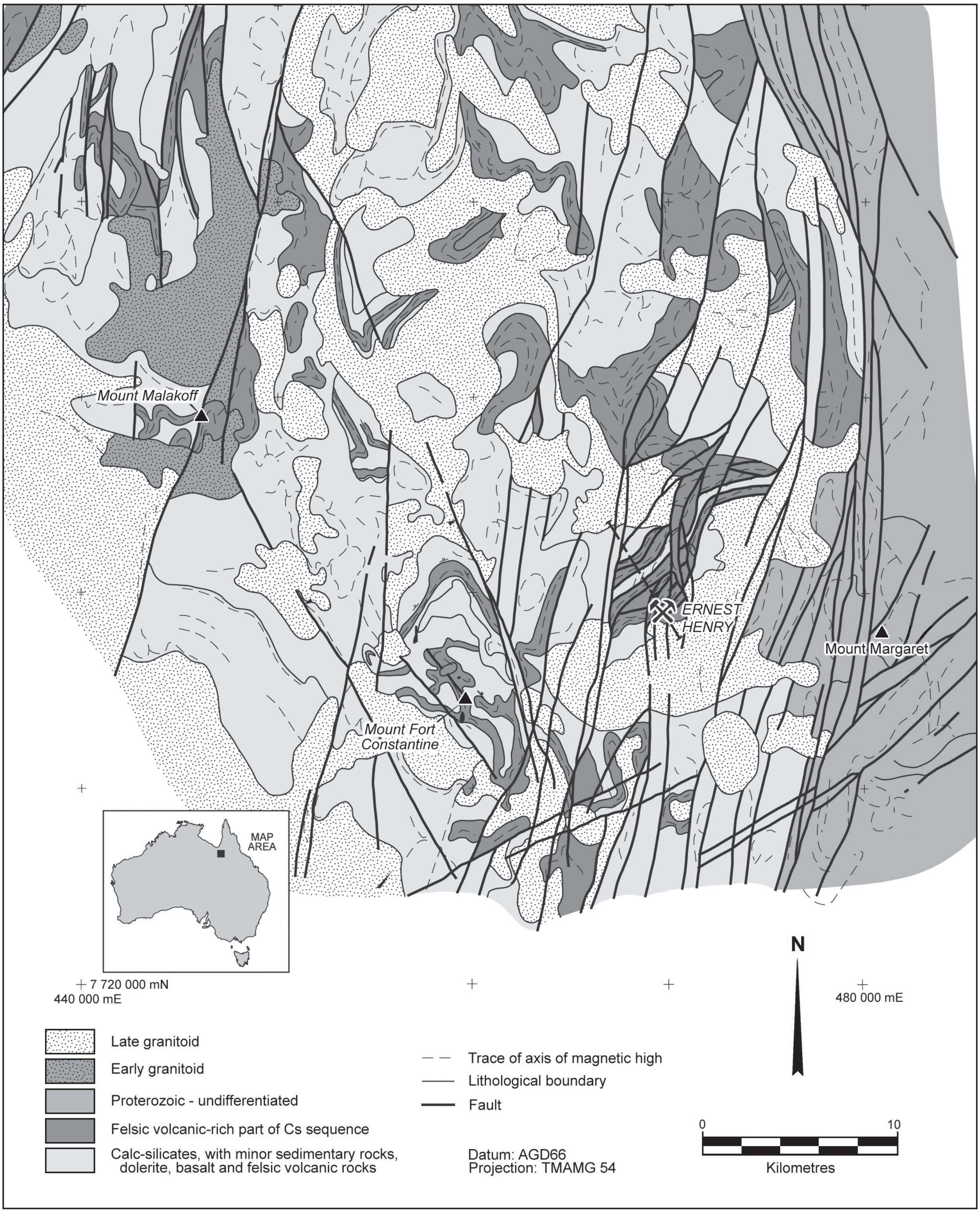

Figure 3: Aeromagnetic interpretation of the Ernest Henry region, showing granitic intrusives, structure and magnetic highs.

even in well-mapped regions. Their absence should not be seen as a negative factor, especially if scapolite is widely distributed in the region.

- Gravity data could be critical in the discovery process, both to elucidate geology and for direct targeting, especially if dealing with hematite-dominant mineralisation.
- Experience in the Copperbelt and the Western Gawler of South Australia by Equinox suggests that other styles of mineralisation, for example low Fe/ high S, may be of similar age and source to IOCG mineralisation. These styles should be also considered during exploration for IOCG mineralisation.

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