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CURRENT UNDERSTANDING OF IRON OXIDE ASSOCIATED-ALKALI ALTERED MINERALISED SYSTEMS: PART I - AN OVERVIEW

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Abstract - This two part paper discusses the classification, definition and characteristics of what may be termed "iron oxide-alkali altered" mineralised systems - a grouping that collectively incorporates both iron oxide copper-gold (IOCG) *sensu stricto* ores, and otherwise similar deposits that also have abundant related hydrothermal iron oxides and associated alkali alteration, but are copper-gold deficient. It both summarises and reviews the lithospheric- to deposit-scale setting, tectonic and structural controls, associated magmatism, temporal distribution, implied crustal-scale sources and circulation dynamics of ore-related fluids, and the resultant alteration and mineralisation patterns, for most of the world's provinces hosting significant examples of these mineralised systems.

These iron oxide-alkali altered deposits, and IOCG *sensu stricto* ores in particular, are characterised by: (1) the large to giant size (>100 Mt to >9 Gt @ 0.5 to 1.5% Cu, 0.3 to 0.8 g/t Au + REE, ±U, ±Ag) of the more significant examples; (2) the vertical depth of formation window within which they may occur (from >12 to ≤2 km); (3) the regional (>10 to >1000 km^2) and vertical (surface to at least mid-crustal) scale of surrounding alteration systems; and (4) the alkali-iron oxide rich nature (sodic/calcic/potassic+magnetite/hematite) of both regional- and deposit-scale alteration/mineralisation patterns. These characteristics illustrate the lithospheric scale of the regimes responsible for their generation.

All significant IOCG and related deposits are characterised by a clear temporal, but (usually) not close spatial association, with batholithic complexes, composed of both anorogenic granitoids and varying proportions of mantle related, fractionated, mafic to intermediate phases. These magmatic events are accompanied by either (1) extensive outpourings of comagmatic bimodal basaltic-andesitic and felsic lavas and pyroclastics, in varying relative proportions; and/or (2) by numerous and equally widespread, but generally small (although sometimes large) coeval juvenile mafic dykes, plugs, sills and layered complexes. These magmatic complexes extend over areas of tens of thousands of km^2, representing extensive igneous provinces, interpreted to reflect underplates at the base of the sub-crustal lithospheric mantle (SCLM), and/or intraplates immediately below the Moho density filter. The under- and intraplates comprise large fractionating mantle-derived magma chambers, the result of either crustal delamination and detachment, or mantle plume events that triggered decompression melting in the upper mantle, generally at depths of <100 km.

Igneous events of this type, coincident with iron oxide-alkali altered mineralised systems, are distributed throughout the geological record from the Neoarchaean to Tertiary. However, those related to significant IOCG *sensu stricto* deposits would appear to be restricted to: (1) the period of major crustal generation during the Neoarchaean from 2.8 to 2.4 Ga, and (2) the periods following consolidation of the Nuna/Columbia, Rodinia, (the short-lived) Pannotia and Pangea supercontinents, coinciding with extensional phases accompanying the commencement of break-up from 1.60 to 1.45, 0.85 to 0.75, 0.57 to 0.51 and 0.165 to 0.095 Ga respectively.

The under- and intraplates, and associated high temperature metamorphism and anatectic magmatism, acted both as heat engines, driving fluid circulation cells and consequent alteration over large volumes of the crust, and as fluid sources. Structurally controlled fluid cell circulation is reflected by concomitant alteration, occurring as either linear corridors of alteration up to tens × hundreds of kilometres, or by more equidimensional regions associated with orthogonal patterns of faulting or fracturing that may cover tens to >1000 km^2.

Iron oxide-alkali altered mineralised systems are interpreted to have been the result of one or more of: (1) CO_2- and volatile-rich, magmatic-hydrothermal fluids/vapours released directly from fractionating mantle-derived magma chambers or related mafic intrusions in the lower- to mid-crust; (2) hypersaline, iron- and alkali-rich, magmatic-hydrothermal fluids, exsolved within fractionated anorogenic and/or mafic to intermediate juvenile batholiths, which have inherited volatiles, water and other components from the related intraplate; (3) fluids produced by high temperature metamorphism induced by an intraplate, and/or anatectic magmatism; (4) sedimentary formation/basinal waters; (5) surface derived bittern brines, or re-dissolved buried evaporites. Any of these fluids may carry components related to the processes involved in their formation, or exsolved or scavenged from the rocks through which they are circulated.

In most major IOCG provinces, the earliest fluid circulation and alteration occurs on a regional- or district-scale, progressively reducing in areal extent with time, evolving to deposit-scale zones. Regional scale alteration usually commences at depth with early sodic-calcic±iron (albite/scapolite±magnetite), related to either deeply circulated formation/basinal waters or magmatic-hydrothermal fluids, accompanied by a statistical depletion of ore forming solutes in altered rocks. This alteration usually predates ore, with scavenged solutes potentially sequestered for future reworking. Regional alteration progresses, both temporally and spatially upwards (i.e., with decreasing temperature), to potassic with increasing iron oxides (biotite/K feldspar±magnetite), to iron-sodic-calcic (magnetite-scapolite-apatite-actinolite) or iron-potassic-calcic (magnetite-K feldspar-actinolite±carbonate) at deep or shallower levels respectively, both of which commonly host major iron oxide-apatite accumulations. IOCG *sensu stricto* deposits, where developed, generally post date this oxidised, sulphur deficient stage. Fluid inclusion and related data are supportive of, but do not in most cases unequivocally prove, the influence of a second fluid in the formation of IOCG *sensu stricto* deposits, triggering the precipitation of sulphides, most likely of either shallow basinal or of further magmatic-hydrothermal origin.

Alteration patterns associated with these deposits progress both temporally and upwards from the pre-ore regional assemblage at >500ºC, to progressively overprinting biotite and then K feldspar (~450ºC), to chlorite-muscovite-sericite (hydrolytic) and finally to a muscovite and hematite dominant assemblage high and late in the system, at temperatures of <250ºC, often with late carbonate ±quartz veining, and in some instances a late barren siliceous stage.

Most iron oxide-alkali altered deposits are related to rock porosity and permeability on a deposit-scale, occurring in shear zones, tectonic and explosive breccias, or volcanic and/or sedimentary breccias that control aggressive to passive ingress and reaction of fluids with wall rocks, clasts and breccia matrix.

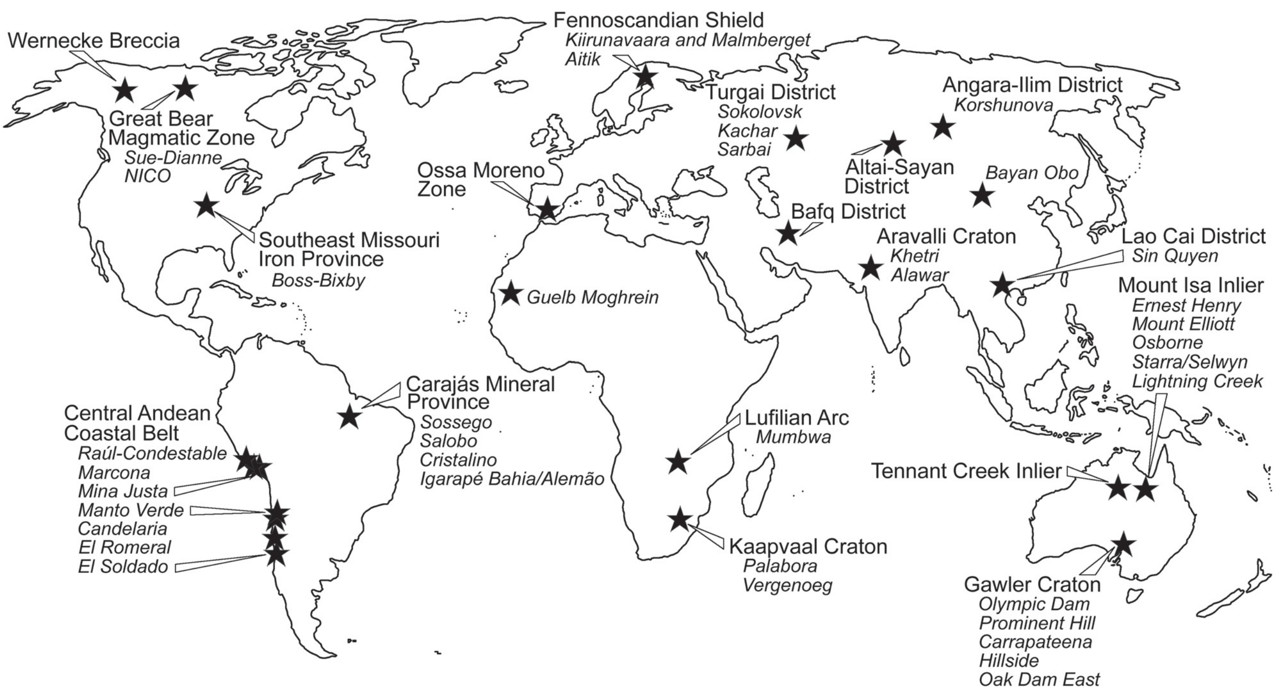

Figure 1: Distribution of iron oxide-alkali altered mineral provinces and deposits discussed in this paper.

Introduction

The discovery in 1975 of the giant Mesoproterozoic Olympic Dam copper-gold-uranium-REE deposit (9.09 Gt @ 0.87% Cu, 0.32 g/t Au, 0.27 kg/t U_3O_8; BHP Billiton, 2010) in the Gawler craton of South Australia, and the recognition of its size and hydrothermal origin, stimulated interest and comparison with a previously known group of iron oxide-rich deposits with overlapping common characteristics. Olympic Dam was found during a conceptual program exploring for sediment hosted copper in the Neoproterozoic cover sequence. It had initially been interpreted as being just such a deposit, hosted by coarse, oxidised, sedimentary breccias within a graben (Roberts and Hudson, 1983; Smith, 1990), until 1983, when exposures in underground exploration openings revealed it to be a hydrothermal breccia (Smith, 1990; Reeve, 1990).

Numerous authors contributed to the evolving understanding of the nature of Olympic Dam and the comparison with other known deposits (e.g., Bell, 1982; Youles, 1984; Lambert *et al.*, 1982; Hauck and Kendall, 1984; Hauck *et al.*, 1989; Hauck, 1990; Sims *et al.*, 1987; Meyer, 1988; Oreskes *et al.*, 1989; Einaudi and Oreskes, 1990; Ghandi and Bell, 1990; Reeve *et al.*, 1990; Oreskes and Einaudi, 1992). Understanding was further stimulated by the discovery in 1987 of Candelaria in Chile, and Ernest Henry in northwest Queensland in 1991. This work, particularly the classic studies of Einaudi and Oreskes (1990) and Oreskes and Einaudi (1992), culminated in the introduction of the term iron oxide copper-gold (IOCG) deposits by Hitzman *et al.*(1992).

This paper will first outline the evolution of the understanding and classification of IOCG *sensu stricto* and the broader related group of what may be termed "iron oxide-alkali altered" mineralised systems, as explained below.

It has been divided into two parts, the first of which is a synthesis of the current understanding of formation and occurrence of deposits that make up this broad class of mineralisation, discussing their similarities, contrasts, characteristics, variations and inter-relationships. The second reviews the current knowledge relating to most of the significant "iron oxide-alkali altered" mineral provinces of the world and the deposits they embrace, presented as a series of separate descriptions that provide background to support the synthesis and conclusions of the first part. It will also constitute a concise reference to many mineral province not covered elsewhere in these volumes, as well as summarising and contributing additional information complementing papers in this compilation.

It integrates the contributions to this and preceding volumes in the series (Porter 2000; 2002), as well as a wide selection of recent and historic papers. Both parts, have a common framework, addressing the lithospheric- to local-scale geological setting, temporal distribution, tectonic and structural controls, associated magmatism, implied crustal-scale sources of metals and fluids, fluid circulation dynamics, resultant alteration patterns and mineralisation styles.

This paper is intended to be read in conjunction with those of this two volume compilation, and preceding volumes, and will refer to diagrams in the constituent papers, rather than reproduce all in this contribution.

Classification

In addition to the Olympic Dam copper-gold-uranium ores, Hitzman *et al.* (1992) in their initial definition of IOCG deposits, included the low-grade copper mineralisation of the Wernecke Mountain breccias (Yukon, Canada), and the Kiruna (Sweden) and southeast Missouri (U.S.A.) iron ore districts, while considering the possible inclusion of the gold-copper-bismuth and gold-cobalt-silver mineralisation of the Great Bear magmatic zone (northwestern Canada), the iron oxide-REE ores of the Bayan Obo district of Inner Mongolia, (P.R. China) and the copper-rich Redbank breccia pipes of the Northern Territory (Australia). These represent a diverse range of commodities, some of which do not include copper and/or gold. Hitzman *et al.* (1992) regarded most of these to be members of the IOCG class, with copper-gold-deficient deposits such as Kiruna being a sub-set. Subsequently, Hitzman (2000) included other significant deposits as old as Neoarchaean (e.g., Sossego in

Classification ... cont.

Brazil) and as young as Pliocene, and suggested all, together, represented a continuum, with the iron oxide-copper-gold and magnetite-apatite ("Kiruna-type") examples representing end members. Haynes (2000) regarded these and additional examples to be part of a broader spectrum of deposits that ranged from iron oxide to iron-sulphide copper-gold. Other authors, e.g., Corriveau (2007) divided the IOCG-class into a number of sub-classes.

Hunt *et al.* (2007), recognising the variation in the fluid types responsible for the formation of different examples of this style of mineralisation, proposed a classification based on fluid sources, specifically those that are: (1) magmatic end-members (e.g., Lightning Creek and Eloise in the Mount Isa Inlier, Australia); (2) hybrid members, involving contributions from both magmatic and non-magmatic fluids (e.g., Olympic Dam and Ernest Henry in Australia); and (3) non-magmatic end-members without input from magmatic fluids (e.g., Wernecke Breccias in Canada, and Tennant Creek in Australia).

Since Hitzman *et al.* (1992) first introduced the term "iron oxide copper-gold", and more deposits have been progressively recognised, it has come into general use for discussion of an increasingly diverse group of occurrences with a wide range of ages, geochemical signatures, structural control, mineralogy, host rocks and local geological setting. A review of occurrences in the Andes of South America (Sillitoe, 2003) and compilations of papers in Porter (2000; 2002) reflect this diversity, although the latter two references (as in this volume) are purposely grouped under the title "Hydrothermal Iron Oxide Copper-Gold and Related Deposits" recognising all do not represent IOCG *sensu stricto* mineralisation.

Williams *et al.* (2005) questioned this diversity of deposits, regarding it as a reflection of gaps in the understanding of the genesis of IOCG mineralisation, requiring the application of a "rather empirical" combination of features to define the deposit class. They specified a set of criteria to define IOCG deposits, which included the following: (1) copper with or without gold as economic metals; (2) hydrothermal vein, breccia and/or replacement mineralisation, characteristically emplaced in specific structural sites; (3) abundant magnetite and/or hematite (although cogenetic deposits in some districts occur in hosts that have suppressed the formation of iron oxides); (4) the iron oxides have low titanium contents compared to those in most igneous rocks; (5) the absence of a clear spatial association with igneous intrusions, such as those that characterise porphyry and contact skarn mineralisation, although those associated with carbonatite intrusions are accepted. Other common features that may not always be present include, (6) a broad temporal-spatial association with batholithic granitoids; (7) occurrence in settings with exceptionally voluminous, generally pervasive alkali, usually sodic, metasomatism; and (8) a diverse suite of associated minor elements which may include various combinations of F, P, Co, Ni, As, Mo, Ag, Ba, LREE and U. This set of criteria excludes iron oxide-apatite (e.g., Kiruna), and iron oxide-REE (e.g., Bayan Obo) deposits, as well as large iron oxide occurrences which satisfy all other criteria, but contain only trace or sub-economic copper and/or gold (e.g., Marcona in Perú with ~1.9 Gt @ 55.4% Fe, 0.12% Cu; Chen *et al.*, 2010).

Groves *et al.* (2010) similarly considered the IOCG group of deposits to have become progressively too-embracing, with the inclusion of what they regard to be associated deposits and potential end-members or analogs, undifferentiated from IOCG *sensu stricto* mineralisation. They argue that consideration of this broad group as a whole obscures the critical features of the IOCG *sensu stricto* deposits, particularly the restricted temporal distribution and tectonic environment of the latter, thus leading to difficulties in developing a robust exploration model. They suggest the full range of IOCG and related deposits be considered as "iron oxide-associated", subdivided into five groups, as follows: (1) iron oxide copper-gold *sensu stricto*, (IOCG); (2) iron oxide-apatite; (3) iron oxide-, REE- and fluorine-rich carbonatites; (4) porphyry copper-gold and iron skarns; and (5) high-grade magnetite-replacement gold±copper deposits.

Groves *et al.* (2010) were concerned that many deposits have been misclassified as IOCG mineralisation, particularly the large Palaeozoic iron oxide (±copper-gold) deposits emplaced in intracratonic shelf host sequences that include carbonate (calcareous) sedimentary rocks, and as a consequence are accompanied by skarn alteration. They and Meinert *et al.* (2005) argue these should be classed as skarn- not IOCG-type ores. It might however, be reasoned that, as IOCG and related mineralisation are the products of interaction between host protoliths and hot, saline to hypersaline, volatile rich fluids, should those protoliths be calcareous, then a skarn alteration assemblage would be expected. Consequently, it is argued here, that if all other permissive criteria are met, these deposits should be considered to represent IOCG or related, as well as skarn-type mineralisation.

The suggestion by Groves *et al.* (2010) that the full spectrum of IOCG and related deposits be given a separate designation has merit, and will be referred to herinafter as "iron oxide-alkali altered" deposits. When considering the full range of deposit that have been allocated to the broader "iron oxide-alkali altered" grouping, the only characteristics that seem to apply to all include (1) the presence of 'significant' iron oxide and (2) the presence of alkali alteration, irrespective of ore or host mineralogy, relationship with intrusives, depth of formation or setting.

It is suggested for the purposes of this paper, that the full spectrum of "iron oxide-alkali altered" mineralised systems be subdivided and discussed as follows.

(1) *IOCG sensu stricto* - a style of mineralisation that: (a) has associated iron oxide alteration and contains anomalous (relative to the surrounding host rocks) quantities, generally >10 to 20%, of low titanium iron oxides (magnetite/hematite) and/or silicates (grunerite/Fe-actinolite/fayalite); (b) contains anomalous copper±gold sulphides, compared to barren iron oxides, i.e., has undergone a distinct phase of copper±gold introduction; (c) exhibits hydrothermal characteristics and is accompanied by alkali (sodic/potassic/calcic) alteration; (d) has a temporal, but not a close spatial association with intrusions; (e) occurs as veins, breccia fill and/or replacement sulphide and displays strong structural and/or porosity controls on a deposit- to ore shoot-scale; (f) is anomalously enriched in LREE; (g) is overall relatively impoverished in iron sulphides compared to iron oxides; (h) lacks significant syn-sulphide quartz veining and silicification directly associated with the copper mineralisation, although silica alteration may accompany copper-poor, gold-rich or late barren phases, e.g., the barren silica-hematite core at Olympic Dam. Mineralisation that satisfies the preceding criteria, but is accompanied by skarn alteration, is still

Classification ... cont.

included in this grouping. This definition describes the style of mineralisation. IOCG *sensu stricto* deposits, however, should contain copper and/or gold as economic principal- or by-products.

(2) *Iron oxide-apatite* - accumulations of variably phosphorous- or apatite-rich iron oxides, that are copper and/or gold poor, but otherwise satisfy the criteria specified for the IOCG *sensu stricto* definition. This grouping excludes immediate intrusive contact skarn altered deposits.

(3) *Mineralisation directly associated with carbonatite and alkaline or alkali altered intrusives* - this grouping incorporates iron oxide-alkali altered mineralised systems with or without copper and/or gold and/or REE that are differentiated from IOCG *sensu stricto* ores by a close spatial association with a coeval intrusion. In contrast, magmatic-hydrothermal fluids related to most other iron oxide-alkali altered mineralised systems are usually transported some distance from a coeval magmatic source before encountering conditions favourable to ore deposition. In deposits of this grouping, alteration and mineralisation would appear to take place adjacent to, or within the peripheries or interiors of a magmatic source, usually as either carbonatite-iron oxide lithophile element (fluorine- and REE-rich) deposits (e.g., Palabora, Bayan Obo), or zonally alkali-altered intrusions with associated concentrations of magnetite and other metals (e.g., Raúl Condestable and Sue Dianne). Where these intrusions cut calcareous country rocks, skarn assemblages will also be represented.

(4) *Overlap and miscellaneous mineralisation* - sharing characteristics of both iron oxide-alkali altered and another ore-type (e.g., some Central Andean Coastal Belt mantos, sediment hosted magnetite-copper-gold accumulations, porphyry deposits with IOCG characteristics or overprints, and some high grade copper-gold deposits associated with older/unrelated iron oxide bodies), and other deposits such as fluorine- and REE-rich "IOCG-like" mineralisation (e.g., Vergenoeg fluorite and REE).

The purpose of incorporating and discussing the full spectrum of iron oxide-alkali altered deposits in this context, is that, by definition they share many of the characteristics of IOCG *sensu stricto* ores, and frequently occur in the same districts and provinces, often in very close association. Arguably, in many cases, they may represent arrested early- or late-phases of the complex sequence of variable processes involved in producing economic IOCG *sensu stricto* mineralisation. Indeed, in most IOCG provinces, there are far more other iron oxide-alkali altered (e.g., magnetite-apatite; sub-economic IOCG-style occurrences; iron oxide deficient copper-gold occurrences; magnetite-copper-apatite-REE bearing carbonatites or magnetite-albitites) than IOCG *sensu stricto* deposits, while in others, the former alone are found. Consequently, an appreciation of whether such occurrences do represent 'incomplete', deeper- or higher-level zones of an IOCG system, and the implications for the occurrence of IOCG ore, is of particular significance to exploration.

Table 1: Tonnage and grade statistics for a selection of copper and/or gold bearing iron oxide-alkali altered mineralised systems.

Deposit	Mt	Cu %	Au g/t	Other	Comment and source
Carajás Mineral Province, Brazil					
Salobo	986	0.82	0.49		CVRD website, 2004; 0.5% Cu cut-off
Sossego	245	1.1	0.28		Lancaster *et al.*, 2000
Cristalino	~500	1.0	0.3		Huhn *et al.*, 1999
Igarapé Bahia/Alemão	219	1.4	0.86		Tallarico *et al.*, 2005
Gameleira	100	0.7	-		Rigon *et al.*, 2000
Alvo 118	170	1.0	0.3		Rigon *et al.*, 2000
Gawler craton, South Australia					
Olympic Dam	9080	0.87	0.32	0.27 kg/t U_3O_8	Total current resource, BHP Billiton, 2010
Carrapateena	203	1.31	0.56	0.27 kg/t U	OZ Minerals Ltd., April, 2011; 0.7% Cu cut-off
Prominent Hill	283	0.89	0.81	2.48 g/t Ag	Pre-mining, OZ Minerals, 2008; 0.5% Cu cut-off
Hillside	170	0.7	0.2		Rex Minerals, Dec., 2010; 0.2% Cu cut-off
Mount Isa Inlier, Northern Australia					
Ernest Henry	226	1.10	0.51		Pre-mining resource, Xstrata, 2009
Mount Elliot	570	0.44	0.26		Ivanhoe Australia, 2010; 0.3% Cu eq. cut-off
Osborne	27	1.4	0.8		Original resource, 1991, Ivanhoe Aust., 2010
Roseby Corridor	132	0.7	0.06		Altona Mining Ltd, 2010; 0.3% Cu eq. cut-off
Tennant Creek Inlier, Northern Australia					
Warrego	6.95	2.0	6.6	0.32% Bi	Production + reserve; Wedekind *et al.*, 1989
Juno	0.45	0.33	56.1	0.57% Bi	Total production to closure; Wedekind *et al.*, 1989
Asia					
Khetri Belt, India	140	1.1 to 1.7	0.5		Knight *et al.*, 2002
Sin Quyen, Vietnam *	~50	0.9	0.4		Wu, J.C., 2007 and sources quoted therein
Central Andean Coastal Belt					
Candelaria, Chile	470	0.95	0.22	3.1 g/t Ag	Marschik and Fontboté, 2001
Mantoverde, Chile *	410	0.58	0.11		Benavides *et al.*, 2007, AngloAmerican Chile, 2007
Mina Justa, Perú	347	0.71	0.03	3.8 g/t Ag	Chariot Resources, 2006; 0.3% Cu cut-off
El Soldado, Chile	>200	1.4		~6 g/t Ag	Boric *et al.*, 2002
Raúl-Condestable, Perú	>32	1.7	0.3	6 g/t Ag	de Haller *et al.*, 2006
Great Bear Magmatic Zone, Canada					
Sue Dianne	8.4	0.8	0.07	3.2 g/t Ag	Pre-mining resource, Corriveau *et al.*, 2010
NICO	31.7	-	0.91	0.12% Co, 0.16% Bi	Pre-mining resource, Corriveau *et al.*, 2010
Africa					
Palabora, RSA	~1200	0.59	Au, PGE, Ag, U recovered from tails.		Production+resource, Mine visit
Mumbwa, Zambia	87	0.94	0.05		Inferred res., Blackthorn Res. 2009; 0.5% Cu cut-off
Guelb Moghrein, M'ritania	33.4	1.12	1.41		First Quantum Minerals, 2008

* Sin Quyen - an additional 50 Mt has been reported at an unspecified grade (Vietnam Mineral Company announcement, Sept. 2010).

** Mantoverde - oxide and dump leach production + resource. An additional 440 Mt @ 0.56% Cu, 0,12 g/t Au hypogene resource has been outlined (Rieger *et al.*, 2010a)

Tonnage and Grade

The bulk of the more significant IOCG *sensu stricto* deposits yield moderate to large copper-gold resources, as detailed in Table 1. Most of those that are in production, or are planned to be exploited, have resources in the range of ~100 to ~500 Mt @ 0.5 to 1.5% Cu with variable gold, generally from 0.3 to 0.8 g/t Au. Salobo is above average while Olympic Dam is exceptional. As in all ore types, there are a number of smaller high grade (e.g., Osborne, Warrego) and numerous sub-economic resources not listed.

The statistics listed in Table 1 are dominantly economic, not geologic resources. Many IOCG *sensu stricto* deposits contain substantial cores of higher grade mineralisation, grading outwards to lower metal contents, without sharp, geologically defined outer limits. As a consequence, the margins to ore are usually based on cut-off grade, selected on the basis of economics of mining and treatment, a feature shared with most porphyry copper-gold deposits. These characteristics permit flexibility in the definition of resources to suit mining methods and variation in metal prices, e.g., the underground reserve at Olympic Dam of 589 Mt @ 1.81% Cu, 0.66 g/t Au, 0.59 kg/t U_3O_8 (BHP Billiton Annual Report, 2010) within the largely open pit total resource in Table 1. Another example of the economic grade variation, relates to the Selwyn/Starra deposit in Queensland, northern Australia, mined as a gold deposit at a time of low copper prices during the 1980s. The total production was from a series of high-grade gold-rich-shoots (mining reserve, 1988 of 5.3 Mt @ 1.98% Cu, 5.0 g/t Au; Kary and Harley, 1990) within the broader, more continuous mineralised zone (total resource of 253 Mt @ 0.34% Cu, 0.48 g/t Au, at a 0.2% $Cu_{equiv.}$ cutoff; Sleigh, 2002). Similarly, at a higher cut-off of 1.0% $Cu_{equiv.}$, the resource at Mount Elliott (Table 1) becomes, 62 Mt @ 1.01% Cu, 0.4 g/t Au (Ivanhoe Australia website).

Major apatite-bearing iron oxide (dominantly magnetite) deposits commonly found in the same metallogenic provinces/settings as IOCG *sensu stricto* mineralisation, with comparable associated alteration and geochemical characteristics, may be very large. In general they exceed the tonnage and iron grade of all but the very largest IOCG *sensu stricto* deposits. Some of the most significant examples include the 1.88 Ga *Kiirunavaara* and *Malmberget* deposits, both in northern Sweden, with total historic production + resources of 2.5 Gt @ 60 to 68% Fe, and 0.9 Gt @ 45% Fe, respectively (Billström *et al.*, 2010). Within the Southeast Missouri Iron Province (USA), eight known major (e.g., *Pea Ridge, Bourbon, Kratz Spring, Camels Hump* and *lower Pilot Knob*) and numerous minor magnetite and hematite deposits are known, totalling in excess of 1 Gt of ore at grades of 35 to 56% Fe. These are dated at 1.48 to 1.45 Ga (Seeger, 2000).

The Cambrian *Bafq* district in Iran comprises a total of 1.5 Gt @ ~65% Fe in thirty four "zones of magnetic anomalism" (Daliran, 2002). The three Carboniferous magnetite-apatite deposits of the *Turgai Belt* to the east of the Urals in northern Kazakhstan, contain a total of ~2.7 Gt @ ~43% Fe, the largest of which, *Kachar,* comprises ~1 Gt @ 45% Fe (Hawkins *et al.*, 2010). The eleven largest of the Permo-Triassic *Angara-Ilim* apatite-bearing, magnetite-rich breccia-pipes in south-central Siberia contain geological resources of ~18 Gt @ 20 to 50% Fe. Three of these (*Korshunovskoe, Rudnogorskoe* and *Tatianinskoe*), which are currently being mined, together incorporate remaining reserves of some 450 Mt @ 35 to 50 wt.% Fe (Soloviev, 2010b, and sources quoted therein).

The Late Jurassic *Marcona* deposits in southern Perú contains ~1.95 Gt @ 55.4% Fe, 0.12% Cu (Chen *et al.*, 2010), while the Early Cretaceous, 600 × 25 km *Chilean Iron Belt* deposits represent a total of ~2 Gt @ 60% Fe, and include five large resources of 200 to 400 Mt each (e.g., *El Romeral, El Algarrobo*) plus smaller satellites (Oyarzun *et al.*, 2003).

All of these, with the exception of Marcona, only contain trace amounts of sulphides, commonly on their peripheries, and are mined for iron with minimal contaminants, such as sulphur or other metals. However, most IOCG provinces frequently also contain other lower grade accumulations with or without associated sulphide mineralisation. Examples include the magnetite-apatite at the ~1.6 Ga *Acropolis* prospect (~500 Mt of vein to massive magnetite/hematite with associated apatite and low-grade copper intervals; Direen and Lyons, 2007), and *Oak Dam East,* (~560 Mt @ 41 to 56% Fe; Davidson *et al.*, 2007) where "barren" magnetite-apatite and hematite includes a 10 to 60 m thick layer of sub-economic copper-gold-uranium mineralisation. Both of these occurrences are within 60 km of, and temporally coeval with, Olympic Dam in the Gawler craton of South Australia.

The *Vergenoeg* fluorine-iron deposit in South Africa contains ~175 Mt at 28.1% CaF_2, with ~42% Fe (Fourie, 2000). The *Bayan Obo* REE-iron deposit in China includes a resource of ~1500 Mt of iron oxides (35 wt.% Fe) with 6 wt.% REE_2O_3 and 0.13 wt.% Nb (Smith and Wu, 2000).

Crustal Setting

The most significant of the known IOCG *sensu stricto* deposits are of large to giant size (Table 1), and are characterised by the range in vertical depth of formation over which they may occur (from ≥12 km, e.g., Salobo, to ≤2 km, e.g., Olympic Dam), and the regional scale of the related alteration systems within which they fall, e.g., the Olympic IOCG Province, which includes alteration zones of >1000 km^2 (Skirrow *et al.*, 2002; Hayward and Skirrow, 2010; Conor *et al.*, 2010); the Carajás Mineral Province where structurally controlled altered corridors extend over intervals of 20 to >50 km (Xavier *et al.*, 2010); and the Cloncurry District, where both laterally extensive zones and networks of anastomosing, structurally controlled corridors of alteration are developed over intervals of tens to hundreds of kilometres (Kendrick *et al.*, 2008; Mark *et al.*, 2005; Oliver, 1995; Brown and Porter, 2010, Rusk *et al.*, 2010). By comparison, Escondida (Chile), one of the largest known porphyry copper systems (~7.35 Gt @ 0.68% Cu), lies within an alteration halo of ~ 200 km^2 (Rio Tinto, 2004; Richards *et al.*, 2001).

Another of the characteristics of all significant IOCG *sensu stricto* deposits is a clear temporal, but not close spatial relationship to major magmatic intrusions (Williams *et al.*, 2005). This may be taken to imply that the intrusions are not necessarily directly causative, but rather the product of the same processes/events that influenced the development of the mineralised system.

Together, the distribution and scale of these characteristics suggest the major iron oxide-alkali altered mineralised systems responsible for such deposits should be considered on a crustal- to lithospheric-scale (e.g., Groves *et al.*, 2010).

A comparison of the composition, distribution and crustal setting of the host sequences and coeval intrusive complexes found in the provinces that contain major

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economic IOCG *sensu stricto* deposits, reveals many similarities. However, variations in the level of ore formation and exposure, and inhomogeneities within the crust, mean those similarities are seldom expressed in exactly the same way within the upper crust, even for deposits accepted to be IOCG *sensu stricto*.

The most common similarity in the majority of provinces is the presence of voluminous batholithic complexes, composed of both anorogenic granitoids, and mantle related mafic to intermediate phases, in varying proportions. These intrusions are broadly coeval with mineralisation, and are commonly accompanied by comagmatic outpourings of bimodal basaltic, basaltic-andesitic and felsic lavas and associated pyroclastics, often largely subaerial, erupted from fissure vents or caldera complexes, rather than from stratovolcanoes. The proportion of mafic to felsic volcanic rocks varies from felsic to mafic dominance within the pile, across a province and from province to province. Almost all are also characterised by numerous and widespread small juvenile mafic dykes, sills and stocks, while some also include layered mafic complexes that range from small to giant.

Many of these magmatic events have previously been attributed to subduction related magmatism. However, their scale, composition, distribution and setting suggest that most are more likely to have been either largely anorogenic, generated by anatectic melting induced by high temperature mantle under- or intraplates, or by mantle fractionation and assimilation of lower crust. Underplates usually form in the lower sub-crustal lithospheric mantle (SCLM), where magma may exploit deep structures to rise through the SCLM, and pond as intraplates, commonly at the Moho, which acts as a density filter impeding the buoyant upward passage of dense mantle material. Under- and intraplates represent large volume, fractionating mantle magma chambers.

The magmatism coeval with iron oxide-alkali altered mineral systems typically takes the form of large igneous provinces with intrusive and/or volcanic rocks covering areas (commonly oval-shaped to equidimensional, but also in some cases elongate) with a diameter of hundreds to more than a 1000 km. These igneous provinces may involve up to, and more than, 1 million km^3 of magma, producing voluminous batholiths and/or volcanic piles as thick as 10 km. They are variable in occurrence and composition, depending upon the structure and density/composition of the overlying crust, the degree of anatexis induced within the lower crust, and the fractionation of the under- or intraplate magma chamber and degree of lower crustal assimilation to produce phases that may rise through the Moho and into the middle to upper crust.

Igneous provinces seen in iron oxide-alkali altered provinces may vary from: (1) widespread I- and A-type granitoid batholiths with voluminous coeval bimodal (largely felsic) volcanic rocks and widely distributed minor mafic sills, dykes and small intrusive bodies (e.g., Gawler Range Volcanics/Hiltaba Suite intrusives of the Gawler craton in South Australia; Eastern Granite-Rhyolite Province of eastern USA; Malani Igneous Suite volcanics and Erinpura Granite of the Aravalli craton, India); (2) extensive anorogenic (A-type) mafic to felsic batholiths and widespread small dykes and sills of mafic to ultramafic rocks, with no associated (or preserved) coeval volcanic field (e.g., Williams-Naraku batholiths of the Cloncurry district, in the Mount Isa Inlier of northern Australia); (3) extensive, thick bimodal, but dominantly felsic, volcanic rocks, capping an almost equally extensive, but denser layered mafic to ultramafic complex, separated by voluminous associated A-type granites (e.g., the Rooiberg Group volcanics and Bushveld Complex in South Africa); (4) thick bimodal, but dominantly basaltic to andesitic lavas and pyroclastics, and associated voluminous batholiths, varying from gabbroic to granodioritic in composition, which are of primitive parentage in an extensional continental margin regime (e.g., the Central Andean Coastal Belt of northern Chile and southern Perú), or similar volcanic and intrusive rocks within an Archaean cratonic extensional regime (e.g., the Carajás Mineral Province in Brazil); (5) very extensive basaltic lavas and peripheral pyroclastics, with associated dolerite sills and dykes, but no major felsic volcanic or intrusive rocks (e.g., the Siberian Traps of Russia).

Although it only hosts a few modest, magnetite-fluorite iron oxide-alkali altered mineralised systems (e.g., Vergenoeg), the comprehensively studied Rooiberg-Bushveld Complex has been dissected by erosion, sufficient to reveal its architecture and provide an insight into the formation of intracratonic, anorogenic, complexes characterised by extensive bimodal intrusion and volcanism. A detailed description is included in the second part of this paper, with sources fully cited.

The Rooiberg-Bushveld Complex was intruded into the Mesoarchaean to Palaeoproterozoic Kaapvaal craton, close to its northern margin at 2.05 Ga, in an extensional regime. Its development commenced with the injection of a large intraplate of mantle material, through the SCLM, to the continental crust (most likely immediately below the Moho). This large mantle magma chamber induced melting of the adjacent lower crust to produce voluminous anatectic magma that penetrated to the surface and formed a bimodal, but dominantly felsic volcanic pile (the Rooiberg Felsite), up to 3.5 km thick, covering an estimated oval-shaped area of >110 000 km^2, with associated felsic granophyre intrusives. This was closely followed by injection of multiple pulses of mafic to ultramafic magmas from the main lower intraplate chamber to form a major 7 to 8 km thick layered complex covering an area of ~65 000 km^2, in the mid to upper crust (the Rustenburg Layered Suite). This latter suite was the result of fractionation in the intraplate magma chamber, to produce a melt with a density sufficiently light to buoyantly rise above the Moho. The Rustenburg Layered Suite, however, was still more dense than the volcanic suite, and updomed, but did not penetrate the more buoyant volcanic sequence, which in the preserved section is only cut by a few mafic to ultramafic dykes and sills. The final stage involved the anatectic generation of large volumes of anorogenic granite which ascended from adjacent to the intraplate, through the Rustenburg Layered Suite to its level of buoyancy, between the layered ultramafic complex and the capping largely felsic volcanic pile (Schweitzer *et al.*, 1995; Kinnaird, 2005; Cawthorn and Molyneux, 1986; Kleeman and Twist, 1989). The Vergenoeg deposit breccia pipe cuts the Rooiberg Felsite and is coeval with late Rooiberg-Bushveld magmatism.

This model reflects a variant of that anticipated to have occurred in the other examples. It is likely the injection of voluminous mafic to ultramafic magma to produce a giant layered ultramafic complex represents an abnormal end-member, which usually only comprises multiple, generally small mafic to ultramafic dykes, sills and stocks accompany anorogenic granitoids and volcanic sheets in such regimes. The more usual limited size of associated mafic to ultramafic intrusions (particularly within low

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density felsic or alumino-silicate crust) reflects a density contrast, and lack of positive buoyancy of the more mafic rocks, which may generally only be injected into dilational structures, rather than rising as a batholithic mass.

The great majority of iron oxide-alkali altered provinces were developed within intracratonic settings, removed from active plate margins, usually by hundreds of kilometres. The magmatic activity associated with these provinces is dominantly anorogenic, and may be controlled by major structures, including earlier sutures between amalgamated cratonic blocks within the intracratonic setting. An example is the linear, 1.88 to 1.84 Ga *Great Bear Magmatic Zone* (GBMZ) of northern Canada, interpreted to cover an area in outcrop and below cover of ~1200 × 100 km. It is developed above the eroded ~2.1 to 1.88 Ga arc and suture between the accreted Slave craton to the east and the Hottah terrane to the west. Following collision and concomitant folding, the suture zone is interpreted to have undergone orogenic collapse, involving extension, delamination and thinning of the crust to allow upwelling and decompression melting of mantle fertilised during the Hottah subduction, which in turn triggered metamorphism, anatexis of the overlying crust and production of a complex suite of poorly deformed mafic to felsic magmatic rocks. Felsic and intermediate magmatism predominates, occurring as batholiths, sub-volcanic intrusions and volcanic rocks, with coeval mafic magmatism as minor volcanic rocks, dykes and sills which constitute the GBMZ (Corriveau *et al.*, 2010 and sources cited therein).

The most notable exception to an intracratonic setting is the *Central Andean Coastal Belt* of northern Chile and southern Perú, which was developed on a continental margin and hosts associated major IOCG *sensu stricto* deposits (e.g., Candelaria, Mantoverde). A detailed description of this belt, which is the basis of this summary, is included in the second part of this paper, with sources fully cited.

Prior to the emplacement of the voluminous primitive parentage batholiths and comagmatic volcanic rocks that were contemporaneous with IOCG mineralisation in this province, subduction had been dormant for over 55 m.y., from the Late Permian to Mid Jurassic, following the final assembly of Gondwana/Pangea. Towards the end of this orogenic hiatus, updoming, high heat flow and anorogenic felsic magmatism (accompanied by limited mafic to ultramafic sills, dykes and stocks) are recognised in the geological record over a wide area of the central Andes in western South America (Fig. 9; Charrier *et al.*, 2007 and sources quoted therein). This suggests post mountain building delamination and detachment (cf. Fig. 2b) and the development of a lower crustal mantle under-/intraplate that anatectically melted the adjacent lower crust to produce the observed anorogenic felsic magmatism.

Delamination and detachment below this part of the crust during either the Pre-Andean or Andean tectonic cycles is supported by the current anomalously shallow Benioff zone, which is at a depth of only 50 to 100 km as far inland as western Argentina (Proffett, 2003, and sources quoted therein). The basement to this part of the Central Andes is dominantly composed of slivers of Palaeo- to Mesoproterozoic exotic terranes accreted to the continent during the Proterozoic to Early Palaeozoic (Fig. 6; Ramos, 2008), which would be expected to represent a total lithospheric thickness of at least 200 km (e.g., Artemieva and Mooney, 2001).

When oceanic crust creation recommenced on the mid-ocean ridge in the palaeo-Pacific ocean to the northwest, and the obliquely advancing, cooled, brittle, dense oceanic slab of the Phoenix plate began to roll-back, a zone of transtension developed along the western margin of the continent. This zone, reflected by the Atacama Fault, paralleled the frozen subduction zone of the Mid Devonian to Late Permian Gondwana Tectonic Cycle, and the series of sutures between the slivers of exotic basement terranes.

A ~90 m.y. period of roll-back induced extension ensued, from the Late Jurassic to late Early Cretaceous. During this interval, fractionation progressively took place in the under-/intraplate to produce voluminous fractionated juvenile, tholeiitic to calc-alkaline mafic to felsic magmas, of mantle derived parentage. These magmas were sufficiently light to breach the Moho and rise through the attenuated and thinned crust with minimal contamination.were emplaced into a series of batholiths, each as much as 50 km long, of noritic and gabbroic, to quartz diorite and leucocratic tonalite and granodiorite in composition. These intrusions were accompanied by thick (5 to >10 km), comagmatic, subaerial to locally shallow submarine basaltic-andesitic, to andesitic to dacitic lavas and tuffs, which are described as being “more akin to a flood basalt province” (Sillitoe, 2003), developed along the major transcurrent, transcrustal Atacama fault zone (Fig. 9). Sillitoe (2003), notes that these magmas were fertilised. During the period of roll-back and extension, the slab was still sinking, being partially melted and contributing fluids to fertilise the asthenospheric wedge and promote melting and recharge of the under-/intraplate fractionating magma chamber.

The hiatus in subduction from the Late Permian, followed by the period of roll-back extension to the late Early Cretaceous, represents an interval of ~145 m.y. of a dominantly extensional regime with no net advance before contraction began again in earnest in the late Early Cretaceous. As such this setting has much in common with the Precambrian iron oxide-alkali altered provinces, not dissimilar to the setting in a zone of extension and delamination associated with an intracratonic suture, as described for the GBMZ.

A further variation on this theme is afforded by the *Ossa Morena Zone* in southern Spain, where a large mafic to ultramafic intraplate was injected into the middle crust along a decollement zone. This intrusion accompanied delamination and thermal collapse following subduction and collision between the Iberian plate and Portuguese Zone at the end of the Palaeozoic Variscan orogeny (see Carriedo and Tornos, 2010, in volume 4 of this series). This intraplate most likely originated from decompression melting of remnant subduction metasomatised asthenosphere. The emplacement of this mass of high-temperature juvenile rocks into the middle crust (and most likely a deeper associated intraplate at the Moho) produced crustal melting, fractionation and the consequent formation of water-rich, highly contaminated melts, synchronous with high-T/low-P metamorphism and widespread anatexis. This magmatism was coeval with, and related to, iron oxide-alkali altered mineralised system within the region. A detailed description of the Ossa Morena Zone, is included in the second part of this paper, with sources fully cited.

The two major iron oxide-rich styles of mineralisation within the *Carajás Mineral Province* in Brazil, namely the giant 2.7 Ga Carajás banded iron formation (BIF) iron ores and the 2.7 to 2.5 Ga IOCG *sensu stricto* deposits (e.g., Cristalino, Sossego, Salobo), overlap the major global, late Neoarchaean, period of magmatic activity and crust creation from ~2.7 to 2.5 Ga. Both styles of

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mineralisation are hosted within an east-west trending, 400 × 100 km band of thick Neoarchaean (2.76 to 2.73 Ga) bimodal, but mainly mafic to intermediate volcanic rocks, with lesser interbedded chemical and clastic sediments. Trace element studies suggest crustal contamination of the volcanic rocks (Lobato *et al.*, 2005a), and that they were deposited on attenuated continental crust (Zucchetti, 2007; Zucchetti *et al.*, 2007). The volcanic pile and Mesoarchaean basement are intruded by a series of granitoids, including 2.76 to 2.74 Ga syntectonic alkaline granites, 2.76 Ga mafic-ultramafic layered complexes, as well as 2.76 to 2.65 Ga gabbro sills and dykes, 2.70 Ga calc-alkaline monzogranite, 2.65 Ga porphyritic dacitic to rhyolitic rocks, 2.57 Ga A-type granites, 2.51 Ga peralkaline, meta-aluminous granitic rocks, and widespread late 'within-plate' A-type, alkaline to sub-alkaline granites associated with 1.88 to 1.87 extensional events (e.g., Xavier *et al.*, 2010; Grainger *et al.*, 2002). Geochronologic data suggest that formation of the Carajás IOCG deposits may possibly be linked to three metallogenic events: ~2.74, 2.57 and 1.8 Ga (Xavier *et al.*, 2010 and sources cited therein).

This major period of magmatic activity from 2.7 to 2.5 Ga (most likely intracratonic and extension related), may be the result of mantle underplating and anatexis, as suggested by Teixeira *et al.* (2009), particularly the A-type and alkaline granites coeval with the main phases of IOCG mineralisation. In addition, it has been suggested that the iron oxide component of the Carajás IOCG deposits may be related to the BIF hosted iron deposits, either as the sub-surface hydrothermal replacive equivalent of the ~2.74 Ga exhalative iron formations, or part of a regional event at ~2.57 Ga that is also responsible for post-depositional hypogene upgrading of iron oxides to ore-grade in those BIFs (Lobato *et al.*, 2005; Hagemann *et al.*, 2005; Figueiredo e Silva *et al.*, 2008).

The core of the *Fennoscandian Shield* comprises the Meso- to Neoarchaean Kola-Karelia cratons in the east, composed of 3.5 to 2.9 Ga gneissic tonalite-trondhjemite-granodiorite, followed by 2.9 to 2.6 Ga greenstones and calc-alkaline volcanic rocks, consolidated after the last major stage of granitoid intrusion at 2.65 Ga. The early Palaeoproterozoic, was characterised by two pulses of extension and intracratonic rifting, from 2.45 to 2.39, and 2.2 to 2.0 Ga, accompanied by recurrent, dominantly mafic (komatiitic and tholeiitic to calc-alkaline), with lesser intermediate to felsic magmatic activity, and deposition of sedimentary rocks, largely over the partly concealed Norrbotten craton to the west of the Kola-Karelia block.

A change occurred between 1.9 and 1.8 Ga, involving calc-alkaline andesites and related volcaniclastic sedimentary rocks deposited in subaerial to shallow water settings on the margin of the Norrbotten craton, while Svecofennian subduction took place involving the amalgamation of several microcontinents and island arcs onto the southwestern margins of the combined Archaean Karelia, Kola and Norrbotten cratons.

The major magnetite-apatite deposits at Kiirunavaara and Malmberget, as well as the epigenetic copper-gold deposits of the region, are hosted by the geographically restricted 1.89 Ga Kiirunavaara Group trachyandesitic to rhyodacitic volcanic rocks that overlie Archaean basement of the Norrbotten craton in the Kiruna-Gällivare district, approximately 200 km inboard of the of the northwest-southeast trending subduction suture. A thick sequence of up to 10 km of Palaeoproterozoic sedimentary and volcanic rocks was deposited to the southwest of the subduction zone. These, and the sequences overlying the craton, were multiply deformed and metamorphosed during the intrusion of voluminous 1.92 to 1.87 Ga granitoids with associated gabbros. Subsequently, a 1.88 to 1.86 Ga quartz monzonite-adamellite-granite suite (interpreted to be comagmatic with the Kiirunavaara Group volcanic rocks) was emplaced, followed by the generation of anatectic A- and I-type granites during another major stage of deformation and metamorphism between 1.82 and 1.77 Ga (Billström et al., 2010 and sources quoted therein).

The precise crustal setting of the magmatism associated with the major iron oxide-alkali altered mineralised systems of the shield, and their relationship to mantle and/or subduction influences is unclear.

The vast, ~4 million km^2 *Siberian Traps* basaltic large igneous province, with which the large Permo-Triassic breccia pipe magnetite deposits of the Angara-Ilim district (and Noril'sk-Talnakh nickel-copper-PGE) deposits of the Siberian craton are related, has been attributed to a major mantle plume underplating event that has volumetrically overwhelmed the Siberian craton without producing associated felsic anatectic melts. Nor does it appear to have produced any IOCG *sensu stricto* mineralisation, other than weak late copper sulphide impregnations, despite the high magnetite content of the pipes, potential copper rich source mafic rocks and a thick halite-anhydrite bed transgressed on the upward passage of the breccia pipes which contain abundant matrix anhydrite.

A number of iron oxide-alkali altered mineral provinces do not have major associated magmatic events coeval with IOCG-style mineralising events. One of the more notable examples is the *Wernecke Breccia* province of northwestern Canada, where large breccia complexes are developed over extensive areas within a thick intracratonic sedimentary sequence, but only contain low grade mineralisation (on present knowledge). The host sequence is only intruded by relatively minor mafic to intermediate dykes and sills, and granitoids, and is locally overlain by a limited unit of mafic to intermediate subaerial volcanics. The lack of significant coeval anorogenic igneous activity has been offered as an explanation for the absence of higher-grade mineralisation, possibly reflecting the absence of major mantle induced magmatic activity (e.g., Conor *et al.*, 2010).

The preceding demonstrates the presence, mode of occurrence, and extent of significant magmatism, temporally, but not (usually) spatially associated with iron oxide-alkali altered mineralised systems in all of the selected provinces discussed (with the exception of the Wernecke and Ogilvie Mountains).

Although felsic magmatism is volumetrically dominant, compared to the coeval mafic intrusions in most of these mineral provinces, in some cases the latter appears to be spatially more closely related to mineralisation. An example of this relationship is illustrated by a detailed GIS-based spatial analysis and numerical modelling study of the Eastern Fold Belt in the Mount Isa Inlier (McLellan *et al.*, 2010, this volume). This exercise analysed the association between a range of criteria and the widespread IOCG *sensu stricto* and other iron oxide-alkali altered mineralisation of the fold belt. It revealed that copper-gold deposits within the study area have a strong spatial association with mafic intrusive rocks, with a significant proportion located either <650 m from, or within, these lithologies. In contrast, it emphasised the relatively weak spatial association between copper-gold occurrences and the coeval felsic intrusions of the Williams-Naraku batholiths. The authors of the study

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caution that the rheology and reactivity of mafic rocks may partially influence their associations with mineralisation. Nevertheless, these relationships point to a common association between mafic and felsic magmatism, and mineralisation.

This latter observation is consistent with the implied or suspected mantle influence in the anatectic generation of felsic magmatism, in the guise of sub-lithospheric mafic under- and associated sub-crustal intraplate magma chambers. The possible presence of under- and intraplates has been interpreted from a number of indications, including reflection in deep seismic profiles, tomography, regional gravity, anorogenic magmatism, and large igneous provinces (LIPs).

LIPS are generally formed remote from plate boundaries, unrelated to "normal" sea-floor spreading and subduction, and are areally extensive (usually >100 000 km^2), and often, but not exclusively, broadly oval-shaped. They comprise mafic volcanic terranes, which may include continental flood basalts (e.g., Siberian Traps), rift basin and rift margin volcanism, giant oceanic plateaus, large mafic-ultramafic provinces (e.g., the Bushveld Complex), large scale dyke swarms (e.g., Gairdner and Mackenzie dykes of Australia and Canada respectively), or other groupings of small to moderate sized mafic to ultramafic dykes, sills and stocks. The latter are often sparsely distributed over wide areas, representing either conduits to an eroded flood basalt, or minor fugitives from a deep magma chamber that has not breached to the upper crust (Ernst and Buchan, 2002; Campbell, 2005). Claoue-Long and Hoatson (2009) define a number of such LIPs across Australia occurring as sparsely distributed minor to major mafic dykes, sills and plugs (e,g., the ~1780 Ma Hart LIP) and other widespread mafic/ultramafic events not sufficiently voluminous to be classified as LIPs (e.g., the ~1590 Ma Curramulka Event).

Some authors include comparable large felsic anorogenic magmatic provinces associated with, and resulting from the anatectic melting of the lower-crust by mantle sources, as siliceous large igneous provinces (SLIPs; e.g., Bryan, 2007; Allen *et al.* (2009) when describing the ~1590 Ma Gawler Range Volcanics and Hiltaba Suite of the Gawler craton). Most LIPs do not occur in isolation, but in continent-wide to globally distributed coeval pulses (Abbott and Isley, 2002; Condie, 2001, 2002, 2004, 2005; Rogers and Santosh, 2004; Zhao *et al.*, 2004). However, it should be emphasised that while LIPs or significant mafic/ultramafic igneous events are found in conjunction with many iron oxide-alkali altered mineralised systems, the converse is not true (i.e., not all LIPs have associated iron oxide-alkali altered mineralised systems).

LIPs and some significant mafic/ultramafic igneous events are interpreted to reflect major mantle melting events, related to either mantle plumes, or to regions of crustal delamination and detachment. The latter may (1) be developed below an intracratonic extensional rift basin, (or rifted margin) often focussed on previous sutures or other major structures, or (2) occur along suture zones, closely succeeding continent-continent collision. Both plume impact, and delamination and detachment may result in medium- to high-degree decompression melting of asthenospheric mantle, which usually only takes place at depths of <100 km (e.g., Kerrich *et al.,* 2005; Begg *et al.,* 2010).

In the case of mantle plumes, channeling to thinner crust, updoming and thermal erosion caused by the diapiric rise of the hot plume, brings the plume head to sufficiently shallow depths to promote melting (Campbell, 2005). Some super-plumes may thermally erode the sub-crustal lithospheric mantle (SCLM) to exploit structural weaknesses and breach the crust to the surface (e.g., the Siberian Traps), but frequently they form a hot, gradually cooling molten layer that underplates the SCLM.

Delamination, subsequent detachment and sinking of denser, tectonically destabilised and/or thermally metamorphosed lower lithosphere, is followed by the consequent upwelling of asthenospheric mantle to fill the vacated volume at relatively shallow depths, where it melts to form an underplate (Schott and Schmeling, 1998; Lustrino, 2005a, 2005b; Meissner and Mooney, 1998).

Refer to Fig. 2, and associated extended caption for additional background relating to the formation of mantle plumes and delamination and detachment processes.

In zones of structural weakness in the lithospheric mantle, magma from an underplate may diapirically rise through the SCLM to the base of the Moho, which generally represents a major density change, or density filter (if below continental crust), restricting the buoyant rise of the heavier mantle material and causing it to pond and form an intraplate. Zones of structural weakness include sutures from earlier collisions, particularly those marking crustal thickness changes, as between thick *Archaean and thinner Proterozoic crust, or between Proterozoic and even thinner Phanerozoic or oceanic crust. These sutures represent zones of weakness where pre-existing structures may be reactivated or new fracture zones initiated.

An intraplate magma chamber represent a high heat source sheet, usually at the base of the crust below the Moho, which may then fractionate *in situ*. It will also induce high temperature metamorphism and anatectic melting of the immediately overlying lower continental crust to produce migmatites and anorogenic (A-type) intrusions which then fractionate and release phases that rise to form lopolith-like batholiths at their level of buoyancy within the crust (e.g., Hiltaba Granite in the Gawler craton, Williams-Naraku batholiths in the Mount Isa Inlier). While the density contrast precludes the intraplate mantle magma chamber from initially rising beyond the Moho, it may exchange volatile rich fluids with the otherwise dry anatectic/anorogenic magmas forming above the Moho, or release those same fluids into the crust along structural/dilational weaknesses such as major transcrustal faults (Fig. 3). In addition, fractionated mantle material from the intraplate may be injected into dilational zones in the crust (e.g., the widespread, sparse, generally minor and structurally controlled, ultramafic to

* Two populations of total lithospheric thickness are evident in the Archaean, one of 300 to 350 km, including continental crust of ~45 km (Baltic shield, Siberian platform, West Africa, Canadian shield?), and a second of 200 to 220 km, including continental crust of ~35 km (parts of southern Africa, western Australia, South America and India). Available data suggest the former represent cratons with deep roots formed above high temperature mantle plumes, while the second comprise tectonically stacked/imbricated SCLM lithospheric plates characteristic of Archaean shallow angle subduction of buoyant oceanic crust (see subsequent footnote). Temporal variations in subsequent total lithospheric thickness averages (i.e., crust + SCLM, assuming an average crustal thickness of 40 km) are: early Palaeoproterozoic, 240±40 km; late Palaeo- to Neoproterozoic, ~180±70 km; Phanerozoic, ~140 km; modern oceanic lithosphere, ~45±70 km near mid-ocean ridges, to 90±70 km by subduction, as progressively more SCLM is accreted (Artemieva and Mooney, 2001). These variations in thickness reflect a corresponding change in composition and degree of depletion of the SCLM, from highly depleted and refractory harzburgite in the Archaean, to mildly depleted lherzolite in the Phanerozoic (Artemieva and Mooney, 2001, Kerrich *et al.*, 2005).

mafic dykes, plugs and sills that define the mafic/ultramafic events in the Gawler craton and Mount Isa Inlier), or into major collision related or late inversion thrusts (e.g., the IRB of the Ossa Morena Zone in southern Iberia).

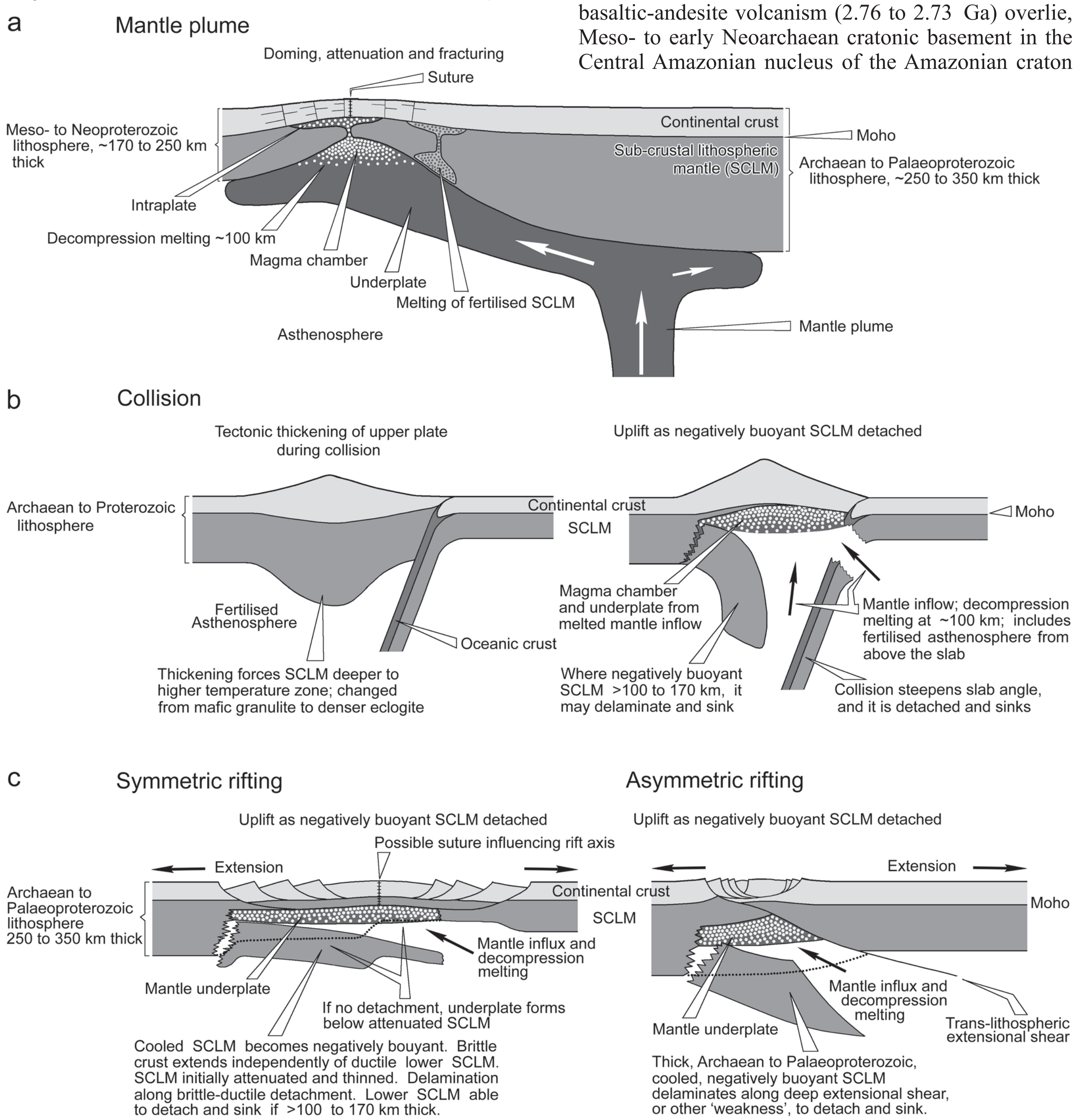
Under-/intraplate mantle melted from a trapped remnant subduction-related asthenospheric wedge (e.g., behind a detached subduction slab; Fig. 2b) will be metasomatised. As such the melt will be hydrated and contain volatiles to generate volatile-rich fluids that may be either exchanged with otherwise dry anorogenic granitoids across the Moho, and/or injected into the crust via the same dilational structures that provide passage for mafic to ultramafic dykes, sills and stocks from the chamber (Fig. 3). Fertilised asthenosphere is also more susceptible to decompression melting.

Where fractionation produces a sufficiently buoyant phase within the under-/intraplate magma chamber, and the crust is under extension, that phase may cross the Moho and rise further along deep transcrustal structures to produce juvenile batholiths and bimodal basalt to andesitic and usually lesser felsic volcanic lava and tuff sheets (e.g., Carajás Mineral Province, Central Andean Coastal Belt).

Temporal Distribution

Currently there are only seven districts world-wide that contain large (>100 Mt), economic (or potentially so), IOCG *sensu stricto* resources, i.e., the Gawler craton and Mount Isa Inlier in Australia, the Carajás Mineral Province and Central Andean Coastal Belt in South America, the Aravalli craton of India, Lufilian Arc of Zambia and Lao Cai district of northern Vietnam and southern China (Table 1). Consequently there is too small a statistical population from which to draw firm conclusions on what strictly determines their temporal distribution, and new discoveries will no doubt change the patterns that are suggested. Nevertheless, the following age groupings can be isolated, and placed into the framework of the supercontinet cycle.

(1) ***~2.8 to ~2.4 Ga*** - The main IOCG *sensu stricto* deposits of the Carajás Mineral Province (e.g., *Salobo, Igarapé Bahia/Alemão, Cristalino* and *Sossego*) were formed during this period of intense global magmatism and crustal growth. A-type and other granitoids and gabbros (2.76 to 2.51 Ga) intrude, and extensive basaltic to basaltic-andesite volcanism (2.76 to 2.73 Ga) overlie, Meso- to early Neoarchaean cratonic basement in the Central Amazonian nucleus of the Amazonian craton



Temporal Distribution ... cont.

(Figs. 6, 7 and 8). Mineralisation in the main deposits is dated at either 2.74 or 2.57 Ga, with, in some cases, both ages recorded in the same orebody (Xavier *et al.*, 2010 and sources cited therein). Significant magnetite-apatite mineralisation is also present in the Carajás Mineral Province (as distinct from the Carajás BIFs). The Central Amazonian cratonic province overlies an imbricated SCLM, which according to Artemieva and Mooney (2001) reflects Meso- to Neoarchaean style shallow, buoyant subduction. The 2.49 Ga *Guelb Moghrein* IOCG deposit (Kolb *et al.*, 2010) in Mauritania occurs within the West African craton, part of the interpreted Archaean Atlantica protocraton (Rogers and Santosh, 2004) that also includes the Amazonian craton (Fig. 6).

A Neoarchaean to Palaeoproterozoic supercontinent (Kenorland) has been proposed from 2.8 to 2.1 Ga, although this is speculative (e.g., Williams *et al.*, 1991; Groves *et al.*, 2010; Goldfarb *et al.*, 2010 and references cited therein). In this context the 2.74 and 2.57 Ga Carajás Mineral Province mineralisation would coincide with peak to post-peak magmatism, cratonic creation and assembly. However, the evidence for such a supercontinent is not convincing, and hence it has not been considered herein. It is probable instead, that there were three amalgamated clusters of Archaean cratons with similar characteristics that persisted in their association through Nuna/Columbia and Rodinia. They comprise: (1) *Ur*, that dates from 3.0 Ga and includes the Kaapvaal (South Africa), Western Dharwar and Singhbhum (India), the Pilbara and possibly Mawson/Gawler (Australia/Antarctica) cratons. Ur was fringed by granite-greenstone dominated terranes which were active from ~2.7 to 2.5 Ga (e.g., the Zimbabwe, Aravalli and Yilgarn cratons) but not cratonised with the core of Ur until after 2.5 Ga; (2) *Arctica*, that encompasses most of the North American cratons, plus Baltica and Siberia, which were amalgamated by 2.5 Ga; and (3) *Atlantica*, that was assembled before 2.0 Ga, and incorporates parts of the Amazonian, São Francisco, Rio de la Plata, Guyana, Congo/Kasai and West African cratons (Rogers and Santosh, 2004). However, the Central Amazonian province of the Amazonian craton at least, and possibly also the Man and Reguibit cores in the West African craton, were stable by 2.8 Ga, with the former overlain by a thick ~2.7 basaltic sequence that was not deformed into a greenstone belt (cf. Pilbara and Kaapvaal cratons).

(2) ***~2.05 Ga*** - The *Vergenoeg* iron oxide-fluorite and *Palabora* IOCG-carbonatite deposits were developed in direct association with the Rooiberg-Bushveld felsic-mafic complex and satellite Palabora intrusion respectively in South Africa. The Rooiberg-Bushveld complex represents large scale anorogenic magmatism accompanied by injections of fractionated mantle magma, related to extension and a major mantle melting (underplate forming) event. Mantle melting took place below the thick Meso- to early Neoarchaean Ur protocraton, which also overlies imbricated SCLM (e.g., Artemieva and Mooney, 2001). This activity followed a significant global hiatus in magmatic activity between ~2.45 and ~2.2 Ga, and is coincident with the onset of assembly of the Nuna/Columbia supercontinent, which extended from ~2.1 to ~1.8 Ga (Rogers and Santosh, 2004; Condie *et al.*, 2009; Condie, 2005).

(3) ***~1.9 to 1.80 Ga*** - This interval encompasses the giant magnetite-apatite deposits (*Kirunavaara* and *Malmberget)* and lesser IOCG *sensu stricto* mineralisation (e.g., *Rakkurijärvi*; Smith *et al.*, 2010) of the Fennoscandian Shield; as well as the smaller intrusion-related IOCG deposits (*NICO* and *Sue-Dianne*) of the Great Bear Magmatic Zone of northern Canada, and the swarm of low tonnage, high grade ores of the Tennant Creek Inlier in northern Australia (Table 1).

A group of smaller, mineralogically distinct deposits in the Carajás Mineral Province (e.g., *Breves, Águas*

Figure 2 (facing page)**:** Generation of mantle magma underplates. A number of mechanisms have been postulated for the formation of mantle underplates that appear to be important to the development of iron oxide-alkali altered provinces. These include:

(a) *Mantle plumes*, which originate at the boundary zone between the outer core and lower mantle (5150 km), catalysed by the rapid temperature gradient and compositional change at that interface. A sufficiently large buoyant mass must first accumulate to overcome the viscosity of the mantle, before a plume can finally break out as a large mushroom head, with a slender tail or feeder, following in the shadow of the head. As the head rises through the mantle, it grows. Super plumes may have heads with a diameter of 1000 to 1200 km and tails that are 100 to 200 km across in the upper mantle. They take ~100 m.y. to rise to the base of the lithosphere, where the head flattens and expands to double its diameter (Campbell, 2005). Where impacting upon the base of the sub-crustal lithospheric mantle (SCLM) at depths of <150 km, the plume head is channelled laterally to areas of thinnest lithosphere, still by solid state flow, where it undergoes decompression melting (e.g., Begg *et al.*, 2010) to form an underplate magma chamber. The thinnest SCLM is commonly a focus of strain/transcrustal structures, often corresponding to a suture between two amalgamated plates, which can provide a passage for upward stoping of magma to the density filter of the Moho where an intraplate chamber may form. Groves *et al.* (2010), and other sources quoted therein, suggest the underplate may alternatively partially melt the lower SCLM which will then rise and also form the intraplate at the base of the Moho. The neck of the plume will continue to recharge the underplate and magma chamber to in turn recharge an intraplate. The large volume of hot mantle and its buoyancy results in updoming of the lighter crust, accompanied by radial fracturing and often associated dyking.

(b) *Collision induced delamination and detachment*. Following continent-continent collision, thickened, thermally metamorphosed SCLM (left), transformed from light mafic granulite to denser eclogite when isostatically forced lower into the mantle, becomes less buoyant and may be delaminated along a line of weakness (often a decollement or similar accommodating structure at the brittle-ductile transition) to peel-off and sink (right). Frequently, the locked and steepened subducting slab becomes detached to sink into the asthenosphere, triggering the main delamination of destabilised SCLM from the upper plate. Detachment only occurs when the detached SCLM has sufficient mass, usually corresponding to a thickness of >100 to 170 km. After the negatively buoyant SCLM is detached, the lighter crust will be updomed and an inflow of mantle material will replace the volume of the detached SCLM, and updoming, to form an underplate/ magma chamber. Decompression melting of mantle to form the magma usually only take place at depths of ~100 km (after Lustrino, 2005a; 2005b; Meissner and Mooney, 1998). Intraplates may subsequently form above the underplate. It is possible that this same process may occur at stalled continent-ocean collision zones when the slab cools, becomes brittle and is detached.

(c) *Continental rift induced delamination and detachment*. Where thick, cooled SCLM that is >100 to 170 km (i.e., Archaean to at least Mesoproterozoic) underlies a continental rift zone, it may be delaminated and detached to sink into the asthenosphere. Extension is usually accommodated in the brittle crust by listric faulting, and in the ductile SCLM by lateral shear and attenuation. Decollement/ detachment structures near the Moho are often the focus of delamination (symmetric rifting), or trans-crustal lithospheric extensional shears (asymmetric rifting). The volume occupied by any detached SCLM and the concomitant updoming is filled by an influx of mantle material to undergo decompression melting to form an underplate magma chamber, usually below the Moho, although available fractures (e.g., sutures that focus the formation of the rift) may serve to allow magma to rise and pond below the Moho. For thinner SCLM, or where no detachment occurs, the attenuation of the SCLM creates a volume at its base where decompression melting produces a thin, transient underplate. (Modified after McKenzie, 1978; Fraser *et al.*, 2007; Thompson, 1999).

Temporal Distribution ... cont.

Claras, Gameleira and *Estrela*) has been attributed to a third, younger pulse of mineralisation in that province. Those of this group that have been dated, return ages of ~1.8 Ga (Grainger *et al.*, 2008), and may be related to 1.88 to 1.87 Ga extension and coincident intense ~1.8 Ga anorogenic magmatic activity of the giant 1100 × 1400 km silicic LIP centred to the west, but overlapping onto the Central Amazonian cratonic province (Figs. 6 and 7).

These deposits were all generated during a period of major global crustal growth marking the culmination of assembly of the *Nuna/Columbia supercontinent, which persisted until ~1.8 Ga (Zhao *et al.*, 2002; Condie, 2005) when it was consolidated.

(4) ***~1.65 to 1.45 Ga*** - This interval brackets many of the world's more significant IOCG *sensu stricto* deposits, including those of the Gawler craton (e.g., *Olympic Dam, Prominent Hill, Carrapateena, Hillside*) from ~1.59 to ~1.57 Ga; the Mount Isa Inlier (e.g., *Ernest Henry, Mount Elliott*) mainly from 1.55 to 1.50 Ga; the low grade *Wernecke Breccia* IOCG, at ~1.6 Ga; the sub-economic *Boss-Bixby* IOCG mineralisation in South-east Missouri at 1.48 to 1.45 Ga. In addition, significant, large low- (~10% Fe) to high-grade (>40% Fe) iron oxide (magnetite and some hematite) accumulations, mostly with associated apatite are recorded in the Gawler craton (e.g., *Acropolis*); Mount Isa Inlier (e.g., *Lightning Creek*); South-east Missouri (e.g., *Pea Ridge*), which are of similar age to the IOCG *sensu stricto* mineralisation in the same districts.

This period corresponds to the initiation of extensional tectonics and development of rift basins within the Nuna/Columbia supercontinent, marking the commencement of its break-up. All of these deposits: (a) are developed within Palaeo- and/or early Mesoproterozoic rocks, (b) occur outboard of known or inferred Archaean basement, (c) are associated with interpreted mantle induced mafic underplating, (d) occur in association with overlapping known mafic/ultramafic igneous events, (e) which in turn are inferred to be related to either crustal extension and delamination or mantle plume activity. The exception is the Wernecke Breccia, for which there is lesser evidence of significant mantle activity or anorogenic magmatism (apart from late mafic volcanism and small dykes and sills), nor of economic IOCG mineralisation.

Disintegration of the Nuna/Columbia supercontinent was complete by 1.2 Ga, overlapping with the assembly of Rodinia from 1.3 to 1.0 Ga, which in turn, was consolidated by ~0.9 Ga (Condie, 2004; Rogers and Santosh, 2004; Li *et al.*, 2009; Reddy and Evans, 2009)

(5) ***~0.85 to 0.75 Ga*** - This interval includes the only significant global episodes of intracontinental anorogenic and/or coeval mafic magmatism, within the Rodinia supercontinent, from 0.825 to 0.80, at 0.78 and from 0.755 to 0.750 Ga (Abbott and Isley, 2002), corresponding to the onset of extension, marking the commencement of its break-up (Li *et al.*, 2008). Anorogenic magmatism occurred in diverse regions across Rodinia, but particularly on the margin of the Aravalli craton in India, where post-tectonic ~0.85 to 0.80 Ga A-type granites and a large overlapping 0.8 to 0.7 Ga comagmatic bimodal, but dominantly felsic volcanic sheet was formed, at a similar time to the significant IOCG *sensu stricto* ores of the ~0.85 Ga *Khetri* and *Alwar* copper belts. Rodinia had disintegrated into a small number of blocks by ~0.75 Ga (Condie, 2004; Rogers and Santosh, 2004; Li *et al.*, 2009; Reddy and Evans, 2009).

(6) ***Cambro-Ordovician*** - The large *Kitumba* IOCG *sensu stricto* deposit (Mumbwa project; Table 1) in the Lufilian Arc of Zambia was formed at ~535 Ma (Hanson *et al.*, 1993; Nisbet *et al.*, 2000; Lobo-Guerrero, 2010). Mineralisation is associated with the late-tectonic Hook granite that accompanied inversion of the large, late Neoproterozoic Katangan rift basin. Significant, coeval magnetite-apatite accumulations are also recognised within the Lufilian Arc.

The giant *Bafq* magnetite-apatite±hematite ores of Iran (Daliran, 2002) have been dated at 539 to 527 Ma (Stosch *et al.*, 2010), and are associated with albite-actinolite-chlorite altered bimodal volcanism in a rift setting (Daliran, 2002).

The 530 to 500 Ma magnetite-albitite deposits of the *Ossa Morena Zone* in southern Iberia, are associated with magmatism that followed post continent-continent collision (Carriedo and Tornos, 2010 and sources cited therein).

These all corresponds closely with the break-up of the short lived (60 m.y.) interim supercontinent Pannotia, which formed between the breakup of Rodinia and the assembly of Pangea. Pannotia had been amalgamated by ~600 Ma, and began to break-up at ~540 Ma (Li *et al.*, 2008; Dalziel, 1991).

Widespread iron oxide mineralisation with associated alkali alteration was also developed in the carbonate dominated cratonic sequences of the *Altai-Sayan* region of Russia and Kazakhstan during this period, although the dates are not well constrained (Soloviev, 2010a in volume 4 of this series). Some of these latter deposits are directly related to intrusive contacts (and hence excluded), while others are distal to coeval granitoids. Most of the latter, in addition to the characteristic iron-alkali alteration and associated apatite, are also accompanied by skarn minerals, as would be expected of hydrothermal mineralisation emplaced in a carbonate rich cratonic sequence. The iron oxide-alkali altered mineralised systems of this region were dominantly of magnetite-apatite, with no large IOCG *sensu stricto* deposits yet

* Modern plate tectonics, subduction and large scale convergence of continental masses may have first appeared during the assembly of Nuna/Columbia marking a transition related to cooling of the Earth's interior. Hotter Archaean upper mantle resulted in a greater degree of melting at spreading centres and a calculated thickness of oceanic crust at those centres of ~11 km (compared to modern ~6 km), and a commensurately thicker SCLM residue, depleted in compatible elements following basalt extraction. Archaean SCLM had a harzburgite composition, compare to the denser modern, mildly depleted, lherzolite (densities of 3.36 and 3.38 g/cm^3 respectively). Modern oceanic lithosphere becomes negatively buoyant before reaching a subduction zone where it sinks steeply. In contrast, thicker, hotter, faster moving and less dense Archaean oceanic lithosphere would remain buoyant longer and reach a subduction zone before becoming negatively buoyant. Consequently, it would be subducted at a very much shallower angle than at present, forming imbricated stacks (Davies, 1992; Groves *et al.*, 1976). Modelling (Davies, 1992), suggests the crossover to negatively buoyant subduction would have been at around 2.0 Ga. Although subduction is evident from before 3.1 Ga, the characteristically roughly equidimensional ~1000 to 1500 km diameter of Meso- to Neoarchaean cratons, composed of oval-shaped granites, separated by elongate, steeply dipping keels of greenstones may be taken to imply the dominance of a mixed mantle plume and subduction regime, in contrast to the more extensive, elongate geometry, typical of modern orogens that prevailed from the late Palaeoproterozoic (Groves *et al.*, 2005).

Temporal Distribution ... cont.

discovered. Similar mineralisation in this region continued into the Silurian and Devonian (Soloviev, 2010a).

(7) ***Carboniferous to Triassic*** - The progressive amalgamation of the supercontinent of Pangea was concluded soon after the Mid-Carboniferous. During the Early Carboniferous (~350 to ~330 Ma) consolidation of Pangea, a second pulse of iron oxide-alkali altered mineralisation (magnetite-albitite and small IOCG deposits) took place in the *Ossa Morena Zone* of southern Iberia. This pulse was associated with anorogenic magmatism, immediately following further continent-continent collision (Carriedo and Tornos, 2010).

The giant alkali altered magnetite-apatite deposits of *Kachar, Sarbai* and *Sokolovsky* in the Turgai district of northern Kazakhstan (Hawkins *et al.*, 2010) were developed within a rift sequence, following the collisional closure of the Trans-Uralian Zone in northern Kazakhstan. These ores are coeval with an Early Carboniferous (Upper Visean) gabbro-diorite-granodiorite intrusive complex, and underlain in the same district by younger (late-Upper Visean to Serpukhovian) large scale orthomagmatic titano-magnetite bearing gabbros, indicating the continuing influence of mantle processes.

Prior to the commencement of break-up of Pangea, a mantle super-plume event centred on the western margin of the Siberian craton produced the Siberian Traps, outpouring of basaltic lavas and tuffs, the largest preserved LIP in geological history. This event was associated with a number of mineral associations, including the Angara-Ilim district magnetite breccia pipes (e.g., *Korshunovskoe, Rudnogorskoe and Tatianinskoe*; Soloviev, 2010b) as well as the vast Noril'sk-Talnakh copper-nickel-PGE deposits and the breccia-hosted hematite, F, Ba, Sr, REE, U, Mo carbonatites of Central Tuva (Soloviev, 2010a; 2010b).

(8) ***Late Early Jurassic to late Early Cretaceous (~165 to 95 Ma)*** - Following the amalgamation of Pangea, there was a slow-down of subduction and crustal generation at mid-ocean ridges, culminating in a hiatus or minimal activity (at least in the South American segment of the supercontinent) for approximately 55 m.y. This lasted from the latest Permian to earliest Jurassic, with associated anorogenic magmatism towards the end of the period (Charrier *et al.*, 2007). A period of slab roll-back ensued on the west coast of South America, accompanied by extensional tectonics (reflecting the break-up of Pangea), and the release of voluminous juvenile basaltic to basaltic-andesite magma as large batholiths, lava flows and tuffs sheets along the margin of the continent. This mantle-influenced activity led to the development of the IOCG *sensu stricto*, magnetite-apatite and the other iron oxide-alkali altered deposits of the *Central Andean Coastal Belt* in northern Chile and southern Perú. The main IOCG *sensu stricto* deposits (e.g., *Candelaria* and *Mantoverde*) are dated at 120 to 112 Ma (although those at the extremities of the belt, such as the *El Soldado* manto and *Mina Justa*, are between 108 and 95 Ma), and the magnetite-apatite ores of the Chilean Iron Belt (e.g., *El Romeral* and *El Algarrobo*) and *Marcona* in southern Perú, were emplaced between 130 and 110 Ma and 162 to 156 Ma respectively. In total, this represents a period of over 65 m.y., which was followed from 95 Ma by increasing convergence and a renewal of subduction related accretion.

While iron oxide-alkali altered mineralised systems are distributed throughout the geological record from ~2.8 Ga, the major IOCG *sensu stricto* deposits (as currently known) would appear to be restricted to the age brackets: (1) from 2.8 to 2.4 Ga; (2) between 1.60 and 1.45 Ga; (3) from ~0.85 to 0.75 Ga; (4) from 530 to 500 Ma and (5) ~165 to 95 Ma.

These age brackets correspond to: (1) the period of major magmatism and crustal generation during the Neoarchaean from 2.76 to 2.5 Ga, and (2) the periods succeeding consolidation, and coinciding with extensional phases marking the commencement of break-up of the Nuna/Columbia, Rodinia, Pannotia and Pangea supercontinents.

The development of magnetite-apatite deposits throughout the geological record, from ~2.8 Ga, is also highlighted, both contemporaneously with major IOCG *sensu stricto* deposits during periods of continental break-up, and coeval with smaller IOCG occurrences and other iron oxide-alkali altered mineralised systems during intervals of supercontinent amalgamation.

Some caution should be exercised when considering the distribution of these deposits relative to the supercontinent cycle, as the evolution of the supercontinents, and whether they actually fully coalesced is still the subject of uncertainty. These tentative conclusions are offered as a guide to further research and will, no doubt, require revision as new deposits are discovered and studied.

Fluid Circulation, Alteration and Mineralisation

One of the hallmarks of iron oxide-alkali altered mineralised systems, and IOCG *sensu stricto* deposits in particular, is the large-scale alteration patterns within which they fall, ranging from early, regional-scale zones, which are progressively reduced in areal extent with time, to more restricted, but still often large, local halos directly associated with individual ore deposits.

It is reasonable to consider that these large-scale alteration patterns reflect, and are a direct product of, their crustal-scale, tectono-magmatic setting.

They occur within settings in which deep-seated, lithospheric-scale magmatism, metamorphism and heat transfer play an important role, interpreted in many provinces to be related to hot, mantle under- and/or intraplates above zones of asthenospheric upwelling and decompression melting, with concomitant lower crustal anatexis and metamorphism (e.g., Oliver *et al.*, 2008). Mineralised provinces are commonly developed where earlier accretion/subduction is interpreted to have metasomatised (and hydrated) the underlying asthenosphere and SCLM (e.g., Hayward, 2008; Oliver *et al.*, 2008).

Regional- to district-scale alteration patterns are structurally controlled by networks, corridors and anatomising patterns of faults that usually include transcrustal structures, and often cover areas of >10 to >1000 km^2, extending to the middle crust. They generally involve sodic-calcic assemblages, which temporally evolve to potassic and iron oxide rich phases, and usually predate, the more localised alteration associated with sulphide mineralisation (e.g., Kendrick *et al.*, 2008).

Barren iron oxide deposits with variable associated apatite, where present, almost invariably predate IOCG *sensu stricto* deposits, and are usually associated with the waning stages of regional alteration, sometimes as repeated pulses, distributed over a period of time.

The more localised alteration zones, accompanying individual iron oxide-alkali altered deposits represent either evolution of the hydrothermal regime, or the development of special circumstances conducive to the deposition of ore at a particular location or district.

Williams *et al.* (2010; this volume) discusses the range and types of fluids that can occur in association with IOCG *sensu stricto* deposits and the circulation of those fluids. They explain that in an individual ore system these can comprise a number of different ore fluid components that may not all have the same source, and that economic IOCG *sensu stricto* deposits include examples in which key components (especially copper) had different sources in different deposits/provinces. They list the principal components of importance as: (1) water ±volatiles, (2) chlorine, (3) sulphur, (4) iron, copper, gold (the diagnostic ore components) and (5) other potentially economic metals (e.g., uranium, REE) that may be differently-sourced to the copper and gold.

Williams *et al.* (2010) also list many studies of IOCG deposits (employing fluid inclusion petrography, microthermometry and "conventional" light element, i.e., H, C, O, S stable isotope geochemistry), particularly those in Australia and Brazil, that have uniformly confirmed the role of brines (in many examples involving more than one type) in the formation of ore, commonly with an associated carbonic phase. These brines frequently include both deeply sourced/circulated, and shallow to surface derived fluids.

Alteration

A comparison of the descriptions in the second part of this paper, allows the following synthesis. For sources of information and more detailed arguments and examples, refer to the individual descriptions.

The formation of major iron oxide-alkali altered mineralised systems is preceded by the development of regional- to district-scale alteration patterns. In most cases this alteration is initially characterised by sodic-calcic assemblages, commonly albite and/or scapolite calc-silicates±magnetite, localised either within broad zones (up to several km wide) centred on major transcrustal faults over intervals of tens to hundreds of kilometres (e.g., Mount Isa Inlier; Carajás Mineral Province), or as more pervasive zones controlled by networks of structures (e.g., sections of the Gawler craton) or by both structures and lithological permeability (e.g., the Punta del Cobre district of the Central Andean Coastal Belt in Chile).

The regional alteration pattern often progresses temporally and spatially upwards, from sodic-calcic to potassic-iron (biotite/K feldspar-magnetite) to iron-potassic-calcic (magnetite-K feldspar±actinolite±carbonate). High- and/or low-grade magnetite-apatite mineralisation is usually present in most provinces and is hosted within the latter assemblage. This progression is best seen in those provinces tilted sufficiently to observe both deeper and shallower regimes (e.g., Gawler craton; Central Andean Coastal Belt). In deep systems, the potassic assemblage is less obvious, with a temporal progression instead to albite-acinolite-magnetite. An example of the latter is the deeply exposed sections of the Carajás Mineral Province, where large massive magnetite bodies are associated with actinolite-rich variants of the regional sodic-calcic (scapolite-albite) alteration, without significant regional biotite and K feldspar, and where large, massive, magnetite bodies are enveloped by apatite-rich 'actinolitite'. In other more deeply exposed systems (e.g., the Eastern Fold Belt of the Mount Isa Inlier), there is also evidence of a pre-ore potassic-(manganese-barium) assemblage overprinting the regional sodic phase for several kilometres around Ernest Henry, represented by intense biotite-magnetite alteration. Further south, the rocks around the Mount Elliott deposit, also deeply exposed, are characterised by a dominant scapolite/albite regional assemblage.

In the shallower Punta del Cobre and Mantoverde districts of northern Chile, district-scale sodic-calcic albite/scapolite assemblages appear to be temporally and spatially closely coincident with iron-potassic K feldspar-magnetite alteration, possibly straddling the sodic to potassic depth transition. It should be noted however, that both the Punta del Cobre and Mantoverde districts are complicated by an early, lower temperature (basinal brine related?) hematite development, overprinted and converted to mushketovite during the main magmatic high temperature district-scale sodic/potassic-iron phase.

The generalised alteration zonation described above may be complicated by local lithological or structural factors, e.g., in the Candelaria pit area, sodic-calcic alteration is again evident above the potassic and chloritic zones, within the overlying Abundancia Formation, possibly reflecting the presence of evaporite-bearing beds within that part of the sequence (Marschik and Fontboté, 2001).

Where the host sequence in the province/district includes carbonates or calcareous tuffs, the alteration pattern is complicated by the development of skarn minerals and other calc-silicates - the usual alteration product of the interaction of hot, volatile laden hydrothermal fluids with such rocks, irrespective of that solution's affiliation (e.g., the Corella Formation of the Mount Isa Inlier; Punta del Cobre district of Chile; Prominent Hill and Hillside on the Gawler craton; the Uralian and Siberian magnetite-apatite deposits, etc.).

Alteration at the deposit-scale is subject to a vertical zonation, as best illustrated by a composite vertical section through the deposits of the southeastern segment of the Carajás Mineral Province (see Fig. 13 in Xavier *et al.* (2010), this volume). In this district, the background regional alteration is dominantly sodic-calcic, without an apparent overprinting regional- to district-scale potassic assemblage. At the deepest levels within this composite section, the background regional sodic-calcic and sodic alteration (albite-scapolite at ~500ºC) prevails. Upward this is overprinted by actinolite, magnetite (~500ºC) and sulphides with a relatively narrow potassic (biotite) fringe to the ore. Higher still, the potassic alteration halo to sulphides (biotite and K feldspar, at ~460ºC), is progressively more extensively developed at the expense of the earlier, higher temperature sodic assemblage, to become dominant where the first muscovite-sericite (hydrolytic) alteration appears. In the upper levels of the system, chlorite, muscovite and hematite dominate at temperatures of <250ºC (Xavier *et al.*, 2010).

Deposits elsewhere in the world tend to overlap intervals of this spectrum, e.g., Mount Elliott has a dominant scapolite-albite assemblage with ore associated magnetite, actinolite and lesser K feldspar alteration. Ernest Henry is accompanied by potassic-iron alteration as early intense biotite-magnetite, followed by K feldspar and sulphides. Candelaria has a vertical zonation from sodic-potassic at depth, grading up into a dominantly potassic suite in the bulk of the orebody, with chlorite-sericite in the upper sections, all with associated-magnetite, although hematite also appears at the top of the system. Olympic Dam is characterised by hematite-sericite-fluorite-barite with copper

Fluids and Alteration ... cont.

sulphides, which passes at depth into low grade to barren magnetite-carbonate-chlorite-pyrite ±copper sulphides.

Fluid Types, Origin, Evolution and Composition

Provinces hosting iron oxide-alkali altered mineralised systems appear to represent settings in which deep-seated, mantle-driven, lithospheric-scale magmatism, metamorphism and heat transfer are responsible for generating fluids, and/or driving fluid circulation and the concomitant redistribution of metals, volatiles and other fluid transported components on a crustal to local scale. The circulation of these fluids in turn, causes the alteration described in the previous section and the associated mineralisation.

Most of these fluids are characteristically strongly- to hypersaline in composition.

The following is based upon the more detailed descriptions in the second part of this paper, which includes available isotope, fluid chemistry, geochronology and geothermometry data for many of the worlds main iron oxide-alkali altered mineral provinces.

Iron oxide-alkali altered mineralised systems and IOCG *sensu stricto* deposits may be formed at a wide range of levels within the crust (from, >12 to <2 km), in contrast to porphyry-style mineralisation (~1 to ~5 km). Both represent mineralising columns that extend from the SCLM to the surface, although porphyry mineralisation forms within a restricted pressure-temperature window and fluid source/transport path regime (see the "Porphyry and IOCG Mineralisation" section below). The greater range of depths at which iron oxide-alkali altered and IOCG *sensu stricto* mineralisation is precipitated, implies control on ore deposition is chemical, involving reactions between two or more fluids, or fluids and rocks, rather than a pressure-temperature window alone involving a single fluid. The common and variable enrichment of a wide range of other elements with different solution chemistries in IOCG *sensu stricto* deposits adds further weight to the possibility more than one fluid is involved (e.g., Williams *et al.*, 2010).

A variety of fluid types/sources have been identified in iron oxide-alkali altered provinces around the world. The influence of one or more (usually two, but sometimes more - but not always the same fluid types in each instance) is invoked as the prime agent responsible for scavenging, promoting exsolution, transporting and mixing of ore forming components to precipitate ore deposits (Williams *et al.*, 2010). These include the following (Fig. 3) fluid types and some examples of the occurrence of each:

(1) ***Fluids released from a fractionating mantle-derived under- or intraplate*** that is at or below the Moho, or from related intrusions in the lower to middle crust. These fluids are of magmatic origin, and are usually CO_2-rich and are characterised by their H, O, C and S content. Other accompanying components will be influenced by the composition of their magma source, which may vary from tholeiitic to alkaline.

H, O, C and S bearing fluids, released either directly from enriched mantle melts, or indirectly from related mafic magmas intruded into the mid-crust, may interact with other fluids (e.g., saline, oxidised brine from felsic magmas) or with felsic batholiths through magma mingling and the consequent contribution of CO_2- rich fluids/vapours, to exsolve large volumes of Fe-Na hydrothermal fluids (Oliver *et al.*, 2008; Perring *et al.*, 2000).

The passage and presence of these CO_2-rich mafic/mantle-related fluids/vapours is indicated by the presence of calcite-bearing veins with mantle-like carbon isotope values that are widespread in some provinces hosting iron oxide-alkali altered mineralised systems (e.g., Mount Isa Inlier), and calcite veining in IOCG deposits (e.g., Ernest Henry; Oliver *et al.*, 2008).

The presence of widespread, mantle derived CO_2 fluid inclusions in hydrothermal systems provides an insight to the depth at which exsolution of volatiles may have occurred. Baker (2002; 2003) notes that the three most important volatiles found in magmas, in decreasing order are, water, CO_2 and chlorine (the latter being the principle ligand for metals). He also notes that the key to forming ore deposits in a magmatic environment is the generation of volatiles from the magma, requiring volatiles to saturate from the magma and form a separate fluid phase. Due to solubility constraints, a CO_2-free, hydrous felsic magma will only commence to form hydrothermal fluids at a depth of ~2 kbars (<10 km). However, as CO_2 has around one tenth of the solubility of water, the same magma with ~1 wt.% CO_2, would exsolve CO_2 vapor at pressures of 20 kbars (70 km), thereby having a major impact on the depth and pressure at which volatiles can begin to exsolve. The mingling of CO_2-rich mafic magma, or introduction of CO_2-rich vapour from a deep, mantle related mafic source to an anorogenic felsic magma, would facilitate both the release of volatiles, and expand the vertical range over which mineralisation may be formed.

Asthenospheric mantle that is subjected to decompression melting at greater depths (generally >100 km, depending upon the volatile content that influence the solidus), will undergo low degree partial melting (<5%) to produce low volumes of alkalic (Na-K-rich) magma, high in sodium and potassium, compared to that undergoing decompression melting at shallower depths of <100 km which result in more voluminous quantities of tholeiitic (Fe-Mg-rich) magma from high degree partial melting (e.g., Farmer, 2005). It is unlikely the amount of alkalic magma produced would be sufficient to release the volume of alkali-rich fluid required to alone produce the volume of regional sodic-calcic alteration observed in major iron oxide-alkali altered mineral provinces. However, this mechanism has been attributed to the generation of alkalic lava fields and carbonatites in particular, which are sometimes found peripheral to more voluminous tholeiitic developments.

Groves *et al.* (2010) suggest fluids of this type are involved in the majority of IOCG *sensu stricto* deposits on the basis of the carbonic content of ore brines, the ubiquitous enrichment of ores in LREE, and their gold content, all implying a deep alkaline magmatic source, with the mantle/SCLM being the most likely source of these components. The same authors and Hayward (2008), argue that domains overlying mantle/SCLM that includes (post-collisional) trapped remnant back-arc asthenospheric wedges and metasomatised SCLM that are hydrous and contain anomalous volatile and gold contents, are more favourable sources of fluids for IOCG *sensu stricto* mineralisation. See the "Mafic/Ultramafic Intrusions and IOCG Mineralisation" section below for examples of the release of these fluids.

(2) ***Saline to hypersaline fluids exsolved from large intermediate to felsic intrusions,*** usually comprising mingled combinations of oxidised anorogenic and/or mantle-derived magmas, the composition of which are influenced by the chemistry of the (1) original crustal lithologies that contributed to the anorogenic melt (e.g., Carriedo and Tornos, 2010); (2) volatiles exchanged with mantle-derived under- or intraplates located at or below the Moho or injected into the middle crust (e.g., Groves *et al.*, 2010); or (3) fractionated mantle-derived mafic to ultramafic intrusions that have crossed the Moho and mingled with the anorogenic melt (e.g., Perring *et al.*, 2000; Pollard, 2001; Oliver *et al.*, 2008).

The source intrusions may vary from dominantly anorogenic with minor mantle derived phases (e.g., Hiltaba Suite of the Gawler craton), to those that are almost entirely of fractionated juvenile mafic to intermediate magma (e.g., Central Andean Coastal Belt). Carriedo and Tornos (2010, in volume 4 of this series) describe anatectic intrusions in the Ossa Morena Zone of southern Iberia that are derived in part from partially melted, stratabound Cambrian massive magnetite units that produced a magnetite-rich (from an exsolved, immiscible magnetite phase) albitite.

Perring *et al.* (2000), Pollard (2001) and Oliver *et al.* (2008) describe the Lightning Creek magnetite prospect (6 million m^3 @ ~10 vol.% magnetite) within the roof-zone of the Williams Batholith in the Mount Isa Inlier. Mineralisation is accompanied by abundant CO_2-, iron- and copper-rich fluid inclusions, and extensive albite-K feldspar alteration. They argue this accumulation and the large volumes of associated fluids released into the country rock, represents a magmatic-hydrothermal transition. Mingling of mantle-derived, mafic-ultramafic magmas and anorogenic felsic melts, released CO_2 into the latter, promoting exsolution of a dominantly iron-sodium hydrothermal phase that produced voluminous magnetite mineralisation, sodic alteration and a sodic-iron-copper rich fluid (see the Lightning Creek description of the "Mount Isa Inlier" section in the second part of this paper). Similar magmatic-hydrothermal transitions are reported by Chen *et al.* (2010a) at Marcona in the Central Andean Belt of Perú, and by Velasco and Tornos (2009), from the Chilean Iron Belt. Both result in the deposition of magmatic magnetite-apatite accumulations and the release of voluminous alkalic and hypersaline hydrothermal fluids into the country rock (see the "Iron Oxide Apatite Mineralisation" section below).

Magmatic fluids are invoked in forming the regional alteration of the Eastern Fold Belt of the Mount Isa Inlier, following Isan orogeny peak metamorphism at 1595 to 1580 Ma, accompanying emplacement of the Williams-Naraku batholiths and related intrusions between 1550 and 1500 Ma. Alteration was largely structurally controlled albite-actinolite-magnetite-titanite±clinopyroxene (Baker *et al.*, 2008). Large parts of the latter regional sodic-calcic alteration is associated with the formation of breccia complexes that are particularly well exposed along the Cloncurry fault, predominantly in the roof and along the margins of the Williams and Naraku batholiths, developed during multiple episodes of granitoid intrusion (de Jong and Williams, 1995; Mark, 1998; Mark and de Jong, 1996).

(3) ***Fluids produced by high temperature metamorphism***, induced by an under- or intraplate, zone of anatexis or related batholithic magma chamber. These are derived from fluids of both (1) initial formational origin, expelled by metamorphism, and (2) subsequently, those held in the mineral lattices or released from minerals transformed by the metamorphism. These fluids would of necessity, be transmitted via structural permeability. Their composition would be influenced by the chemistry and content of formational waters, the composition of the metamorphosed protolith, and the availability of metals and volatiles either liberated by the metamorphism and/or exchanged with the under- or intraplate.

Although a range of authors suggest these fluids may be involved in the formation of deposits, few relate them to specific examples, although Oliver *et al.* (2008) invokes the interaction of early basinal fluids and subsequent metamorphic fluids for generation of the smaller, high grade Osborne deposit during peak metamorphism within the Mount Isa Inlier (see the "Mount Isa Inlier" section in the second part of this paper for details).

(4) ***Sedimentary formation/basinal water*** circulated by heat from an under- or intraplate, and/or anatectic magmas, with or without transfer of volatiles and other component from those heat sources.

The influence of this type of fluid is exemplified by the initial stages of regional alteration in the Eastern Fold Belt of the Mount Isa Inlier, prior to Isan orogeny peak metamorphism at 1595 to 1580 Ma. Kendrick *et al.* (2008) describe fluids that are deeply circulated by intraplate, anorogenic magmatic and metamorphic heat sources. These include hypersaline hydrothermal fluids that had a dominant origin from sedimentary formation water, and produced regional albite alteration. The saline content of these fluids is interpreted (on the basis of halogen ratios) to have largely originated from halite/evaporite rich units of the sequence through which the fluids were circulated (e.g., the Corella Formation of Cover Sequence 2; Fig. 5), although a magmatic source of some of the salinity is not excluded. The significance of the Corella Formation (now regionally altered to scapolite-diopside rich calc-silicates) is indicated by the detailed spatial analysis and numerical modelling exercise of McLellan *et al.* (2010; this volume), which found a strong correlation between the occurrence of copper-gold mineralisation and proximity to (within 750 m) the contact between the Corella Formation and Soldiers Cap Group (of Cover Sequence 3) in the Eastern Fold Belt of the Mount Isa Inlier.

(5) ***Surface derived bittern brines, or re-dissolved evaporites***. Meteoric waters may percolate down structures in an extensional regime to deliver bitterns to an underlying waning magmatic system, or through basin inversion, deliver recent evaporitic units to relative depth for dissolution and redistribution.

Experimental/fluid inclusion and related data from most IOCG provinces are supportive of, but do not in most cases unequivocally prove, the influence of two or more fluids in the formation of IOCG *sensu stricto* deposits, although Groves *et al.* (2010), argue these deposits are the result of a deep, mantle-derived, magmatic fluid.

Regional sodic-calcic alteration patterns may be produced by the circulation of any single, or a combination of the fluids types listed above, sometimes mixed, and often in multiple, separated cells with different contributing fluid sources (e.g., Kendrick *et al.*, 2008; Oliver *et al.*, 2008). This pre-mineralisation stage may be no more than the reflection of a favourable tectonic/fluid circulation regime and have no direct relationship to the actual formation of mineralisation. Alternatively, fluids may scavenge solutes from the rocks they alter (as supported by the statistical depletion of

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metals from the regionally altered rocks, particularly mafic lithologies, in the Mount Isa Inlier; Oliver *et al.*, 2008), to potentially be focussed and sequestered as disseminations or veins in faults/shear zones that become the conduit utilised by subsequently circulated fluids to remobilise those metals for redeposition (e.g., Oliver *et al.*, 2008).

The temperatures at which regional sodic-calcic alteration takes place vary widely, depending upon whether it is related to shallow circulation of basinal fluids (e.g., the first pre-peak metamorphism phase alteration in the Mount Isa Inlier; or alteration in the hangingwall at Candelaria), or to deep magmatic sources where it may be >300 to 600ºC (e.g., post peak metamorphism in the Mount Isa Inlier; or Mantoverde district in Chile).

Where the system evolved to produce regional- to district-scale albite/scapolite ±magnetite or biotite/K feldspar ±magnetite alteration, embracing more localised barren albite or biotite/K feldspar-actinolite-magnetite-apatite concentrations, temperatures were frequently in the range of 600 to 400ºC, with most having isotope signatures, Br/Cl ratios and other data that support a magmatic origin. This stage of mineralisation may occur as more than one pulse, distributed over a period of time in different parts of the province (e.g., the Central Andean Coastal Belt).

This more restricted, iron oxide rich phase appears to represent a transition from regional to deposit-scale alteration, and constitutes the first of the two stage process many researchers favour (e.g., Hayward and Skirrow, 2010; Rusk *et al.*, 2010; Chen, 2010; Xavier *et al.*, 2010; Oliver *et al.*, 2008; Haynes *et al.*, 1995) for the development of IOCG *sensu stricto* deposits. The iron oxide source may be either magmatic-hydrothermal, exsolved from anorogenic and/or fractionated mantle-derived felsic batholiths (e.g., Lightning Creek, Perring *et al.*, 2000; Ossa Morena Zone, Carriedo and Tornos, 2010), or stripped from the crust (e.g., from iron rich sediments in the Mount Isa Inlier, Rusk *et al.*, 2010; Oliver *et al.*, 2008; banded iron formations or magnetite-rich greenstones in the Fennoscandian Shield, Billström *et al.*, 2010). Iron oxide-alkali altered provinces are sometimes in sections of the crust containing anomalous pre-existing iron accumulations (e.g., the vast exhalative Carajás BIF in the host rocks of the Carajás Mineral Province; the Middleback BIF found sporadically within the Olympic IOCG Province of the Gawler craton).

The regional scale alteration stages are generally characterised by dominant oxidation and absence of sulphides, with only minor late stage copper sulphides (a few hundred to occasionally a thousand ppm Cu) on the margins of magnetite-apatite accumulations (e.g., El Romeral, Chile; Kiirunavaara, Sweden; Acropolis, South Australia; Kachar, Kazakhstan). However, in the example of Lightning Creek, magnetite mineralisation is accompanied by fluid inclusion carrying ~1% Cu, without any associated sulphides, possibly reflecting an absence of sulphur or a similar trigger to precipitation (e.g., Perring *et al.*, 2000).

IOCG *sensu stricto* deposits almost invariably constitute paragenetically late introduction of copper ±gold ±REE ±uranium (the "copper-phase"), overprinting iron oxide-apatite mineralisation similar to that developed late in the regional-scale alteration phase, but not with high grade (≥50% Fe) massive magnetite-apatite accumulations.

The transition from regional-scale, oxide dominant to deposit-scale sulphide-bearing alteration and mineralisation is illustrated by the range of deposits found in many provinces, including: (1) large tonnage magnetite-apatite rich accumulations (10 to >60% Fe) with only trace to minor copper (<100 to ~500 ppm Cu; e.g., Acropolis, Gawler craton; El Romeral, Central Andean Coastal Belt; large unnamed massive magnetite-apatite accumulations in the Carajás Mineral Province; Kiirunavaara, Fennoscandian Shield); (2) large tonnage magnetite/hematite deposits (40 to 55% Fe) with sub-economic zones of copper (0.1 to 0.4% Cu; e.g., Oak Dam East, Gawler craton; Marcona, Central Andean Coastal Belt); (3) Hematite/magnetite (20 to 40% Fe) mineralisation with moderate grades of copper (0.45 to 0.7% Cu) ±precious metals (e.g., Mantoverde, Central Andean Coastal Belt; Prominent Hill and Hillside, Gawler craton); (4) Large tonnages of hematite/magnetite (20 to 40% Fe) with high grades of copper (0.9 to 1.2% Cu) ±gold (e.g., Olympic Dam, Gawler craton; Ernest Henry, Mount Isa Inlier; Cristalino, Carajás Mineral Province; Candelaria, Central Andean Coastal Belt;). See Table 1 and the "Tonnage and Grade" section for metal contents of individual deposits.

The "copper-phase" mineralisation is largely restricted to the deposit-scale and is frequently attributed to a second, fluid that reacts with either: (1) barren early stage, poorly mineralised magnetite/hematite, already deposited; (2) a deeply sourced hot fluid within a reservoir that is already precipitating magnetite/hematite; or (3) a combination of both (e.g., Olympic Dam - Hayward and Skirrow, 2010 and Haynes *et al.*, 1995; Central Andean Coastal Belt - Chen 2010; Carajás Mineral Province - Xavier *et al.*, 2010). Examples are as follows. For more detail see the descriptions in the second part of this paper.

Two main fluid inclusion types are recognised in all of the IOCG *sensu stricto* deposits of the Carajás Mineral Province, one that is high temperature and hypersaline, the second cooler, and only moderately saline. Stable isotope data does not unambiguously provide evidence for either a magmatic or evaporative/bittern source for the high temperature-hypersaline fluids, while the lower temperature variety is taken to represent influx of meteoric fluids under hydrostatic, brittle conditions at the brittle-ductile to brittle transition. The mixing of the two is interpreted to be responsible for ore deposition in all of the deposits, irrespective of depth (Xavier *et al.*, 2010).

The Ernest Henry deposit in the Mount Isa Inlier, is interpreted to have been emplaced at a depth of 6 to 10 km. Rusk *et al.* (2010) and Williams *et al.*, (2010, and sources cited therein) consider that, on the basis of a halogen signature similar to the mantle, a high $^{40}Ar/^{36}Ar$ ratio typical of magmatic fluids, timing relative to intrusions, temperature and other data, the deposit was largely the product of magmatic fluids. Overpressured fluids are interpreted to have exsolved following internal mingling of mantle-derived mafic rocks with the coeval felsic anorogenic batholith. These fluids subsequently explosively breached the impermeable carapace above the intrusion to form a breccia pipe, and then interacted with a second, external, deeply circulating fluid with low Br/Cl and $^{40}Ar/^{36}Ar$ ratios, suggestive of halite (i.e., evaporite) dissolution by near surface sedimentary formation waters (or scapolite breakdown).

Chen (2010; this volume) argues that the main Andean IOCG *sensu stricto* deposits (Candelaria, Mantoverde and Mina Justa) were formed by an early magmatic fluid, responsible for magnetite mineralisation, with only a weak accompanying copper content. The magnetite accumulation was subsequently invaded by oxidised brines, expelled during the inversion of adjacent, shallow, back-arc

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volcanosedimentary basins containing oxidised evaporite-bearing lacustrine-playa sequences. These basins were contiguous with the coeval, large scale, Late Jurassic to late Early Cretaceous volcanic piles that host the magnetite. This late brine is interpreted to have contributed both copper and sulphur, with the existing magnetite being oxidised to hematite during the deposition of chalcopyrite. Both Mantoverde and Mina Justa have lower magnetite sections with chalcopyrite and pyrite, passing upwards into specular hematite and sulphides with increased copper grades. The hematite zone is well developed at Mina Justa, forms the upper section of most orebodies at Mantoverde, but only a thin cap at Candelaria. However, while Chen (2010) and Chen *et al.* (2010) have good experimental data indicating the importance of this second basinal fluid at Mina Justa in Perú, Marschik and Fontboté (2001), Rieger *et al.* (2010) and Rieger *et al.* (2010a) present a case (based on isotope data) for the copper mineralisation at Candelaria and Mantoverde, being the result of a copper-rich magmatic brine depositing copper over the earlier stage magmatic magnetite, with the cooler surface brines/meteoric fluids only assisting precipitation by cooling the magmatic fluids, and possibly contributing some sulphur.

These authors all infer the involvement of two fluids in formation of ore. The first being high temperature, most likely of magmatic origin, although a deeply circulated basinal or metamorphic origin cannot always be precluded. This initial fluid appears to be oxidised and responsible for the iron oxide and possibly weak copper mineralisation. In some deposits, e.g., those of the Tennant Creek Inlier in Northern Australia, data favours an initial basinal fluid. The second fluid would appear in most cases to be late and responsible for the formation of copper sulphide mineralisation, in many cases a shallowly derived oxidised, bittern or re-dissolved basinal evaporite brine that has introduced copper and/or sulphur. It shallow deposits, this fluid usually results in the oxidation of magnetite and overprinting by hematite, accompanied by the precipitation of copper sulphides (e.g., Olympic Dam, Mina Justa). However, to "make" ore, the required composition of each fluid will need to complement the other, e.g., a barren magnetite mass or copper-poor iron oxide rich primary solution will require combination with a copper and sulphur source, while a copper-rich, sulphur-poor(?) "Lightning Creek" brine will require a sulphur source, etc.

Another variation on this theme has been suggested for some specific situations. It involves a single fluid encountering a lithology that promotes precipitation of its solutes, without the involvement of another early fluid. Williams *et al.* 2005 (and sources cited therein) have divided the host rocks in these cases into two main categories, namely, (1) magnetite ±hematite ironstones and (2) carbonaceous rocks.

The ironstones need not be the result of the same processes responsible for copper-gold deposition, with the distribution of those metals in some instances being partly independent of the ironstone on a district to mine scale. In some cases, the driving mechanism appears to have been sulphate reduction by magnetite to form hematite (Gow *et al.*, 1994; Rotherham, 1997; Skirrow and Walshe, 2002). In others, relatively reduced fluids sulphidised the iron oxides to form pyrrhotite-bearing and hematite-free ore (Huston *et al.*, 1993; Skirrow and Walshe, 2002). Examples include the Starra/Selwyn and Osborne deposits in the Mount Isa Inlier, Australia, both described in more detail in the second part of this paper.

Where carbonaceous rocks influence the deposition of ore, mineralisation is characterised by graphite destruction and the formation of carbonate, as well as hematitic alteration, which is commonly better developed in nearby graphite-free lithologies. These observations suggest redox reactions between ore oxidised fluids and graphite contributed to sulphide deposition, with in some cases, preexisting pyrite or pyrrhotite in the host rocks possibly contributing sulphur. Iron oxides are typically minor, with an antipathetic relationship to graphitic rocks (e.g., Greenmount and Mount Dore in the Mount Isa Inlier; Krcmarov and Stewart, 1998; Williams and Skirrow, 2000; Brown and Porter, 2010).

The El Soldado manto deposit in the Central Andean Coastal Belt of Chile has been included as an iron oxide-alkali altered deposit (e.g., Haynes, 2000). It occurs as a stratabound/stratigraphically restricted, clusters of mostly vein-like and discordant accumulations within a submarine, bimodal calc-alkaline basalt-rhyodacite unit. A two stage mineralising system comprised a low temperature phase of 130 to 120 Ma diagenetic framboidal pyrite related to petroleum migration, mixed with a high temperature (>300ºC) hydrothermal phase at ~103 Ma, coincident with batholith emplacement, that deposited early hematite (±magnetite), followed by chalcopyrite, bornite and chalcocite, mostly replacing pre-existing pyrite, with the excess iron forming hematite. Weak to strong alteration accompanies the ore, composed of calcite, chlorite, quartz, albite, hematite and rare epidote and clay (Boric *et al.*, 2002).

The preceding observations are consistent with the conclusions of Williams *et al.* (2010; this volume), who emphasise, (1) different IOCG *sensu stricto* deposits formed in a variety of differing hydrological systems ranging from (a) high levels, where both cool surficial and deeply-sourced fluids reacted, and (b) deeper systems, some, but not all of which, display evidence for a direct input of magmatic fluid, although scant data suggest even these may have a component of shallower fluid input; (2) despite uncertainty about the composition of source reservoirs and fractionation of silicate minerals, there is good evidence that many IOCG ore fluids had salinities derived from more than one source, and that these were not the same in each case (e.g., ±magmatic, ±dissolved evaporite/meta-evaporite, ±evaporated surface water); (3) only circumstantial evidence links the principal economic metals in IOCG *sensu stricto* deposits to any particular source. Also it is apparent that not all of the economic components of a given deposit have the same source (e.g., copper and uranium at Olympic Dam).

Billström *et al.* (2010, volume 4 of this series) similarly discuss this broad view of the formation of iron oxide-alkali altered mineralised systems. They propose a process of "sowing" and "growing" in the Fennoscandian shield, related to the long and complex geological evolution of the region, involving three basic stages. Iron, and to some extent copper and gold, were concentrated in the shield during an initial Karelian (sowing) stage prior to 2.1 Ga, involving recurrent mantle plume activity with numerous layered intrusions, komatiite and picrite eruptions. Important components of this early sowing stage included evaporites (the source of salinity) and mafic igneous rocks, the principal source of copper and a contributing source of gold. This was followed by two Svecofennian (growing) stages of element mobilisation (involving iron, copper and gold) at 1.92 to 1.87, and 1.85 to 1.79 Ga respectively, triggered by metamorphic and magmatic episodes and the formation of brines that scavenged metals previously

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'sewn'. Scavenging and redistribution was controlled by large scale convection cells which precipitated IOCG *sensu stricto*, magnetite-apatite and other related deposits and ore-styles when fluids encountered structural and chemical fluid-mixing traps in suitable host rocks.

As the fluid cells responsible for iron oxide-alkali altered mineralising systems are frequently of crustal-scale, it is inevitable that circulating fluids will encounter a wide range of lithologies with differing contents of available metals, ligands and volatiles, influencing (and modify) the properties of those fluids and their solutes. Similarly, fluids will encounter, rocks and other fluids of varying chemical and physical characteristics that will similarly influence what they precipitate and when, i.e., there will be a large variation between segments of a particular province and between provinces. Consequently, it is unreasonable to expect a tight definition and closely constrained set of conditions for the occurrence iron oxide-alkali altered mineralised systems and IOCG *sensu stricto* deposits. Rather, an open mind must be maintained when considering this style of mineralisation, reading the signs and anticipating the possibilities.

Structural Control, Shears, Faults and Breccias

Structural Control

Most, if not all significant iron oxide-alkali altered and IOCG *sensu stricto* deposits show a strong structural control, although the character of the relationship varies between and within iron oxide-alkali altered mineral provinces. In some, e.g., the southeastern part of the Mount Isa Inlier, Carajás Mineral Province and the Central Andean Coastal Belt, the location of deposits is strongly influenced by proximity to major transcrustal fault zones.

In the southeastern *Mount Isa Inlier*, deposits such as Mount Elliot, Mount Dore and Starra/Selwyn are all associated with subsidiary parallel and branching faults distributed within 2 km on either side of the major Mount Dore Fault Zone, which has a lateral extent of >100 km, and also controlled the distribution of regional alteration (Fig. 5). Some of the deposits within this zone, e.g., Mount Dore, are tabular and more closely controlled by shearing, while the Mount Elliott mineralisation is hosted by a breccia pipe in a zone of cross-faulting on the margin of the Mount Dore Fault zone (Kendrick *et al.*, 2008; Mark *et al.*, 2005; Oliver, 1995; Brown and Porter, 2010, Rusk *et al.*, 2010).

Most of the known IOCG deposits of the *Carajás Mineral Province* are located along, or adjacent to, a regional shear zone that defines the contact between the metavolcano-sedimentary units of the host Itacaiúnas Supergroup and basement rocks of the Xingu Complex. This ~60 km-long, up to several km wide, overall east-west-striking shear zone is characterised by biotite-scapolite mylonites, controls the location of the Alvo 118, Sossego-Sequeirinho and Cristalino deposits, together with several other minor occurrences and a number of large, barren massive magnetite bodies (Fig. 8; Xavier *et al.*, 2010; Monteiro *et al.*, 2008).

The major westnorthwest trending Cinzento shear zone, on the northern margin of the province, hosts the Salobo and Igarapé Cinzento/Alvo GT46 deposits. The Salobo deposit is entirely within the Cinzento shear zone, emplaced under brittle-ductile conditions, resulting in lenticular shaped ore shoots, with little brecciation (Souza and Vieira, 2000).

In the Sossego-Sequeirinho district in the southeast, the latter deposit comprises an "S" shaped, tabular orebody, whose tips are hosted by separate, parallel, sub-vertical eastsoutheast-trending shears in foliated granitoids and schists. These are linked by an offsetting northeast-southwest sinistral fault zone that hosts the bulk of the deposit within mineralised breccias. These two directions are the dominant structural trends in the district (Domingos, 2009). Intense hydrothermal alteration within a few hundred metres into the hanging wall of high angle faults belonging to these two structural trends, surrounds the other ore deposits at Sossego-Sequeirinho. Rocks in the immediate footwall of these same faults have been intensely mylonitised and subjected to biotite-tourmaline-scapolite alteration (Monteiro *et al.*, 2008).

The belt of IOCG and magnetite-apatite deposits of the *Central Andean Coastal Belt* in northern Chile are closely distributed within a 5 to 10 km wide corridor of anastomosing northnorthwest, north and northnortheast ductile and brittle faults, the Atacama Fault Zone (AFZ), that extends for over 1000 km (Fig. 9). Two similar, less developed, parallel corridors, the Tigrillo and Chivato fault systems, are located ~20 km to the west and east of the AFZ respectively. These three structures the early reflect the eastward progression of tectonic and magmatic activity with time. They were initiated during a transtensional regime accompanying slab roll back, and later, during the late Early Cretaceous were reactivated as transpressive structures, resulting in inversion of evaporite bearing back-arc basins (Arévalo *et al.*, 2006; Benevides *et al.*, 2007; Chen, 2010). Most of the significant magnetite-apatite deposits of the Chilean Iron Belt (e.g., El Romeral, El Algarrobo) and the Mantoverde IOCG system are distributed along the AFZ. However, Candelaria is associated with the Paipote fold and thrust system part of the regional Chivato fault zone, 20 km east of the main AFZ (Fig., 10a; Arévalo *et al.*, 2006).

The Paipote fold and thrust system includes the steeply dipping Ojancos-Florida Shear Zone (separating the Copiapó Batholith from the host Punta del Cobre Formation west of the mine), as well as the Paipote, Ladrillos and Cerrillos thrusts and Tierra Amarilla anticline (Fig. 10a). The Candelaria deposit is found at the intersection of the synplutonic low angle Candelaria shear zone and a set of steep northwest to northnorthwest aligned brittle faults (e.g., Lar Fault; Fig. 10b), within a thick unit of coarse volcaniclastic rocks (Arévalo *et al.*, 2006; Marschik and Fontboté, 2001). Within the Candelaria mine area, the Candelaria Shear is largely flat lying (only exposed in the open pit), generally parallel to lithological banding, and is represented by a broad zone of shearing (highly foliated and potassic altered biotite schist and mylonites) over 100 m thick, corresponding to the upper part of the orebody (Arévalo *et al.*, 2006). The Candelaria Shear would appear to be a flat lying splay of the steep Ojancos-Florida Shear Zone to the west (Fig. 10a).

Mantoverde is distributed within, or immediately adjacent to, a 12 km interval of a strike-slip transfer zone obliquely connecting two branches of the AFZ (see Fig. 2 in Rieger *et al.*, 2010, this volume).

Mina Justa, in southern Perú, is within reactivated listric faults associated with the regionally important, northwest-trending Treinta Libras fault system several km to the northeast (Fig. 9; Chen, 2010; Chen *et al.*, 2010).

Some provinces such as the Olympic IOCG Province of the *Gawler craton* and the Eastern Fold Belt of the *Mount Isa Inlier* show evidence of the association of IOCG mineralisation with major structural corridors in some zones, while in others, major deposits occur at fault intersections or in shear packages where no particular structure dominates within a network of faulting. In the south of the Olympic IOCG Province, the Hillside deposit (Conor *et al.*, 2010) is composed of a series of north-south trending tabular, shear controlled bodies that parallel the immediately adjacent major regional Pine Point Fault Zone (Fig. 2, in Conor *et al.*, 2010, this volume) while to the north in the Mount Woods Inlier, the Prominent Hill mineralised system also has a tabular form, developed immediately adjacent, and largely parallel, to an east-west terrane boundary structure, at its intersection with northwest trending fault zones (Freeman and Tomkinson, 2010, this volume). In the central section of the province however, the Olympic Dam and Carrapateena IOCG *sensu stricto* deposits and other subeconomic IOCG or barren magnetite deposits are found in an area where a network of generally northwest and northeast trending faults dominate. The northwest trending controlling structures at Carrapateena, Olympic Dam and Prominent Hill are parallel to, and 10 to 50 km in the hanging wall of the major Elizabeth Creek fault zone (Fig. 4) that is believed to mark the eastern boundary of the Archaean nucleus of the Gawler craton (Fig. 8 in Hayward and Skirrow, 2010). The deposits in this central part of the province appear to have formed during a short lived northnorthwest-southsoutheast directed extension episode that coincided with eruption of the Gawler Range Volcanics (~1595 to 1590 Ma), but was preceded and succeeded by more protracted northwest-southeast to northnorthwest-southsoutheast contraction (Hayward and Skirrow, 2010, and sources quoted therein).

Similarly, variations in structural setting are evident in the *Mount Isa Inlier*. While deposits such as Mount Elliott, are closely associated with major transcrustal structures, further north, the Ernest Henry orebody is in a zone characterised by more evenly distributed structures. Nevertheless, the latter orebody is hosted by a zone of brecciation, sandwiched between two northeast trending shear zones, the hanging wall and footwall shear zones. Coward (2001) suggested these two shear zones form part of a linked duplex of at least four faults or shear zones. The strike of this combined structure varies between approximately northnortheast and eastnortheast on a 10 km scale. The orebody is located at a pronounced flexure in the shear fabric of this structure. It is likely that these local zones of deformation reflect long-lived structures that have been reactivated and mineralised during the Isan orogeny (Blenkinsop *et al.*, 2008).

The Mumbwa mineralised system, in the Lufilian Arc of Zambia, follows a northnorthwest-trending structure for ~25 km, with the main Kitumba deposit toward its southern extremity. At the deposit-scale the main mineralised breccia at Kitumba is located towards the northeastern margin of the late-tectonic, composite, ~560 Ma Hook granite, elongated along this same structure, which is offset by a series of northeast-trending faults. The northnorthwest trend is broadly parallel to the margin of the advancing Congo craton during basin inversion, while the northeast direction is parallel to the major Mwembeshi shear zone 20 km to the south, which parallels the southern depositional edge of the Katangan Supergroup country rock (Fig. Luf).

The deposits of the Lao Cai district of northern Vietnam and southern China are distributed within and parallel to the major northwest-trending Red River (Song Hong) fault zone, a major structural complex accommodating lateral strain associated with the Himalayan collision of the Indo-Australian and Eurasian plates. The Red River Fault zone comprises a package of anastomosing, late, brittle, dextral faults, which dislocated what may have originally been a single continental-scale, up to 30 km wide, 60 to 12 Ma, mylonitic shear zone with sinistral, transpressive shear kinematic indicators. This shear zone also encloses rocks with evidence of late Palaeozoic and Proterozoic deformation. Although the known mineralisation and the main deposits, including Sin Quyen show a strong structural control, both on a district- (distribution of deposits) and deposit-scale (orebody, ore shoot, and vein elongation), information is not available to determine the age of mineralisation, which may be Proterozoic, Permian or perhaps Cenozoic.

Neoproterozoic mineralisation within the Khetri and Alwar districts of northwestern India, is controlled by shear zones, related to the major northeast-trending Kaliguman lineament, one of a series of parallel structures following the structural trend of the Mesoarchean Aravalli Mobile Belt overlying the margin of the Archaean Aravalli-Bundelkhand proto-continent.

Brecciation and Porosity

There is a close observed relationship between IOCG *sensu stricto* ores and breccias, with many deposits being hosted within or in association with brecciated masses, as outlined in the series of descriptions in the second part of this paper. Since Reeve *et al.* (1990) proposed that the Olympic Dam deposit was formed within multiple mafic maar-diatreme volcanoes, there has been a tendency for many such IOCG-related breccias to be regarded as maar-diatremes and by extension, to interpret ore deposition as accompanying explosive release associated with their formation. However, not all such deposits are hosted within breccia pipes, some being within shear zones (e.g., Hillside; Conor *et al.*, 2010). Some breccias are tectonic, apparently unrelated to explosive release (e.g., Sequeirinho, Xavier *et al.*, 2010; some of the Mantoverde ores, Rieger *et al.*, 2010). Others again may represent relatively passive hydrothermal replacement within "flat-lying" porous-permeable sedimentary and/or volcanic breccias (e.g., Prominent Hill, Freeman and Tomkinson *et al.*, 2010; Candelaria, Arévalo *et al.*, 2006).

More recently, McPhie *et al.* (2010) have suggested the Olympic Dam Breccia Complex may not be a maar diatreme, but an upwardly propagating zone of hydrothermal brecciation covering an area of 50 km^2, that postdated an early Mesoproterozoic sedimentary sequence deposited above, or during the waning stages of the Gawler Range Volcanics. Nevertheless, the broader brecciation complex does enclose individual zones of phreatomagmatic brecciation related to mafic dykes.

Explosive release of overpressured fluids through the carapace of the Williams-Naraku batholith does seem a reasonable explanation of the Ernest Henry and related breccias in the Mount Isa Inlier. However, these were formed at a depth of 6 to 10 km and are not of maar-diatreme origin. It is likely that the rapid devolatilisation and consequent fluid overpressuring and release that appears to take place as a result of mingling of mantle derived mafic and anorogenic felsic magmas may be responsible for many similar breccias in the Mount Isa Inlier (e.g., Rusk *et al.*, 2010; Oliver *et al.*, 2008).

Ore precipitation triggered by explosive pressure-release alone would appear to be at odds with an origin caused by

Structure and Breccias ... cont.

the mixing of two fluids indicated for many deposits, except if the mixing is assumed to have taken place before release, or one fluid is released into the second, in which case explosive release as such is not critical, unless the release of pressure triggers precipitation of the mixture.

It may be that breccia zones represent a reservoir through which fluids aggressively to passively migrate, mix and/or react over time to form matrix-fill and intense replacement textures, in contrast to the hydrostatically supported fracturing characteristic of porphyry systems, where more acid, sulphur and silica-laden fluids form fracture fill veins in a relatively passive regime (cf. Williams *et al.*, 2010).

Iron Oxide Apatite Mineralisation

Iron oxide-apatite deposits were originally included in the IOCG family of deposits by Hitzman *et al.* (1992). Since then, a number of authors have questioned their inclusion and their connection with IOCG *sensu stricto* mineralisation (e.g., Williams *et al.*, 2005; Groves *et al.*, 2010). Their distribution, and relationships with IOCG *sensu stricto* deposits detailed throughout this paper, would strongly suggest that most iron oxide-apatite occurrences are part of the same tectono-magmatic and related hydrothermal fluid circulation regime that is responsible for the generation and deposition of IOCG *sensu stricto* mineralisation. While many are barren, some do carry zones of sub-economic grade copper-gold mineralisation (e.g., Oak Dam East in the Gawler craton; Marcona in Perú), and as such may represent incompletely developed IOCG *sensu stricto* deposits. Most would seem to fall within the iron-potassic-calcic or iron-sodic-calcic regional alteration phase that predates the "copper stage" of IOCG *sensu stricto* deposition.

However, a number of the large high grade magnetite-apatite deposits, such as Kiirunavaara and Malmberget in Sweden; El Romeral and El Algarrobo in the Chilean Iron Belt, El Laco also in Chile and Marcona in Perú, have been interpreted to in part, or completely, comprise magnetite flows or intrusions (Nasland *et al.*, 2004; Nyström and Henríquez, 1994; Frietsch, 1978; Chen *et al.*, 2010a). The most studied of these, Kiirunavaara in the Fennoscandian Shield in Sweden (see description in the second part of this paper), is considered by Billström *et al.* (2010) to have formed from a "magnetite magma" at ~1.88 Ga, although it also has features best explained by a magmatic-hydrothermal overprint. Many other magnetite-apatite accumulations are best explained by hydrothermal replacement alone (e.g., Acropolis in the Gawler craton).

Chen *et al.* (2010a) note that deposition of the magnetite orebodies at Marcona in Perú was preceded from ~177 to 162 Ma by Mg-Fe metasomatism producing cummingtonite and phlogopite-magnetite assemblages and widespread sodic albite-marialite alteration. However, they report evidence indicating the actual orebodies, emplaced from 162 to 156 Ma, represent massive magnetite intrusions, the product of hydrous iron oxide melts, without obvious associated micro- or megascopic indications of iron metasomatism. The ores occur as intimately associated, immiscible, amoeboid interfingering, massive magnetite and dacite phases. They interpret the formation of these bimodal ores to reflect co-mingling of oxide and silicate melts, exsolved during the mixing of juvenile andesitic and rhyolitic (or rhyodacitic) parental magmas, enhanced by dissolution of quartz from the intruded host Marcona Formation sediments. They conclude that crystallisation of the oxide melts at 800 to 700°C, to form magnetite-actinolite±biotite aggregates, released large volumes of brines responsible for the intense potassic and/or sodic metasomatic halos to the orebodies. Quenching of these magmatic fluids to <400°C resulted in the precipitation of further, but metasomatic magnetite and substantial pyrrhotite and pyrite, and only minor chalcopyrite, accompanied by actinolite/tremolite, the termination of K feldspar alteration, and by phlogopite supplanting biotite. This final low-magnetite, sulphide-dominated stage formed in a relatively reduced and cooler (360 to 160°C) regime.

Velasco and Tornos (2009) present evidence from a study of the abundant melt, gas and liquid-rich inclusions from two of the significant deposits of the Chilean Iron Belt, Carmen de Fierro and Fresia. Their data confirms the existence of an immiscible iron oxide-apatite melt that separated from a parental silicate-rich primitive magma. They claim the presence of melt-liquid inclusions in apatite, and the textures in ore, indicate the magnetite-apatite rocks crystallised directly from fluid-rich melts, accompanied by repeated pulses of exsolution of magmatic fluids. While early-trapped melts suggest a magmatic origin, later fluid inclusions, also trapped in apatite crystals, are typical of hydrothermal fluids. They interpret these data to reflect a magmatic-hydrothermal transition in water-saturated conditions, from the exsolution of an immiscible iron oxide-apatite melt from a parental magma, to the generation of hydrothermal fluids that resulted in a complex and large-scale brine circulation event, probably responsible for the formation of neighbouring replacement hematite-magnetite and actinolite-apatite-rich veins (cf. exsolution of magnetite and alkalic brines at Lightning Creek in the Mount Isa Inlier; development of magnetite-albitites in the Ossa Morena Zone in Iberia - see more detailed descriptions in the second part of this paper).

The observations of Velasco and Tornos (2009) suggest an evolutionary path of exsolution from a felsic batholith to produce mineralisation that comprises: (1) early exsolved hydrous, oxidised, sodic-calcic-iron hydrothermal fluid; (2) exsolved, immiscible magmatic magnetite-apatite alone, to (3) the same mineralisation overprinted on its outer margins by hydrothermal fluids (as interpreted at Kiirunavaara) to (4) deposits that are purely the result of hydrothermal magnetite-apatite replacement, resulting from the release of voluminous oxidised, sodic-calcic-iron hydrothermal fluid. Those accumulations that are dominantly of high-grade, massive, magnetite-apatite magma, are less likely to react with a later second fluid, except on their peripheries and along fractures, compared to less concentrated replacement and pore-fill accumulations deposited from hydrothermal fluids that are still resident in the interstices.

These examples, from the Chilean Iron Belt, Marcona in Perú and the Lightning Creek deposit in the Mount Isa Inlier, demonstrate processes that result in the generation of both large volumes of iron oxides, and oxidised iron-rich hypersaline magmatic brines that may be circulated and contribute directly to the formation of IOCG *sensu stricto* deposits. It is therefore suggested that, while at one extreme, sulphide-poor massive magnetite-apatite ores differ from IOCG *sensu stricto* deposits, there is a progression between the two and they are both representative of the larger iron oxide-alkali altered group of deposits, and parts of the same crustal scale, multifaceted magmatic-hydrothermal mineralising systems.

Porphyry and IOCG Mineralisation

Most definitions of IOCG deposits emphasise that, whereas mineralisation is almost invariably temporally coincident with igneous intrusions, unlike porphyry-style ores, they are (usually) characterised by the absence of a clear spatial association with those intrusions (e.g., Hitzman *et al.*, 1992; Williams *et al.*, 2005).

Although it has been demonstrated that temporally coincident intrusions may generate magmatic-hydrothermal fluids that contain many of the components required for IOCG mineralisation (e.g., Lightning Creek), this spatial separation suggests that some of the key determinants for deposition are usually only found outside of the intrusions (e.g., the suggested absence of available sulphur at Lightning Creek within the oxidised host granitoid; Perring *et al.*, 2000).

Nevertheless, a number of deposits have been accepted by various authors as being of "IOCG-style", although they do have a clear spatial association with intrusions. These include: (1) Raúl-Condestable in Perú (Williams *et al.*, 2005; deHaller *et al.*, 2006; De Haller and Fontboté, 2009); (2) a group of albitite associated magnetite-apatite occurrences with or without minor copper in the Ossa Morena Zone in southern Iberia (Carriedo and Tornos, 2010); and (3) NICO and Sue-Dianne, and the mineralisation of the Port Radium-Echo Bay district within the Great Bear Magmatic Zone of northern Canada (Corriveau *et al.*, 2010; Goad *et al.*, 2000).

Many of these are from an otherwise similar setting to that of IOCG *sensu stricto* deposits, with comparable patterns of alteration and mineralisation. Some have been offered as representing a transition to "porphyry" style ores (e.g., Corriveau *et al.*, 2010). All are described in the second part of this paper.

In addition, some iron oxide-alkali altered mineral provinces also include coeval gold-rich porphyry deposits, e.g., Andacollo (250 Mt @ 0.62% Cu, 0.25 g/t Au, with additional 90 t of Au in 4 adjacent gold-rich, volcanic breccia-hosted mantos) in the Central Andean Coastal Belt of Chile. Mineralisation at this deposit comprises magnetite/hematite-bearing copper-gold replacement ore, mainly peripheral to a diorite-granodiorite stock, dominantly (80%) hosted within dacitic and andesitic flows, flow breccias and pyroclastic wall rocks. This mineralisation was emplaced more or less contemporaneously with Candelaria, 275 km to the north (Lincoln and Tellez, 1995).

Table 2: Comparison of the related magmatism and mineralisation of porphyry and IOCG deposits

	Porphyry copper	IOCG *sensu stricto*
Magma source	Melting of asthenospheric mantle wedge, promoted by lowering of solidus through fertilisation of mantle resulting from volatiles produced by partial melting of a subducted slab.	Decompression melting of asthenospheric mantle, related to lithospheric delamination and detachment, or mantle plume impact, possibly aided by trapped remnant fertilised mantle from earlier subduction.
Transit to Moho	Upward passage through the SCLM to form an intraplate magma chamber at the Moho density filter.	As for porphyry related magmatism.
Transit to crust	Intraplate magma chamber fractionates and assimilates lower crust to produce a generally homogeneous fraction with lowered density allowing magma to cross the Moho and rise to the mid- to upper-crust.	Intraplate magma chamber: (1) melts lower crust to form mainly felsic anorogenic magma that rises, and (2) fractionates as for porphyry magma to rise independently. Results in heterogeneous multiple anorogenic and fractionated mantle-origin magmas that may mingle in the mid- to upper-crust. Bimodal magmatism.
Crustal state	Dominantly compression to transpression; magma passage via dilations, jogs, fault intersections; periodic distribution; concentrated batholiths, stocks, strato-volcanoes, tuff blankets.	Dominantly extension to transtension during IOCG phase, which promotes rise of magma; produces large lopolithic batholiths, calderas, ring dykes, fissure vents, flood basalts and rhyolites.
Magma state	Reduced, sulphur-rich.	Oxidised, magnetite series, reduced-sulphur deficient.
Ore depth	2 to 5 km below surface.	<2 to >10 km below surface.
Relation to intrusion	Coeval intrusion always present as dominant host; very few exceptions; obvious temporal and spatial relationship to ore.	Coeval intrusion usually within 10 km of ore, without obvious spatial association; few exceptions when intrusion has spatial relationship to ore.
Ore control	Hydrofractured host; held open under lithostatic to hydrostatic pressure during mineralisation; relatively passive mineralisation; hosted in cupola, apophysy, stock or dyke swarm of related intrusive rock; ore system confined - breach to surface terminates porphyry phase and initiates epithermal precipitation. Best deposits - overlapping multiple fluid injection and intrusion.	Hosted by hydrothermal, tectonic, volcanic or sedimentary breccias; or shear zones; also in surrounding country rock; usually in more competent, fractured host rocks; aggressive to passive mineralisation.
Ore form	Stockwork and fracture controlled sulphide and quartz-sulphide veining (hydrofracture fill); fracture controlled disseminations; wall rock replacement.	Breccia matrix fill/replacement; sulphide veining.
Alteration	Prograde inner potassic and outer propylitic; retrograde phyllic overprint and argillic overprint and lithocap.	Regional pre-ore sodic-calcic, to shallower potassic-calcic; overprinted by prograde potassic-magnetite in core; overprinted at higher levels by retrograde hydrolytic and hematite.
Ore zoning	Annular-cylindrical, with outer pyrite; main chalcopyrite, inner bornite and barren core; lower magnetite zone; sulphide >> oxide.	Deep magnetite-chalcopyrite core; shallow hematite-chalcopyrite-(bornite-chalcocite); peripheral pyrite. Ore tabular or cylindrical; oxide >> sulphide.

Porphyry copper details after: Richards, 2003; 2005; Kerrich *et al.*, 2005; Hildreth and Moorbath, 1988; Ulrich *et al.*, 2001; Cline and Bodnar, 1991; Cline, 1995; and Seedorf *et al.*, 2005. IOCG details from contributions to this series.

Porphyry and IOCG Mineralisation ... cont.

Tornos *et al.* (2010) describe the minor Tropezón, intrusion-hosted copper-molybdenum-(gold) deposit (1.5 Mt containing separate zones of ~1% Cu and 0.13% Mo) in northern Chile (220 km north of Candelaria), hosted by the small 2 km^2 Tropezón stock, 15 km east of the Atacama Fault Zone in the Central Andean Coastal Belt. They conclude that Tropezón shares features of both porphyry copper and IOCG-style deposits, and represents the deep magmatic-hydrothermal core zone of a much more extensive iron oxide-alkali altered mineralised system. The remainder of that system occurs as a series of iron oxide-copper sulphide veins, breccias and replacement bodies on the outer margins of the intrusion, and within the surrounding country rocks.

The geology and geochemistry of the main Tropezón mineralised zone indicate an initial stage of formation, comprising the exsolution of hydrothermal fluids from the crystallising, medium-grained, Early Cretaceous, quartz diorite Tropezón stock, which crosscuts the dominant granodiorite, quartz monzonite and monzogranite of the regional Early Cretaceous Cerro del Pingo Plutonic Complex. Both the stock and mineralisation are dated at 110.0±2.1 Ma, close to that of the Candelaria and Mantoverde ores.

Alteration within the Tropezón stock comprises a broad, external, biotite dominant, potassic-(calcic) zone that grades inward and downward to a large dome-shaped volume of calcic-iron-potassic alteration, where the quartz diorite is pervasively replaced by an assemblage that includes early massive actinolite with fine-grained magnetite, and younger K feldspar, epidote, quartz, magnetite, pyrite and tourmaline. The innermost, and deepest alteration zone, comprises massive quartz replacing the calcic-iron-potassic hydrothermal assemblage.

A conspicuous feature of the deposit is the presence of two 30 to 60 m diameter, sub-vertical pipe-like tourmaline breccia bodies, composed of coarse-grained, euhedral tourmaline, with accessory quartz, magnetite, K feldspar, molybdenite, pyrite, chalcopyrite, and traces of albite and anhydrite. These pipes postdated the outer potassic-(calcic) alteration zone, but predated the deeper calcic-iron-potassic and quartz alteration zones, and are the product of explosive release of water saturated magmatic fluids.

The hydrothermally altered rocks contain between 1 and 3 vol.% magnetite. The bulk of the copper-molybdenum-(gold) mineralisation is related to the calcic-iron-potassic alteration zone and includes chalcopyrite, molybdenite, bornite and gold, in small veinlets, or intergrown within the actinolite or the K feldspar-epidote-quartz rocks. Fluid inclusion and mineralogical data show the system cooled from near magmatic temperatures to well below 350 to 300°C during ore formation. Mineralisation is zoned, with an upper, ~50 m thick copper-gold shell, separated from the underlying molybdenum mineralisation by a sharp, horizontal boundary. Tornos *et al.* (2010) regarded the pervasive copper-molybdenum-(gold) mineralisation to be mineralogically similar to some porphyry systems of the Andes.

The initial magmatic-hydrothermal stage, described above, was overprinted by a second event, involving the circulation of low-temperature, hematite-stable, basinal brines, which resulted in an overprint of the main mineralised zone by late chlorite, calcite, quartz, epidote and pyrite, locally including significant amounts of hematite. Distal to the main Tropezón deposit, there are abundant prospects with iron oxide-copper mineralisation within the Cerro del Pingo Plutonic Complex and surrounding Late Jurassic to Early Cretaceous andesitic volcanic country rocks. Near the Tropezón breccia pipes, most of the mineralisation is hosted by veins showing a mineralogical zonation from proximal quartz, actinolite, K-feldspar, magnetite and scapolite, to distal quartz-tourmaline and hematite. More distal occurrences, within ~10 km radius, occur as small veins, breccias and replacement bodies, rich in K feldspar, sericite, chlorite and calcite, with hematite chalcopyrite and minor bornite. Tornos *et al.* (2010) note that the second stage, distal hematite-rich mineralisation is structurally and mineralogically similar to that of the Mantoverde deposit, where fluid inclusion show that the orebody was associated with the circulation of boiling connate brines at temperatures of ~250 to 220°C, resulting in the almost complete conversion of much of the magnetite to hematite (Benavides *et al.*, 2007).

Tropezón illustrates the deep exsolution of copper-gold-iron bearing magmatic-hydrothermal fluids from a felsic, fractionated, mantle-derived magma. It also shows the style of mineralisation, resembling a hybrid porphyry-IOCG deposit that may be formed from those fluids alone within the associated intrusion. Mineralisation related to this same fluid is also represented in the surrounding country rock, distributed around the fluid escape tourmaline breccia pipes. It further demonstrates the role of a late phase, deeply circulated second (in this case, cooler, saline, basinal) fluid in modifying the mineralogy and further distributing mineralisation more distally into the surrounding country-rock.

It is likely that a number of the deposits listed at the beginning of this section share some of the characteristics interpreted at Tropezón, whereby early mineralisation is the result of exsolution of, and deposition from, magmatic-hydrothermal fluids, within or adjacent to an intrusion. In some cases, a second fluid may penetrated to, or into, the intrusion and either influence deposition near the intrusive margin, or at a late stage modify and redistribute mineralisation.

Raúl-Condestable, in the Central Andean Coastal Belt, Perú, is notable for the close temporal and spatial association of its mineralisation with a tonalite porphyry stock and by the distribution of ore which largely occurs as an envelope encapsulating that stock (de Haller *et al.*, 2006; de Haller and Fontboté, 2009), including an inner shell of quartz-biotite stockwork veining. Nevertheless, it otherwise has an alteration assemblage typical of IOCG mineralisation. These characteristics make it more akin to a hybrid IOCG-porphyry deposit. De Haller and Fontboté (2009) present evidence that the Raúl-Condestable ore was deposited from a magmatic fluid, mixed with seawater derived brines, which cooled and contributed ~30% of the sulphur to the ore. This suggests the main mineralisation was a product of magmatic-hydrothermal exsolution, and that cooler, saline brines in the immediately adjacent country rock assisted by quenching and by contributing additional sulphur to the precipitation of mineralisation. For more detail see the description in the second part of this paper.

Corriveau *et al.* (2010), describe a close spatial and genetic relationship between porphyry stocks and IOCG-like mineralisation at the NICO and Sue Dianne deposits, and those of the Port Radium-Echo Bay district, all of which are within the Great Bear Magmatic Zone of northern Canada. These authors suggest these examples illustrate a continuum between IOCG and porphyry copper mineralisation.

Porphyry and IOCG Mineralisation ... cont.

They interpret the Port Radium-Echo Bay district to represent a 1.87 to 1.86 Ga stratovolcano/cauldron collapse structure, dominantly composed of porphyritic to amygdaloidal andesitic tuff, flows, breccia and debris flows, with a comagmatic core comprising a complex of dioritic sub-volcanic stocks and plutons. Alteration is centred on, and most intense within, the core sub-volcanic diorite intrusions, with progressive outward mineral zones, made up of typical IOCG assemblages (sodic-calcic and potassic, with strongly developed hematite and magnetite, etc.; Corriveau *et al.*, 2010, in volume 4 of this series).

Similarly, at Sue Dianne, mineralisation and alteration are developed in association with a fault bounded breccia complex within a pile of well-preserved rhyodacite ignimbrite sheets. Hydrothermal brecciation and alteration emanates from the apex of an albitised porphyry stock low in the complex, extending upwards for approximately 300 m to where it is assumed to have breached the palaeosurface. These breccias are now capped by an interpreted fall-back breccia and palaeoregolith, and lie within a zonal pattern of strongly iron oxide enriched, typical IOCG alteration (Corriveau *et al.*, 2010). For more detail see the descriptions in the second part of this paper.

These observations invite an interpretation that evolving Na-K-Fe-Ca±Cu±Au-bearing magmatic-hydrothermal fluids were exsolved from underlying fractionated batholiths of the Great Bear Magmatic Zone, rising with, and mineralising and altering relatively shallow sub-volcanic intrusions and surrounding wall-rocks.

Although the examples discussed in this section represent deposits with characteristics that overlap porphyry-copper-gold style mineralisation, the main similarity is the apparent exsolution of magmatic-hydrothermal fluids from a batholithic magma chamber and the consequent alteration and mineralisation of an associated shallow intrusion. In most other respects there are clear differences at the deposit-scale, particularly in the chemistry, type of alteration, mineralisation style and ore textures.

Both porphyry copper-gold and most iron oxide-alkali altered mineralised systems are the product of processes that take place within a magmatic column that extends from the asthenospheric mantle to within ~2 km of the surface. However, because of the differences in their settings, there are consequent contrasts in the magmas and fluids produced within the columns, as summarised in Table 2. Nevertheless, rare examples of porphyry-style mineralisation do occur within established iron oxide-alkali altered mineral provinces (e.g., Andacollo in the Andean Coastal Belt in Chile) with some shared characteristics of IOCG deposits, specifically associated iron oxide alteration.

The Aitik copper-gold deposit (summarised in part 2 of this paper) in the Fennoscandian Shield in northern Sweden has been interpreted as a hybrid porphyry/IOCG deposit. However, it would seem that it represents a porphyry style deposit that has been metamorphosed and ~100 m.y. later been overprinted by a regional iron oxide-alkali altered mineralised system that has modified the mineral assemblage and redistributed, or added mineralisation (Wanhainen and Martinsson, 2010 Billström *et al.*, 2010).

One of the key contrasts between porphyry copper-gold and IOCG *sensu stricto* ore systems is that the former are solely the product of a fluid that has been fractionated within the magma column between the Moho and the orebody (with some late input from meteoric waters in the formation of retrograde zones), whereas most IOCG *sensu stricto* deposits, with few exceptions, would appear to be the product of two or more fluids, one or more of which are generated and circulated beyond the confines of the magma column.

The closest comparison between porphyry-style and IOCG mineralisation may be represented by the alkalic porphyry copper-gold deposits. These are mostly generated from juvenile mantle-derived magmas in an intraoceanic arc environment and are related to alkalic, monzonitic intrusions. They produce copper-gold mineralisation with alkalic (sodic-potassic-calcic) and iron oxide alteration, including associated massive magnetite accumulations, within alkalic stocks and often comagmatic andesitic volcanic wall-rocks.

Mafic/Ultramafic Intrusions and IOCG Mineralisation

The most significant examples of mid-crustal mafic and ultramafic intrusions and layered complexes associated with iron oxide-alkali altered mineralised systems include the Rooiberg-Bushveld Complex and its satellite Palabora mafic-carbonatite plug, both in South Africa, and the IRB of the Ossa Morena Zone in Southern Iberia (see descriptions in the second part of this paper). These complexes comprise differentiated mantle magma, injected into relatively dense middle crust as layered complexes, sills, dykes or stocks, sourced from a deep mantle magma chamber, most likely a sub-lithospheric underplate or sub-crustal intraplate. Mineralisation associated with these intrusions may reflect processes involved in the direct release of magmatic-hydrothermal fluids from mafic intrusive complexes.

Layered complexes of this type can contain appreciable orthomagmatic magnetite, occurring as extensive massive cumulate layers, breccia-pipes extending upwards from the cumulate layers and zones of disseminations, all of which are usually titanium- and vanadium-rich, and not of an IOCG affiliation (e.g., within the Upper Zone of the Rustenburg Layered Suite of the Bushveld Complex). However, hydrothermal low-Ti magnetite is also present in mineralised zones associated with the late stage evolution of these complexes. Key examples include the Vergenoeg iron oxide-fluorite deposit within the Rooiberg-Bushveld Complex (Fourie, 2000; Borrock *et al.*, 1998) and the Palabora copper mine (Harmer, 2000; Vielreicher *et al.*, 2000; Groves and Vielreicher, 2001).

The Palabora mafic-carbonatite plug, a satellite of the main Rooiberg-Bushveld Complex, 150 km to the east, comprises a ~2 × 1 km carbonatite pipe in the core of an ~8 × 3 km alkaline complex of dominantly dunite, pyroxenite and apatite-rich pegmatoidal pyroxenite. As such it may represent a more deeply-sourced, lower volume, low-degree partial melt from below the margin of the main chamber that fed the Rooiberg-Bushveld complex (e.g., Farmer, 2005). Other alkaline/carbonatite complexes are also found well within the confines of the Roiberg-Bushveld Complex (Harmer, 2000).

The Palabora complex and Archaean country rocks are overprinted by a destructive metasomatic halo, reflected by satellite intrusions, alteration zones, and aeromagnetic anomalies that extend for tens of kilometers from Palabora itself (Groves *et al.*, 2010). This halo is largely the result of metasomatism (fenitisation) by K-Na-Ca-Fe-Mg and CO_2-rich magmatic chloride brines (with abundant volatiles, particularly fluorine) at a depth of ~12 km.

Experimental and field observations have shown that fluxing agents required to maintain a carbonate melt at geologically feasible temperatures include fluorine (Gittins

Mafic/Ultramafic Association ... cont.

and Tuttle, 1964; Jago and Gittins, 1991) and alkalis (Cooper *et al.*, 1975; Gittins, 1997). This fluid is believed to have been released as a direct result of the carbonatite crystallisation, and resulted in a chemical exchange between the carbonatite mass and surrounding rocks. As the carbonatite began to crystallise low in the system, it is envisaged these fluids were released and moved upwards to alkali-alter, leach and strip metal from the mafic intrusion and Archaean country rocks, to be re-deposited higher in the fluid column in the upper parts of the carbonatite and presumably at higher levels within the crust. Two stages of magnetite and copper mineralisation are observed at Palabora. The first involves the main magnetite (weak copper) phase, with a high Ti (~4%) magnetite, interpreted to be orthomagmatic within the alkaline complex and early carbonatite. The second hydrothermal phase, associated with the late carbonatite dykes, introduced the bulk of the copper mineralisation with lesser, but Ti-poor (<0.1%) magnetite. The Palabora carbonatite may represent the ultimate example of the carbonate-sulphide veining that commonly results from mantle derived CO_2-and alkali-rich magmatic-hydrothermal fluids that are interpreted to contribute to IOCG *sensu stricto* mineralisation as discussed by Oliver *et al.* (2008).

The Vergenoeg breccia-pipe iron oxide-fluorite deposit cuts the Rooiberg Group felsites that predate but overlie the dense main mafic Rustenberg Layered Suite (RLS) of the Bushveld Complex. Two main stages of mineralisation are recognised in the 900 m diameter pipe. The first represents the primary assemblage that made up the original hydrothermal alteration of the felsic volcanic pipe, and is now only preserved at depth. This assemblage comprises fayalite, fluorite and ilmenite with lesser magnetite, apatite, pyrrhotite and REE minerals. The final phase was the introduction of fluorite dykes and veins. This was altered during a secondary hypogene stage that occupies the upper parts of the pipe, comprising an early ferroactinolite, grunerite and titanian magnetite assemblage, and a late secondary stage of hematite, siderite, low-Ti magnetite, ferropyrosmalite, stilpnomelane, biotite, titanite, quartz, and apatite (Borrock *et al.*, 1998). Fluid inclusion, heating-freezing and gas analyses indicate the primary assemblage was the product of CO_2-rich magmatic hydrothermal fluids, while the late secondary stage involved fluids that were a mixture of magmatic and oxidised meteoric water to convert fayalite to magnetite/hematite (Borrock *et al.*, 1998).

Fourie (2000) interpret the ore to have been emplaced at ~1.95 Ga, coeval with the Bobbejaankop Granite of the Lebowa Granite Suite, which is closely associated with a number of similar iron oxide-fluorite deposits in the surrounding district and with the Slipfontein hematite-fluorite-magnetite body with accompanying copper and gold (Fourie, 2000; Kerrich *et al.*, 2005; Pirajno, 2009).

Both Vergenoeg and Palabora reflect processes involving the release of large volumes of alkaline, iron, CO_2- and volatile-rich (particularly fluorine) magmatic-hydrothermal, water dominated chloride brines from fractionated and contaminated mantle melts, resulting in the deposition of large-scale magnetite accumulations, and at Palabora, the deposition of copper mineralisation.

Summary and Conclusions

For the purposes of this paper, the full spectrum of IOCG and related deposits have been collectively referred to as "iron oxide-alkali altered" mineralised systems, incorporating the two main characteristics most used to recognise the wider inter-related group of ores.

These mineralised systems are characterised by the large to giant size of the most significant deposits (Table 1; although smaller examples are also prevalent), the regional and mid- to upper-crustal extent of the alteration halos that enclose these deposits, and the alkali-iron oxide rich nature (sodic/calcic/potassic+magnetite/hematite) of both regional- and deposit-scale alteration/mineralisation patterns. These characteristics illustrate the lithospheric scale of the regimes responsible for their generation.

Most, if not all significant IOCG deposits have a strong structural control, which varies between and within IOCG provinces. In some, the location of deposits is strongly influenced by major transcrustal fault zones which may be up to several kilometres wide, hundreds of kilometres in length, and be represented by an array of interconnected splays and duplexes. Elsewhere, structures are more evenly distributed as an orthogonal set, although individual faults and intersections are important in localising ore deposit and their morphology. These structures are essential for the ingress, focussing and mixing of fluids.

All significant iron oxide-alkali altered mineralised systems and IOCG *sensu stricto* deposits are characterised by a clear temporal, but (usually) not close spatial association with batholithic complexes, composed of both anorogenic felsic granitoids and varying proportions of mantle related, mafic to felsic phases. These magmatic events are accompanied by either: (1) extensive outpourings of comagmatic, bimodal basaltic-andesitic and felsic lavas and pyroclastics, the relative proportion of which vary from example to example; often largely subaerial and erupted from fissure vents or caldera complexes; and (2) by numerous and equally widespread, but usually small, coeval, juvenile, mafic dykes, stocks, sills and occasionally layered complexes. The associated volcanic sheets are absent or not preserved in some cases. These magmatic complexes extend over areas of tens of thousands of km^2, which on the basis of geophysical data, or geological and geochemical character, are interpreted to reflect sub-lithospheric underplates at the base of the SCLM, or sub-crustal intraplate immediately below the Moho density filter (or within the lower crustal mafic transition). These under- and intraplates are interpreted to represent long-lived chambers of fractionating mantle-derived magma that are the result of either mantle plume impact, or crustal delamination and detachment (triggered by either continent-continent collision, or rift related attenuation; Fig. 2) both of which promote mantle upwelling and decompression melting in the upper asthenospheric mantle, generally at depths of <100 km. Figure 3 and the extended caption illustrates the setting described, with further detail of the processes envisaged, and examples described in part 2 of this paper.

The underplates, and more immediately the intraplates, are interpreted to be responsible for the observed, large scale, high temperature-low pressure metamorphism and anatectic/anorogenic magmatism generated from continental crust immediately above the Moho, invariably accompanied by volatile and aqueous exchange, and by mantle-derived magma, fractionated to a density allowing it to cross the Moho and occur as phases within the anorogenic batholiths. They are also responsible for less fractionated juvenile mafic to ultramafic dykes, sills, plugs and layered intrusions injected into dilational openings in the lower- to mid-crust.

Igneous provinces of this type with associated iron oxide-alkali altered mineralised systems are distributed

Summary and Conclusions ... cont.

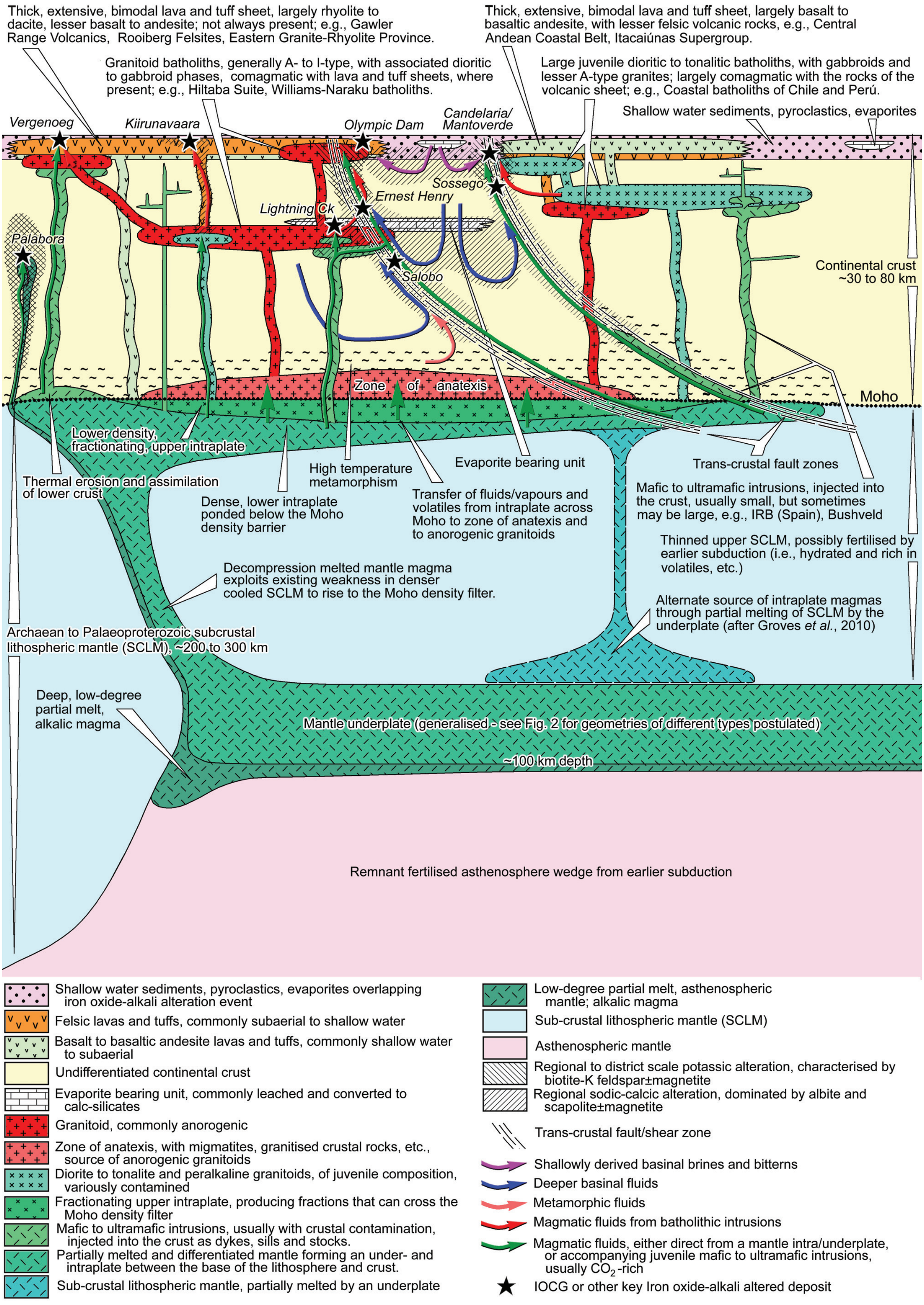

Figure 3: Schematic diagram illustrating the suggested lithospheric setting of IOCG and other iron oxide-alkali altered deposits (not to scale). The key driver of the system is assumed to be the decompression melted mantle underplate magma chambers indicated or inferred below most iron oxide-alkali altered provinces, and the intraplates emplaced between the base of the sub-crustal lithospheric mantle and the Moho, most likely immediately below the latter. Such under- and intraplates may be formed by a number of processes (as summarised on Fig. 8). The intraplate, which is too dense to buoyantly rise above the Moho, is responsible for anatectic melting

Summary and Conclusions ... cont.

throughout the geological record from the Neoarchaean to Late Cretaceous. However, while there is too small a statistical population to draw firm conclusions, significant IOCG *sensu stricto* deposits would appear to be restricted to: (1) the period of major crustal generation during the Neoarchaean from 2.8 to 2.4 Ga, and (2) the periods following consolidation and coinciding with extensional phases marking the initiation of break-up of the Nuna/Columbia, Rodinia, (the short-lived) Pannotia and Pangea supercontinents, from 1600 to 1450, 850 to 750, 570 to 510 and 165 to 95 Ma respectively.

Other iron oxide-alkali altered mineralised systems, IOCG-carbonatite and less significant IOCG *sensu stricto* mineralisation are recorded in these same periods, and between 2100 and 1800 Ma (during assembly of the Nuna/Columbia supercontinent) and from the Carboniferous to Triassic (coinciding with the assembly and consolidation of Pangea, prior to break-up). The major deposits are also mostly located in intervals of crustal thickness variation, reflecting: (1) transition from the thick lithosphere characteristic of Archaean to early Palaeoproterozoic cratons, to the progressively thinner equivalents that developed from the late Palaeoproterozoic, usually occurring outboard of the thicker section; or (2) zones of lithospheric extension and attenuation. Zones of crustal thickness variation are often influenced by collisional sutures related to subduction during the preceding supercontinent amalgamation, or are the focus of new transcrustal structures influenced by strain-localising inhomogeneities. The decompression melt magma generated below these zones is believed to commonly tap remnant asthenospheric mantle (trapped by detached, melting and sinking subductions slabs) and SCLM that was metasomatised (i.e., hydrated and volatile-enriched) during earlier subduction activity (e.g., Oliver *et al.*, 2008; Groves *et al.*, 2010)

The under- and intraplates, and associated high temperature metamorphism and anatexis, as well as the diapirically rising magmatic complexes, act both (1) as heat engines, driving fluid circulation cells and consequent alteration over large volumes of the crust, and (2) as fluid sources. Fluid cell circulation may be controlled by structural permeability, particularly by transcrustal faults producing either linear corridors of alteration up to tens × hundreds of kilometres, or by more equidimensional regions associated with orthogonal patterns of faulting or fracturing that may cover tens to >1000 km^2.

Fluids associated with the formation of both IOCG *sensu stricto* and iron oxide-alkali altered mineralised systems in general, include: (1) CO_2- and volatile-rich, magmatic-hydrothermal fluids/vapours released directly from fractionating mantle-derived magma chambers or related mafic intrusions in the lower- to mid-crust; (2) hypersaline, iron- and alkali-rich, magmatic-hydrothermal fluids, exsolved within fractionated anorogenic and/or mafic to intermediate juvenile batholiths, which have inherited volatiles, water and other components from the related intraplate; (3) fluids produced by high temperature metamorphism induced by an intraplate, and/or anatectic magmatism; (4) sedimentary formation/basinal waters; (5) surface derived bittern brines, or re-dissolved shallowly buried evaporites. Any of these fluids may carry components related to the processes involved in their formation, or exsolved or scavenged from the rocks through which they are circulated.

In most major iron oxide-alkali altered mineral provinces, the earliest fluid circulation and concomitant alteration, occurs as regional-scale patterns throughout the large volumes of rock outlined above, progressively reducing in areal extent with time, evolving to deposit-scale zones, which may still cover areas of as much as

(Fig. 3, cont.)

and high temperature metamorphism of the lower continental crust, initially forming voluminous anorogenic granites, which rise to form batholiths at their level of buoyancy within the crust (e.g., the Hiltaba Suite - Gawler craton; Williams-Naraku batholiths - Mount Isa Inlier; Eastern Granite-Rhyolite Province - USA, Erinpura Granite/Malani Igneous Suite - Aravalli craton, India; Hooke Granite, Lufilian Arc - Zambia, etc.). Comagmatic volcanic sheets of generally subaerial or shallow water lavas and tuffs are frequently (but not always) emplaced (e.g., Gawler Range Volcanics - Gawler craton; Rooiberg Felsites - Kaapvaal craton, South Africa; Eastern Granite-Rhyolite Province - USA, Malani Igneous Suite - Aravalli craton, India, etc.). These are frequently 2 to >4 km in thickness and cover areas in excess of 25 000 km^2. This magmatism is summarised on the left hand half of the diagram).

Fractionation within the intraplate magma chamber produces less dense ultramafic to mafic fractions that may initially be injected along dilational fractures within the crust to form widespread, relatively small dykes, sills and stocks, although some large bodies (e.g., the Rustenburg Layered Suite of the Bushveld Complex) may be emplaced. As fractionation (and assimilation) continues, larger volumes of juvenile magma are generated which are sufficiently buoyant to rise through the Moho to form voluminous dioritic to tonalitic and peralkaline granite batholiths and basaltic to basaltic-andesite volcanic sheets which may dwarf some initial anorogenic granites and felsic volcanic developments (e.g., the Coastal batholiths of Chile and Perú and coeval La Negra Formation volcanism in Chile; and possibly the Itacaiúnas Supergroup volcanics and subsequent intrusions of the Carajás Mineral Province in Brazil). This case is represented on the right hand half of the diagram.

The column below Kiirunavaara represents mingling of mantle derived mafic intrusions which have released carbonic vapours/brines into anorogenic granitoids to exsolve voluminous immiscible hydrous magnetite dominated melts and fluids from the batholith (cf. Lightning Creek, Marcona) that rise to form magnetite-apatite deposits as magnetite intrusions/flows and/or overprinting and associated metasomatic magnetite mineralisation and alkalic alteration.

On the far left, is a diagrammatic representation of the release at ~12 km depth of voluminous magmatic K-Na-Ca-Mg-Fe-F and CO_2-rich dominated chloride brines, triggered by carbonate crystallisation from the Palabora fractionated low-degree partial mantle melting derived intrusion. Above it, is a representation of the Bushveld complex sequence of the Rustenburg Layered Mafic/ultramafic Suite (7 to 8 km thick), Lebowa Granite (3.5 km) and Rooiberg Felsite (3.5 km) and the associated Vergenoeg magnetite-fluorite deposit.

Fractionation of the magmatic systems and the high heat flow generated, result in the exsolution and circulation of hydrothermal fluids, the passage of which is strongly influenced by the mechanical porosity and permeability of the rocks transgressed, particularly transcrustal faults/shears (e.g., Cloncurry, Mount Dore and Pilgrim faults - Mount Isa Inlier; Elizabeth Creek Fault Zone - Gawler craton; Cinzento and Carajás Faults - Carajás Mineral Province in Brazil; Atacama Fault System, Chile; Kaliguman Lineament, India; Red River Fault Zone, Vietnam ?). The five varieties of fluids (or deep vapours) indicated on the legend, are circulated by the heat engine represented by this magmatism, exsolving, scavenging and transporting metals. Evaporite bearing units shown at high and mid-crustal levels, and found in many provinces, contribute Na-Ca-K-Cl and sulphate to the basinal fluids.

Regional scale Na-Ca-Fe alteration is evident within iron oxide-alkali altered provinces, particularly in association with transcrustal faults and their splays, assumed to be channelling either or both magmatic and basinal fluids. At higher levels, this regional alteration is replaced by potassic assemblages and shallow level chlorite-sericite. Note that while density contrasts limit the ascent of mafic to ultramafic rocks above the Moho, there is no such barrier to the transmission of magmatic fluids to the zone of anatexis, or up transcrustal faults. Also, because of the scale of the mineralising systems and the heterogeneity of the crust, there will be considerable variation in the nature of the fluids that dominate in any area, the ligands and metals they scavenge/transport, cause to be exsolved, and eventually precipitate.

Summary and Conclusions ... cont.

50 km^2 (e.g., Olympic Dam). The alteration mineralogy is influenced by both depth, temperature and evolutionary stage. The early regional-scale alteration predates both iron oxide-apatite and IOCG *sensu stricto* mineralisation, and is usually represented at depth by early sodic-calcic assemblages, characterised by albite/scapolite±magnetite, related to either deeply circulated formation/basinal waters or magmatic-hydrothermal fluids, sometimes accompanied by a statistical depletion of ore forming solutes in altered rocks. It is uncertain if this phase is directly related to the generation of mineralisation or is no more than a product of the environment. Some authors (e.g., Oliver *et al.*, 2008) suggest metals are scavenged during this phase and sequestered for later redistribution. The regional alteration pattern often progresses both temporally, and spatially upwards, with decreasing temperature, from sodic-calcic±iron to potassic±iron (biotite/K feldspar±magnetite) and increasing iron oxides at both levels, to iron-sodic-calcic (magnetite-scapolite-apatite-actinolitite), and iron-potassic-calcic (magnetite-K feldspar-actinolite±carbonate) respectively. Major magnetite-apatite accumulations are usually developed within the latter more iron-actinolite rich stages at both levels. All of the preceding are associated with deeply sourced magmatic-hydrothermal or deeply circulated basinal fluids at temperatures of >500ºC, and are characterised by iron oxides and a deficiency of sulphur, except on the margins of the mineralisation where sulphur/sulphate-bearing formational or basinal waters may have influenced the mineralising system.

IOCG *sensu stricto* deposits, where developed, post date this stage. Experimental/fluid inclusion and related data from most iron oxide-alkali altered mineral provinces are supportive of, but do not in most cases unequivocally prove, the influence of a second (or further) fluids in the formation of IOCG *sensu stricto* deposits, the most likely being either of shallow basinal or of further magmatic-hydrothermal origin. While it may be demonstrated that many of the temporally related intrusions are responsible for fluids contributing to the formation of IOCG *sensu stricto* mineralisation, few such deposits form within the source intrusion, implying an additional external ingredient/fluid/physical property is required to allow ore grade and tonnage to be precipitated. In addition, the wide range of depths of formation, suggest they are deposited as a result of fluid-fluid or fluid-rock/mineral reactions, rather than temperature-pressure or other physical conditions.

Alteration patterns associated with the ore stage, progress both temporally and upwards, from the pre-ore regional assemblage (depending on depth of formation) of either sodic-calcic-iron (albite/scapolite-magnetite±actinolite) or potassic-calcic-iron (biotite/K feldspar-magnetite±actinolite) at >500ºC, to progressively overprinting biotite and then K feldspar (~450ºC), to chlorite muscovite-sericite (hydrolytic) and finally to a muscovite and hematite dominant assemblages high and late in the system, at temperatures of <250ºC, often with late carbonate±quartz veining, and in some instances a late barren proximal or distal siliceous stage.

This pattern is somewhat simplified and may be repeated both spatially and temporally, depending on the geological evolution of the province. Individual deposits do not usually bridge all of the idealised alteration zones outlined above, but occupy a window within the spectrum, dependent on their depth and environment of formation.

Most iron oxide-alkali-altered deposits are related to rock porosity and permeability on a deposit-scale, occurring in shear zones, tectonic and explosive breccias, or volcanic and/or sedimentary breccias that control aggressive to passive ingress and reaction of fluids with wall rocks, clasts and breccia matrix.

In the broadest sense, iron oxide-alkali altered, and more specifically IOCG *sensu stricto*, deposits are ultimately the product of inter-related lithospheric- to local-scale geological, structural and hydrothermal fluid circulation events, influencing a diverse range of rocks over an extended period, rather than a well defined process operating on a restricted scale and narrow range of lithologies. The diverse suite of rocks through which the range of fluids are driven will influence the character of those fluids, the solutes sourced and transported, the fluids that may mix, and where. As a consequence there will be a wider variation in the detailed character of resultant deposits than in many other ore styles. Nevertheless it is advantageous to consider the group of deposits as a whole and appreciate the spectrum of possibilities they represent, rather than to attempt to subdivide them into isolated, overlapping ore-types.