ARTICLE

Metamorphic fluid origins in the Osborne Fe oxide–Cu–Au deposit, Australia: evidence from noble gases and halogens

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Abstract The Osborne iron oxide–copper–gold (IOCG) deposit is hosted by amphibolite facies metasedimentary rocks and associated with pegmatite sheets formed by anatexis during peak metamorphism. Eleven samples of ore-related hydrothermal quartz and two pegmatitic quartz–feldspar samples contain similarly complex fluid inclusion assemblages that include variably saline (<12–65 wt% salts) aqueous and liquid carbon dioxide varieties that are typical of IOCG mineralisation. The diverse fluid inclusion types present in each of these different samples have been investigated by neutron-activated noble gas analysis using a combination of semi-selective thermal and mechanical decrepitation techniques. Ore-related quartz contains aqueous and carbonic fluid inclusions that have similar

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Present address: L. A. Fisher CSIRO Exploration and Mining, ARRC Kensington, WA 6151, Australia ⁴⁰Ar/³⁶Ar values of between 300 and 2,200. The highestsalinity fluid inclusions (47-65 wt% salts) have calculated ³⁶Ar concentrations of approximately 1–5 ppb, which are more variable than air-saturated water (ASW = 1.3 - 2.7 ppb). These fluid inclusions have extremely variable Br/Cl values of between 3.8×10^{-3} and 0.3×10^{-3} , and I/Cl values of between 27×10^{-6} and 2.4×10^{-6} (all ratios are molar). Fluid inclusions in the two pegmatite samples have similar 40 Ar/ 36 Ar values of \leq 1,700 and an overlapping range of Br/Cl and I/Cl values. High-salinity fluid inclusions in the pegmatite samples have 2.5-21 ppb ³⁶Ar, that overlap the range determined for ore-related samples in only one case. The fluid inclusions in both sample groups have ⁸⁴Kr/³⁶Ar and ¹²⁹Xe/³⁶Ar ratios that are mainly in the range of air and air-saturated water and are similar to mid-crustal rocks and fluids from other settings. The uniformly low ⁴⁰Ar/³⁶Ar values (<2,200) and extremely variable Br/Cl and I/Cl values do not favour a singular or dominant fluid origin from basement- or mantle-derived magmatic fluids related to A-type magmatism. Instead, the data are compatible with the involvement of metamorphic fluids that have interacted with anatectic melts to variable extents. The 'metamorphic' fluids probably represent a mixture of (1) inherited sedimentary pore fluids and (2) locally derived metamorphic volatilisation products. The lowest Br/Cl and I/Cl values and the ultra-high salinities are most easily explained by the dissolution of evaporites. The data demonstrate that externally derived magmatic fluids are not a ubiquitous component of IOCG ore-forming systems, but are compatible with models in which IOCG mineralisation is localised at sites of mixing between fluids of different origin.

Keywords Osborne · Mt Isa · IOCG · Australia · Argon isotopes · Halogens

Introduction

The iron oxide–copper–gold (IOCG) class of ore deposits encompass a diverse range of mineral occurrences that have debated origin and tectonic significance (Hitzman et al. 1992; Haynes et al. 1995; Barton and Johnson 1996; Pollard 2006). The Eastern Fold Belt of the Mt Isa Inlier, or Cloncurry District, is one of the world's premier IOCG provinces with several mines currently in production (Fig. 1). Furthermore, the region and deposits within it have been subjected to intense geological investigation making it an ideal location to study the diversity of IOCG deposits within a single district (Davidson and Large 1994; Rotherham 1997; Adshead et al. 1998; Mark et al. 2006; Kendrick et al. 2007).

This study focuses on the Osborne deposit which is of special interest because it is associated with pegmatite sheets, not regional granitoids (Fig 1; Morrison 2005; Mark et al. 2006), and it is now favoured to have formed during peak upper-amphibolite facies metamorphism at approximately 1,595 Ma (Gauthier et al. 2001). In contrast, the majority of Cloncurry IOCG deposits are associated with regionally extensive post-1,550 Ma A-type granitoids of the Williams–Naraku Batholith (Mark et al. 2006). The Osborne deposit is further distinguished by paragenetically early iron oxide that is interpreted to represent a metamorphosed banded ironstone (Davidson 1989; Williams 1994). However, ore-related fluid inclusions are petrographically similar at Osborne as in other Cloncurry IOCG deposits, encompassing the variably saline brines and liquid carbon dioxide varieties that are typical of this deposit class (Rotherham 1997; Adshead et al. 1998; Baker 1998; Williams et al. 2005).

In this study, we utilise the noble gases and halogens as conservative fluid tracers to enable a detailed comparison of



Fig. 1 Simplified geological map of the Eastern Succession of the Mt. Isa Inlier showing the location of major IOCG deposits and granite batholiths (modified after Beardsmore et al. 1988)

fluid sources at Osborne with other IOCG in the Cloncurry District (Kendrick et al. 2006a, 2007, 2008). The noble gases are uniquely useful for this purpose because in many cases their transport is coupled to that of major volatiles and they have isotopic compositions that vary by orders of magnitude between deep-crustal and surficial fluid reservoirs (Ballentine et al. 2002; Ozima and Podosek 2002). In addition, they collect in the fluid phase and do not undergo isotopic exchange during wall–rock interaction; therefore, the noble gas concentration provides information on the extent of wall–rock interaction and/or phase separation, as well as the primary fluid origin (Kendrick et al. 2006b). The halogens provide a unique insight on the acquisition of salinity by fluids.

A key aim of this study was to determine the 40 Ar/ 36 Ar and halogen composition of 'metamorphic fluids' preserved in pegmatite fluid inclusions at Osborne. Although these 'metamorphic fluids' have interacted with anatectic melts, we distinguish them from 'magmatic fluids' related to Atype magmatism because anatexis does not necessarily introduce external components to the site of mineralisation. Metamorphic fluids could be partly inherited from sedimentary pore fluids or derived by host lithology devolatilisation (Yardley and Graham 2002). In addition, sedimentary formation waters could have been introduced during metamorphism and are typified by ⁴⁰Ar/³⁶Ar values of approximately 300-2,000 (Torgersen et al. 1989; Turner and Bannon 1992; O'Nions and Ballentine 1993; Tolstikhin et al. 1996; Kendrick et al. 2002). Fluids related to A-type magmatism elsewhere in the Cloncurry District have ⁴⁰Ar/³⁶Ar values of up to approximately 30,000 (Kendrick et al. 2007, 2008). Regardless of the fluid source, the extent of evaporite dissolution and its importance as a source of salinity, are major uncertainties in IOCG terranes (Barton and Johnson 1996; Pollard 2000). Fluids that have dissolved halite can be identified from low Br/Cl and I/Cl values of 0.1×10^{-3} and 10^{-6} that are similar to halite (Holser 1979; Böhlke and Irwin 1992).

Geology

The Osborne deposit lies south of the Mt Isa Inlier under 20–40 m of cover. The mine comprises several discrete ore bodies with a total reserve of 15.2 Mt at 3.0% Cu and 1.05 g/t Au making it one of the larger IOCG deposits in the Eastern Fold Belt (Fig. 1; Tullemans et al. 2001).

The 1S, 2M and 3E ore bodies occur in western and eastern domains that are separated by the post-mineralisation Awesome Fault (Fig. 2; Adshead et al. 1998). The host rock is dominated by sodic-plagioclase psammite interpreted to be equivalent of the Mt Norna Quartzite in the 1,695-1,650 Ma Soldiers Cap Group (Beardsmore et al. 1988; Adshead et al. 1998; Page and Sun 1998; Mark et al. 2006). The psammite has minor pelite horizons and migmatitic zones (Adshead et al. 1998). Two laterally continuous (1.3 km) stratiform horizons of deformed, banded magnetite-quartz-apatite ironstone are important in the western domain. These early, pre-metamorphic, ironstones host a crenulated Cu-Au mineralised shear zone in the eastern part of the mine (Fig. 2; Adshead et al. 1998). Parallel sheets of tholeiitic amphibolite and a podiform body of meta-ultramafic rock are cut by discordant pegmatite sheets that occur throughout the mine, but are most common in the 3E ore body where they both predate and cross-cut mineralisation (Adshead et al. 1998). The presence of migmatites in the psammitic host rock (Adshead et al. 1998) is consistent with a fairly local origin of pegmatitic melts by anatexis during regional metamorphism at upper-amphibolite facies (Mark et al.



Fig. 2 Plan view of Osborne Ore Bodies and section through western domains showing association of ore and silica flooding with ironstones (after Tullemans et al. 2001)

	Stage 0	Stage 1	Stage 2	Stage 3
Magnetite				
Hematite				
Pyrite		silica flooding		
Quartz		Silica fielding		
Chalcopyrite				
Pyyrhotite				-
Molybdenite				-
Gold				
Talc			+	
Biotite				
Siderite				+
Chlorite				
Muscovite				
Ferropyrosmalite				
Dolomite				
Calcite				
Haematite dusting				

 Table 1 Paragenesis of the Osborne ore assemblage (after Adshead 1995)

¹ Stages refer to quartz generation.

1998; Foster and Rubenach 2006). Peak metamorphism (correlated with D2 deformation) occurred at approximately 1,595 Ma in the mine area and is constrained by U–Pb dating of titanite, zircon and monazite (Page and Sun 1998; Gauthier et al. 2001; Giles and Nutman 2002; Rubenach et al. 2008).

The 1,750–1,725 Ma calc-silicate Corella Formation (Page and Sun 1998) is exposed only in the western part of the Eastern Fold Belt (Fig. 1) and is in tectonic contact with the Soldiers Cap Group. Rocks equivalent to the meta-

evaporitic Cl-rich scapolite- and calcite-bearing Corella Formation could be present at a depth beneath the Osborne mine. These rocks are significant because they could be an important source of fluid ligands and volatiles (Oliver et al. 1993). The regionally significant A-type granitoids of the Williams–Naraku Batholith do not outcrop in the mine vicinity (Fig. 1) and were emplaced during the latter stages of the Isan orogeny, after peak metamorphism, during D3 and later deformation (post-1,550 Ma; Page and Sun 1998; Wyborn 1998). The tectono-stratigraphic evolution of the

Table 2 Sample and fluid inclusion assemblage descriptions

Sample					Fluid Inc Pro	lusion A portions	ssemblag (%)	je	Analysis
ID	Description	Mineral	Stage ^a	MS		۵.		LL,D	H- step heat C - crush
Peg				2023			1050		
Osb40	Coarse quartz-feldspar pegmatite with perthitic textures, minor tourmaline and rare specular hematite.	qtz + minor feldspar	peak-met	45	5	15	30	5	Н
Osb852 15	Quartz-feldspar pegmatite with rare perthitic textures.	feldspar + qtz	peak-met	20	0	5	70	5	Н
Osb15	Magnetite bearing coarse-grained silica flooding with minor chalcopyrite.	qtz	1-2	70	10	5	14	1	H, C
Osb22Am	Magnetite rich silica flooding with chalcopyrite hosted within magnetite rich zones.	qtz	1-2	20	35	35	10	0	Н, С
Osb27	Chalcopyrite bearing quartz vein, hosted by hematized feldspathic psammite and ironstone	qtz	0-1	25	10	10	50	5	Н, С
Osb59	Silica flooding with thin bands of magnetite. Chalcopyrite has infill texture.	qtz	1-2	20	40	30	10	0	Н
Osb315 2M	Silica flooding with minor magnetite and coarse chalcopyrite.	qtz	1-2	45	25	10	15	5	Н, С
Osb36B	Silica flooding with magnetite rich zones and coarse chalcopyrite with occasional fine grained pyyrhotite coats	qtz	1-2	60	10	18	10	2	Н
Osb43	Silica flooding with magnetite rich zones and coarse chalcopyrite and minor pyrrhotite	qtz	1-2	45	15	25	15	0	Н
3E									
Osb37B	Magnetite-chalcopyrite-pyrrhotite bearing silica flooding	qtz	1-2	35	20	20	24	1	Н
Osb47	Fine grained silica flooding, with undulose extinction. Chalcopyrite replaces D3 foliation.	qtz	1-2	35	40	20	5	0	н
Vein									
Osb20	Quartz vein containing pyrite and chalcopyrite cross-cut by quartz-magnetite- pyrite-chalcopyrite veins in psammite with accessory hematite and pyrite.	vein qtz	2-3	10	50	35	5	0	Н, С
Osb22Av	Quartz-feldspar vein with coarse chalcopyrite and hematite dusting on feldspar grains hosted by mineralized silica-flooding.	vein qtz	2-3	0	35	65	0	0	Н

Fluid inclusion abbreviations: MS ultra-high-salinity multi-solid, LVD liquid-vapour-daughter, LV two-phase liquid-vapour, CO_2 liquid carbon dioxide, LLcD liquid water, liquid carbon dioxide and daughter minerals

^a Paragenetic stages given in Table 1.

Mt Isa Inlier has been reviewed in detail elsewhere (O'Dea et al. 1997; Betts et al. 2006).

Paragenesis, timing and stable isotopes

Multiple phases of pervasive albitisation (Na–Ca alteration) are preserved at Osborne (Rubenach et al. 2008). However, the main phase is constrained by hydrothermal titanite U–Pb ages of approximately 1,595 Ma, consistent with a dominantly syn-metamorphic origin in the Osborne mine area (Rubenach et al. 2001, 2008). The albitised host rock is overprinted by hydrothermal stockworks of sulphide-poor vein quartz with accessory magnetite and biotite (French 1997).

There are three generations of quartz indicative of prolonged hydrothermal activity: stage 1 quartz termed 'silica flooding' (Adshead et al. 1998), is variably infilled or replaced by stage 2 quartz, which hosts the majority of sulphide- and mineralisation-related magnetite (Table 1). Stage 3 quartz comprises late mineralised veins. Rare molybdenite samples associated with sulphide ore have Re-Os ages of 1,595±5 and 1,600±6 Ma (Gauthier et al. 2001). Taken together, the age and structural data suggest Cu-Au mineralisation closely followed syn-metamorphic albitisation and anatectic melting before regional magmatism, but occurred partly in the brittle regime (Adshead et al. 1998; Gauthier et al. 2001; Foster and Rubenach 2006). Hydrothermal amphibole and biotite Ar-Ar ages of approximately 1,540 Ma (Adshead et al. 1998; Perkins and Wyborn 1998) are now interpreted to indicate either a retrograde phase of alteration or the low closure temperature of the Ar-Ar system (Rubenach et al. 2001).

Oxygen isotope data is distinct for the pre-metamorphic magnetite in the banded ironstones ($\delta^{18}O_{fluid}$ of +5.7‰ to +8.9‰), and later magnetite associated with silica flooding ($\delta^{18}O_{fluid}$ of +8.6‰ to +12.0‰; all values relative to SMOW; Adshead 1995; Mark et al. 2006). Sulphides in stage 2 and 3 quartz have $\delta^{34}S$ in the range –4‰ to + 3‰ (Mark et al. 2006). If sulphur was acquired by leaching igneous rocks, these data are consistent with the involvement of either metamorphic or sedimentary formation waters; however, they do not preclude a magmatic fluid origin (cf. Mark et al. 2006).

Samples and fluid inclusions

Fluid inclusion wafers were prepared for the ore-related quartz and pegmatite samples collected from the 1S, 2M and 3E ore bodies (Table 2). Stage 1 silica flooding is dominated by trail-bound secondary fluid inclusions that are similar to primary and secondary fluid inclusions in the later quartz. The multiple generations of secondary fluid inclusion indicate repeated vein growth and fracturing, which is a characteristic of IOCG samples. As a result, the entire fluid inclusion assemblage in both early and late quartz is representative of different stages in the evolving IOCG system.

Five fluid inclusion types have been distinguished on petrographic criteria. Approximately 2% of the fluid inclusions in early quartz are high-salinity brines (>40 wt % salts) with variable proportions of liquid CO₂. These inclusions are paragenetically early and were trapped in the two-phase field. More abundant ultra-high-salinity (<64 wt% salts) multi-solid (MS) and liquid carbon dioxide (CO₂) fluid inclusions are sometimes observed along a single trail, which provides further evidence for the contemporaneous nature of carbonic and aqueous fluids. Stage 2 quartz and late vein samples are dominated by moderately saline liquid-vapour-daughter (LVD; approximately 26-37 wt% salts) and low-salinity two-phase liquid-vapour fluid inclusions (LV; <30 wt% salts). The high-salinity LVD fluid inclusions lie on trails radiating from chalcopyrite grains and are interpreted to be closely associated with Cu-Au mineralisation (Adshead et al. 1998). The MS, LVD and CO₂ inclusions are between <1 and 20 µm in diameter with many <5 µm in size. LV inclusions are generally smaller (<5 µm) and occur in dense trails.

Homogenisation temperatures recorded for the different populations of aqueous fluid inclusion (MS, LVD and LV) imply that minimum trapping temperatures decreased from



Fig. 3 Br/Cl versus I/Cl. *Small symbols* denote individual heating steps (200–700°C). *Large symbols* represent averages taken over the 500–700°C temperature steps most representative of LVD and MS fluid inclusions. The seawater evaporation trajectories of Zherebtsova and Volkova (1966) and the halite dissolution water of Böhlke and Irwin (1992) are shown for reference. The *error bars* represent the analytical uncertainty with a minimum value of approximately 3% (ESM Table 1). The absolute Br/Cl and I/Cl values have a higher uncertainty of 15% in this irradiation

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Table

Sample/extr	action	$^{40}\mathrm{Ar}^{36}\mathrm{Ar}$		$\mathrm{Cl}^{36}\mathrm{Ar} imes$	$^{40}_{10^{-6}}\mathrm{Ar_{E}/Cl}\times$	NaCl wt %	[³⁶ Ar] nnh ^c	$[^{40}\mathrm{Ar_E}]$	F ⁸⁴ Kr	F ¹²⁹ Xe	$Br/Cl \times 10^{-3}$	I/C1× 10 ⁻⁶	K/C1	X E) (mu	J (hnn
		Max age- corrected ^a	Sample mean (measured)-age corrected ^b	Max	Mean	MS mean	(max) ^d		Range		200-700°0	range	FI range M ≤500°C	Max F	[f+matr	X
Peg. Osb40	Н	$1,672\pm67$	(4,048) 1,087±162*	140 ± 10	53±57	57 (65)	2.5 (2.9)	21 (24)	1.0- 1 4	1.8- 3 0	0.6–1.3	3.8–12	0.08-0.16 6	1 19	95 9	
Osb852 IS	Н	$1,511 \pm 18$	(14,697) 1,144±64*	19±1	145 ± 49	57 (65)	19 (21)	57 (64)			1.6–2.6	14–23	0.18–7.1 7	714 1	5,601 4	123
Osb15	Н	$1,017\pm 8$	$(830) 605\pm 29$	205±13	4±2	55 (64)	1.7 (1.9)	1.5 (1.8)			0.4 - 1.0	2.8-6.5	0.09-1.18 0	1 69 1	33	
Osb22A	Η	873 ± 11	$(575) 499\pm 29$	82±5	5±4	48 (60)	3.6 (4.5)	1.6 (2.1)			1.4–3.8	2.4–12	0.05-0.79 0	1 62.0	~	8
Osb27	Η	778±9	$(900) 545\pm 26^*$	53 ± 3	13 ± 5	40 (45)	4.6 (5.2)	3.6(4.0)			1.7–2.8	7.9–16	0.05-0.13 3	8.16 1	215	'5
Osb27	C	856±24	(620) 582±27	119 ± 8	9±2	40 (45)	2.1 (2.3)	2.5 (2.8)	0.8-	0.7-	0.5 - 2.6	5.2 - 10	0.05-0.09 0	1 60.0	5	17
0.450	п	1 040 ± 17	944429 (930)	C1+071	C+3	20 (20)		1 (2 5)	1.8 0 5	8.5 0 5	1 2 0	0900	1 200 200	1 00 1	0	
60080	4	1,040±1/	0+=+10 (000)	1/0717	7±0	(nn) nr	1.7 (2.1)	((7) 17	-c.o	3.1	0.0-4-1	0.0-6.7	u.u0_u.u	1 67.	0	
Osb315	Η	739±60	(1,173) 527±140*	181 ± 19	$9{\pm}11$	49 (51)	1.7 (1.7)	3.0(3.1)			0.3-0.9	3.5-8.8	0.13-0.90 1	8.1 1	897 3	,362
Osb315	C	853±24	(574) 493±24	120 ± 8	7±3	49 (51)	2.5 (2.6)	2.3 (2.4)	1.0-	1.6 -	0.5 - 0.7	5.2-7.9	0.09-0.10 0	0.10 2	5	<u> 5</u> 62
									1.8	8.5						
ZM Och26D	П	1 603±110	(1 777) 017458*	241+16	0 ± 7	16 (51)	1 2 (1 4)	75 (20)			1 2 0	1 2 12	C 0 C 2 0 0	1 0 0	50	22
GOCOSO	- :	$011 \pm 660,1$	$1,722$ 912 ± 30	241 ± 10	0 1 1 0	(+c) 0+	1.2 (1.4)	(0.6) 6.2			0.0-1./	c1-c.+	0.0/-2.0 2	, , , , , , , , , , , , , , , , , , ,	~	7/
Osb43 3F	Н	$1,614{\pm}68$	$(988) 764\pm 68*$	142±11	$14{\pm}13$	50 (55)	2.2 (2.4)	4.8 (5.3)			1.0-2.0	13–27	0.07-0.16 4	1.5 1.	6	00
$Osb37A^g$	Н	2,236		49	4.4	45	3.5	0.8			1.3 - 2.0	10				
$Osb37B^g$	Η	570		289	0.85	65	0.9	0.25			0.3 - 0.5	3.4-5.0	0.14 - 0.27			
Osb37B	Н	$1,117\pm 25$	(1,066) 591±44	470±32.4	2 ± 1	50 (55)	0.7 (0.7)	0.7 (0.8)	0.8-	1.0-	0.5-0.8	3.2-5.9	0.10-0.11 0	8 66.0	8	61)
Osb47	Н	$1,992\pm13$	(1,082) 833±41	274±18.0	4±2	50 (55)	1.1 (1.2)	1.4 (1.5)	/.1	0.1	0.7 - 1.0	3.2-5.4	0.06-0.09 3	8.73 7	1	85
Osb47	C	$1,401\pm109$	(938) 793±92	281±19.1	$3.6 {\pm} 0.2$	50 (55)	1.1 (1.2)	1.2 (1.4)	1.0 - 1.5	0.7-2.6	0.8-0.9	5.4-26	0.06 0	0.06 7	~	•
Late vein										i						
Osb20	Н	$1,056{\pm}46$	(1,984) 466±32*	152 ± 11	$59{\pm}100$	30 (38)	1.2 (1.5)	12 (15)			0.7 - 1.6	3.1 - 7.0	0.09-0.29 1	5.5 1	45	I
Osb20	C	736±22	(814) 704±44	60 ± 4	8 ± 1	30 (38)	3.1 (3.9)	1.6 (2.1)	1.2-2.1	2.5-6.1	1.0 - 1.4	5.2-6.2	0.10-0.13 0	0.13 1	6	
Osb22Av	Н	444±16	(449) 411±35	63 ± 16	10 ± 15	24 (32)	2.3 (3.1)	1.6 (2.2)	1.1– 1.5	1.1– 1.7	1.4–2.8	2.3–3.8	0.04-0.05 0	0.30 9		2

Reference values ^h									
Meteoric	296			0	1.6–2.7 0	2.1	4.2		
Magmatic	~30 000	~10–30	$\sim \! 1,000$	<8-80	3–6		1–2	10-70	1
Salinity values are <i>H</i> : step heat, <i>C</i> : cru	determined from homogenisation te ush, $^{40}Ar_{F}$: age-corrected excess 40 A	mperature, exc $r (^{40} Ar_E = ^{40} AI$	pt the values 40 Ar _R $^{-4}$	given in it ⁽⁰ Ar _A), ⁴⁰	alics which denote r_R : radiogenic ⁴⁰ $_{I_R}$	mean values vr produced in	calculated from situ since 1,59	phase volumetric studies. 5 Ma, ${}^{40}Ar_{A}$: atmospheric ${}^{40}Ar=295.5 \times {}^{36}Ar$,	:SM
multi-solid fluid in	nclusions, FI: fluid inclusion	:	;						
^a Corrected for pos	it-entrapment production of radiogen	ic ⁴⁰ Ar based o	on the 39 Ar _K	released in	each extraction ste	p and an age	of 1,595 Ma.		
^b The mean (total fi	usion), measured and age-corrected (1.	,595 Ma) ⁴⁰ Ar/	³⁶ Ar values. C	orrected va	lues marked by an	asterisk are es	timated from sele	scted extraction steps (full data set in ESM Tabl	le 1).
^c Ar concentrations	s are based on the mean and maximu	um salinities of	MS fluid inc	lusions and	the tabulated ⁴⁰ A	r_E/Cl or $Cl/^{36}$	Ar values. 1 pp	bb ³⁶ Ar is approximately 1.6×10^3 cm ³ g ⁻¹ F	$H_2O;$
1 ppm 40 Ar _E is ap	proximately 1.8 cm ³ g ⁻¹ H ₂ O.								
^d MS inclusions nc	of present in Osb22Av, so salinities ξ	given are for LV	/D inclusions.						
^e The range of Br/(Cl and I/Cl determined in the temper	ature range 20	0-700°C by st	tepped heat	ing or by in vacuo	crushing (ro	ws denoted C).		
^f K/Cl is estimated	for FI from data obtained at $\leq 500^{\circ}$ C	Ţ.							
^g Data from Kendr	ick et al. (2006a).								
h Reference values	for meteoric water in Ozima and Pc	dosek (2002).	Magmatic flui	ds based p	rimarily on high ⁴	Ar/ ³⁶ Ar fluid	is at Ernest Her	ury (Kendrick et al. 2007).	

more than 400°C in MS fluid inclusions to less than 300°C in LV fluid inclusions. The majority of CO_2 fluid inclusions have melting temperatures of -56.8° C to -58.5° C, indicating a purity of greater than approximately 95–98 mol% CO₂ (Kerkhof and Thiéry 2001), consistent with preliminary laser Raman studies that indicate only minor CH₄ and N₂.

During heating, liquid CO_2 fluid inclusions are amongst the first to decrepitate with only the smallest CO_2 fluid inclusions persisting above approximately 400°C. The aqueous fluid inclusions are preferentially decrepitated at higher temperature with the most saline fluid inclusions decrepitated last. As a result, fluids released between 500°C and 700°C are dominated by the highest-salinity LVD and MS fluid inclusions. These fluid inclusion assemblages and their behaviour during heating are similar to that reported for IOCG samples and related alteration elsewhere in the Cloncurry District (Beardsmore 1992; Dong 1995; Rotherham 1997; Adshead 1995; Baker 1996; Perring et al. 2000; Kendrick et al. 2006a, 2007, 2008).

The pegmatite samples include a coarse grained pod taken from the 2M ore body (Osb40) and a non-porphyritic alkali feldspar granite vein (Osb852) taken from the 1S ore body. Both samples contain fluid inclusion assemblages that resemble those in the ore-related samples and behave similarly during microthermometric heating. In these cases, the primary high-salinity MS fluid inclusions are interpreted to represent a fluid exsolved during crystallisation of the anatectic melt. However, the secondary origin of most LVD and LV fluid inclusions and their similarity to those in the ore samples suggest that they could be related to either metamorphism or IOCG mineralisation. The relative abundances of the different fluid inclusion types and the mineralogy of the samples are summarised in Table 2.

Noble gas and halogen methodology

Fluid inclusion wafers were broken into 1-4 mm fragments and quartz (±feldspar) was hand-picked under a binocular microscope, removing mineral impurities. The wafer fragments were cleaned in an ultrasonic bath using distilled water and acetone, wrapped in Al foil and sealed in silica tubes together with Ar-Ar flux monitors (Hb3Gr, GA1550) and the Shallowater I-Xe standard (Hohenberg 1967; Roddick 1983; McDougall and Harrison 1999; Johnson et al. 2000). The package was irradiated for 150 MW h in position 5c of the McMaster nuclear reactor, Canada (Irradiation designated UM#8). The irradiation parameters (Kelley et al. 1986) were determined as $J=0.0185\pm0.0002$, $\alpha = 0.55 \pm 0.01$ and $\beta = 4.8 \pm 0.3$, indicating a combined fast and thermal neutron fluence of approximately 10^{19} n cm⁻². The resonant neutron correction factors were 1.25 for Br and 1.6 for I (Kendrick et al. 2006a).

Irradiated samples (40–90 mg) were loaded into either modified Nupro® valves for in vacuo crushing or packed into Sn foil packets for analysis in the tantalum resistance furnace. In addition, four unirradiated sample duplicates were loaded into the modified Nupro® valves for in vacuo crushing analysis. Each sample was analysed by either four to six sequential in vacuo crushes or by stepped heating from 200°C to 1,600°C. Stepped heating was cyclical with samples heated from an idle temperature of 100°C to the specified step temperature over a period of 3 min. The duration of each heating step was 20 min. Heating steps increased in increments of 50-100°C between 200°C and 700°C but in increments of 200-300°C at higher temperature (ESM Table 1). Extracted fluid inclusion gas was purified using hot and cold Zr-Al getters and expanded into the MAP-215 noble gas mass spectrometer at the University of Melbourne. Isotopes of Ar, Kr and Xe were simultaneously analysed in peak jumping mode in nine cycles of measurement over a period of 50 min. Argon was measured on the Faraday detector whilst the less abundant isotopes of Kr and Xe were measured on a Johnson electron multiplier at a relative gain of approximately 400. Machine blanks were monitored throughout the period of analysis and, as a percentage of typical sample volumes, remained lower than 1–10% for 40 Ar and <1.5% for 80 Kr_{Br}. Blanks for 36 Ar, 84 Kr, 129 Xe and 128 Xe_I were close to their detection limits (ESM Table 3).

Cl, K, Ca, Br, I and U were determined from the neutron flux and the measured abundance of irradiation-produced nucleogenic (and fissiogenic) noble gas isotopes: ${}^{38}\text{Ar}_{\text{Cl}}$, ${}^{39}\text{Ar}_{\text{K}}$, ${}^{37}\text{Ar}_{\text{Ca}}$, ${}^{80}\text{Kr}_{\text{Bp}}$, ${}^{128}\text{Xe}_{\text{I}}$ and ${}^{134}\text{Xe}_{\text{U}}$. Standard corrections were made for post irradiation decay of ${}^{37}\text{Ar}$ and ${}^{36}\text{Cl}$ (producing ${}^{36}\text{Ar}$) and for other Ar interference reactions based on irradiated pure CaF₂ and K-glass. The Br/Cl and I/Cl values are proportional to the measured ${}^{80}\text{Kr}_{\text{Br}}{}^{38}\text{Ar}_{\text{Cl}}$ and ${}^{128}\text{Xe}_{\text{I}}{}^{38}\text{Ar}_{\text{Cl}}$ and analytical precision is better than 3%. However, based on the reproducibility of sample duplicates in several irradiations, the total 1 σ uncertainty in the absolute Br/Cl and I/Cl values is estimated as approximately 15% for this irradiation. All ratios are molar, but fluid concentrations are given in weight units unless otherwise stated.

Results

The halogens

Fluid inclusions in ore-related quartz have variable halogen compositions that fan out from minimum Br/Cl and I/Cl values of approximately $0.3-0.6 \times 10^{-3}$ and approximately $2-3 \times 10^{-6}$, respectively, up to much higher values (Fig. 3). The maximum measured Br/Cl and I/Cl values are 3.8×10^{-3} and approximately 30×10^{-6} , respectively (Table 3;

Fig. 3). The data do not define fields that can be related to sample location, rather, the extent of variability in the mines largest ore body (1S), for which the greatest number of samples were available (Table 2), is similar to the variation seen throughout the entire mine (Fig. 3). Fluid inclusions in the two pegmatite samples have an overlapping but narrower range of Br/Cl and I/Cl (Fig. 3). The Br/Cl and I/Cl values obtained by in vacuo crushing of four sample duplicates overlap those obtained by stepped heating in most cases (Table 3; see Kendrick et al. 2001).

Intra-sample variability

Fluid inclusions are the only significant reservoir of halogens and noble gases in hydrothermal quartz (Kendrick



Fig. 4 a Cl/³⁶Ar versus temperature. The up temperature increase in Cl/³⁶Ar values (to 600°C) is related to the preferential decrepitation of the highest-salinity fluid inclusions at high temperature. The decrease above 650°C is explained by a minor atmospheric contaminant which is more significant in low gas volume extraction steps (see **b** and text). **b** The proportion of ${}^{38}\text{Ar}_{C1}$ released at 200–700°C. The majority of fluid inclusions are decrepitated between 500°C and 600°C (and at higher temperature >1,200°C; Kendrick et al. 2006a)

et al. 2006a). Stepped heating reveals variation within each sample, compatible with the decrepitation of different fluid inclusion types at different temperatures (Kendrick et al. 2006a). High $\text{Cl/}^{36}\text{Ar}$ values tend to be determined for each sample above 400°C (Fig. 4a), which are compatible with the preferential decrepitation of high-salinity LVD and MS fluid inclusions at high temperatures. Lower temperature extraction steps are dominated by Cl-poor CO₂ and LV fluid inclusions inferred to have lower $\text{Cl/}^{36}\text{Ar}$ values (Fig. 4a). This inference is supported by microthermometry observations.

In most cases, the fluid inclusion Br/Cl value decreases as the temperature of the extraction step is increased from 200°C to 700°C. However, fluid inclusions in sample Osb22a exhibit the opposite behaviour (Fig. 5), and the highest measured Br/Cl value of 3.8×10^{-3} was determined in this sample at 700°C (Fig. 5). Samples Osb20 and Osb43 have fluid inclusion Br/Cl values that increase to maximum values in approximately 300–400°C extraction steps and then decrease to minimum values in the 700°C extraction step (Fig. 5).

The different behaviours of the samples during stepped heating and unpredictable variations in Br/Cl (Fig. 5) suggest that the different fluid inclusion types (LV, LVD, MS) all have variable Br/Cl compositions. This is further illustrated by samples Osb36B and Osb15, which have very similar fluid inclusion assemblages but different Br/Cl and I/Cl values (Tables 2 and 3).

Potassium and radiogenic ⁴⁰Ar_R

Fluid inclusion K/Cl values in ore-related quartz and pegmatite samples obtained by in vacuo crushing or low temperature extraction steps (\leq 500°C), range from 0.04 to 0.29 (Table 3). At higher temperature, several of the quartz samples yield maximum K/Cl of >1. These high values provide evidence for a K-mineral impurity in either the



Fig. 5 Br/Cl versus temperature. High-salinity LVD and MS fluid inclusions are preferentially decrepitated at high temperature

quartz matrix or accidentally trapped in the fluid inclusions of these samples. The quartz samples with maximum K/Cl values of <0.5 contain 15–73 ppm K whereas samples with higher K/Cl values contain 17–1,897 ppm K (Table 3). This variation indicates that the relative abundance of mineral impurities and fluid inclusions or the proportion of high-salinity K-rich fluid inclusions is quite variable between the different samples (Table 2).

The feldspar-bearing pegmatite samples Osb40 and Osb852 have the highest K/Cl values of 61 and 714, respectively (Table 3). Sample Osb852 has a total K concentration of 1.6 wt%, indicating it contains significant K-feldspar (Tables 2 and 3).

$^{40}Ar_R$ correction

Fluid inclusion ${}^{40}\text{Ar/}{}^{36}\text{Ar}$ values have been corrected for post-entrapment radiogenic ${}^{40}\text{Ar}_{\text{R}}$ based on the K content of the sample and an assumed mineralisation age of 1,595 Ma (Gauthier et al. 2001). The age-correction is <5–30% for most extraction steps from the quartz samples. Uncertainties in the deposit age of approximately 60 Ma correspond to a correction of <2% and will not influence the interpretation of these data (full data set available in ESM Table 1).

In contrast, the correction is potentially important for the feldspar-bearing pegmatite samples Osb852 and Osb40. Fortunately, fluid inclusions with negligible ³⁹Ar_K dominate the Ar released from these samples at temperatures of <500°C (Fig. 6) and the age-corrected initial fluid inclusion ⁴⁰Ar/³⁶Ar values are just 2–40% lower than the measured values at these temperatures (ESM Table 1). The similarity of initial ⁴⁰Ar/³⁶Ar values of less than approximately 1,700



Fig. 6 Ar–Ar plateau diagram for pegmatitic quartz–feldspar samples Osb40 and Osb852. Fluid inclusions with very little ³⁹Ar_K but significant ³⁸Ar_{C1} dominate Ar released at <500°C. At higher temperature, Ar is released from the feldspar lattice. Most steps for sample Osb40 have apparent ages between approximately 1,160 and 1,220 Ma, whilst sample Osb852 gives a 'plateau' age of approximately 1,350 Ma. These ages are broadly compatible with the regional cooling history documented in feldspar, biotite and amphibole (Spikings et al. 2001)

(Table 3), calculated for two feldspar-bearing samples with different K content provides confidence in the accuracy of the age-correction. The Ar released above 500°C is dominated by the lattice Ar from the feldspar, and the apparent ages of approximately 1,160–1,350 Ma are similar to regional cooling ages (Fig. 6; Spikings et al. 2001). These ages indicate post-crystallisation Ar loss and it is impossible to calculate initial 40 Ar/ 36 Ar values for these extraction steps.

Fluid inclusion argon

The age-corrected fluid inclusion ${}^{40}\text{Ar}/{}^{36}\text{Ar}$ values are plotted against Cl/ ${}^{36}\text{Ar}$ in Fig. 7. When the high-salinity fluid inclusions with high Cl/ ${}^{36}\text{Ar}$ values also have the highest ${}^{40}\text{Ar}/{}^{36}\text{Ar}$ values, a positive correlation results in Cl/ ${}^{36}\text{Ar}$ versus ${}^{40}\text{Ar}/{}^{36}\text{Ar}$ space (e.g. sample Osb59; Fig. 7). When the LV or CO₂ fluid inclusions have the highest ${}^{40}\text{Ar}/{}^{36}\text{Ar}$ values, a negative correlation results (e.g. sample Osb20; Fig. 7). However, the relatively small range of ${}^{40}\text{Ar}/{}^{36}\text{Ar}$ determined for fluid inclusions in the Osborne samples indicates that all the different fluid inclusion types (CO₂, LV, LVD and MS) have similar ${}^{40}\text{Ar}/{}^{36}\text{Ar}$ values of less than approximately 2,200 (Fig. 7).

In addition to the variation due to decrepitation of different fluid inclusion types at different temperatures (Fig. 4a), a minor atmospheric contaminant may be present. This contaminant is not air adsorbed onto the samples because it persists to high temperatures (Turner and Bannon 1992). It is only significant in low gas volume extraction steps and may explain the decrease in Cl/³⁶Ar between



Fig. 7 Cl/³⁶Ar versus age-corrected ⁴⁰Ar/³⁶Ar. Sample data points define mixing arrays between extraction steps with low Cl/³⁶Ar values, dominated by CO₂ and LV fluid inclusions, and extraction steps with high Cl/³⁶Ar values, dominated by high-salinity LVD and MS fluid inclusions (see *inset*). Reference values are shown for the ⁴⁰AR_E/Cl gradients (*solid lines*). The analyses of selected samples (denoted by *crosses*) have lines of best fit (*dotted lines*) and correlation coefficients (R^2) indicated (see text). LV=liquid-vapour, MS=ultra-high-salinity multi-solid fluid inclusion, LVD = high-salinity liquid-vapour-daughter fluid inclusion, CO_2 = liquid CO₂ fluid inclusion

600°C and 700°C (compare Fig. 4a and b). The contaminant has the effect of reinforcing positive correlations in Cl/³⁶Ar versus ⁴⁰Ar/³⁶Ar space and increasing the scatter around negative correlations, but it cannot explain the total variation (Fig. 7; Kendrick et al. 2007).

Argon concentrations

The ³⁶Ar concentration of high-salinity fluid inclusions has been calculated from the mean salinity and maximum Cl/³⁶Ar value determined for fluid inclusions in each sample (Table 3). Ore-related samples contain MS fluid inclusions with ³⁶Ar concentrations of 0.7–5.2 ppb, encompassing a slightly greater range than air-saturated water (ASW=1.3–2.7 ppb; Fig. 8). MS fluid inclusions in the pegmatite sample Osb40 contain a similar ³⁶Ar concentration of 2.5 ppb, whereas MS fluid inclusions in sample Osb852 have a significantly higher ³⁶Ar concentration of 19 ppb (Fig. 8). The ³⁶Ar concentration is not strongly correlated with the ⁴⁰Ar/³⁶Ar value, but the lowest ³⁶Ar concentrations are calculated for fluid inclusions with the lowest Br/Cl values (Fig. 8).

The ⁴⁰Ar_E concentration of MS fluid inclusions has been calculated from their mean salinity and the mean ⁴⁰Ar_E/Cl values (Table 3). Sample mean ⁴⁰Ar_E/Cl values are approximated by the slopes in Fig. 7 and range from 10^{-6} in sample Osb37B up to approximately 2×10^{-4} in sample Osb852. MS fluid inclusions in ore-related samples have ⁴⁰Ar_E concentrations of 0.7 to 15 ppm, whilst the pegmatite sample Osb852 contains fluid inclusions with elevated ⁴⁰Ar_E concentrations of 57–64 ppm (Table 3).

Noble gas non-fractionation

The fluid inclusion elemental ratios of 84 Kr/ 36 Ar and 129 Xe/ 36 Ar, measured by in vacuo crushing irradiated and non-irradiated samples, are given relative to the atmospheric ratios as fractionation values in Fig. 9 and Table 3 (air has an *F* value of 1). The majority of analyses give fluid inclusion *F* values intermediate between air and air-saturated water (ASW = meteoric or seawater; Fig. 9) similar to fluids from other ore deposits and mid-crustal rocks (e.g. Drescher et al. 1998; Kendrick et al. 2001, 2002, 2007). These mostly unfractionated values suggest that phase separation has been a minor process: fluids that have lost noble gases during phase separation are characterised by *F* values of greater than the air–ASW range (e.g. *F* values at Bingham Canyon; Kendrick et al. 2001).

Fissiogenic 134 Xe_U was preferentially released during stepped heating, indicating that U present at the ppb level is hosted by the quartz matrix (Table 3). As a result, we do not report the *F* values obtained by stepped heating irradiated samples because they are elevated by fissiogenic 129 Xe_U



Fig. 8 a Fluid inclusion ³⁶Ar concentration versus maximum agecorrected ⁴⁰Ar/³⁶Ar value. Air-saturated water (meteoric water or seawater) with 1.3–2.7 ppb ³⁶Ar and ⁴⁰Ar/³⁶Ar of 296 is shown for reference. **b** Fluid inclusion ³⁶Ar concentrations versus mean Br/Cl value (500–700°C). The composition of seawater with 1.3–2.1 ppb

and 84 Kr_U and are not representative of the fluid inclusion composition (ESM Table 1).

Discussion

The involvement of deeply derived magmatic fluids related to A-type magmatism is not favoured at Osborne because (1) the preferred peak-metamorphic timing of mineralisation preceded regional magmatism by more than 50 Myr (Page and Sun 1998; Gauthier et al. 2001; Giles and Nutman 2002; Foster and Rubenach 2006), (2) the fluid inclusion Br/Cl and I/Cl values are extremely variable, which does not favour a single fluid source (Fig. 3), and (3) the fluid inclusions have low 40 Ar/ 36 Ar values of <2,200.

A magmatic fluid signature, similar to that observed in some Ernest Henry fluid inclusions (40 Ar/ 36 Ar approximately 30,000; Kendrick et al. 2007), is unlikely to have



Fig. 9 The ⁸⁴Kr/³⁶Ar versus ¹²⁹Xe/³⁶Ar values are expressed as fractionation values where air has an *F* value of 1: $FX=(X/^{36}Ar)_{sample}/(X/^{36}Ar)_{air}$ Irradiated and unirradiated samples are distinguished (see *key*)

 36 Ar and a Br/Cl value of 1.54×10^{-3} is shown for reference (Zherebstova and Volkova 1966; Ozima and Podosek 2002). Note break in scale on *y*-axis. *Error bars* indicate spread in Br/Cl data not analytical uncertainty and are set at 20% for 36 Ar concentration (Table 3)

been overprinted at Osborne because (1) the fluid inclusions at Osborne and Ernest Henry have similar 36 Ar concentrations (Table 3; Kendrick et al. 2007) and (2) the fluid inclusion *F* values are mostly intermediate of air and air-saturated water (Fig. 9), suggesting that the loss of noble gases during phase separation was a minor process.

The maximum ⁴⁰Ar/³⁶Ar values of approximately 2,200 in fluid inclusions in ore-related and pegmatite samples from Osborne favour the involvement of upper crustal fluids and fluid interaction with (meta)sedimentary host rocks and/or anatectic melts close to the mid-crustal level of mineralisation (Morrison 2005). This conclusion is compatible with the oxygen and sulphur isotope data summarised above (Adshead 1995; Mark et al. 2006).

Metamorphic fluids and formation waters

Carbon dioxide fluid inclusions at Osborne are interpreted to have had a wholly metamorphic origin; there is no evidence for input from the mantle or A-type magmatism (cf. Hollister 1988; De Jong et al. 1998; Pollard 2001, 2006). The Ar composition of metamorphic volatilisation fluids (including CO_2) formed at 1,595 Ma from either the Soldiers Cap Group host rocks or equivalents of the Corella Formation that may underlie the mine can be estimated with a modified form of the K–Ar decay equation.

$$\begin{pmatrix} {}^{40}\text{Ar} \\ \overline{}^{36}\text{Ar} \end{pmatrix}_{\text{fluid}} = 296 + \frac{\left(\text{Kmolg}^{-1}\right)_{\text{rock}}}{\left({}^{36}\text{Armolg}^{-1}\right)_{\text{rock}}} \times \left({}^{40}\text{K}/\text{K}\right) \\ \times (\lambda_{\text{EC}}/\lambda) \times \left(e^{\lambda t_{1,870\,\text{Ma}}} - e^{\lambda t_{1,595\,\text{Ma}}}\right)$$

Based on an average K content of 2–3 wt% (approximately $5-8 \times 10^{-4}$ mol g⁻¹) and a maximum detrital age of 1,870 Ma, equivalent to the regional Barramundi Basement (Page and Sun 1998), the median ³⁶Ar concentration of sub-aerial sedimentary rocks (approximately

 3×10^{-12} mol g⁻¹; Ozima and Podosek 2002) gives a metamorphic fluid ⁴⁰Ar/³⁶Ar value of 1,000–2,000. If the protoliths had a higher ³⁶Ar concentration of $1.5-5 \times 10^{-12}$ mol g⁻¹ close to the highest reported for sub-aerial sedimentary rocks (>10⁻¹¹ mol g⁻¹; Ozima and Podesek 2002), the metamorphic fluid would have had an even lower ⁴⁰Ar/³⁶Ar value of approximately 500 (cf. Table 3).

Primary MS fluid inclusions in the pegmatite samples provide an independent estimate of metamorphic fluid composition because the pegmatites are interpreted to have formed by anatectic melting of sedimentary rocks close to the site of mineralisation (cf. Mark et al. 1998). Both pegmatite samples contain fluid inclusions with maximum 40 Ar/ 36 Ar values of 1,500–1,700 (inferred for the highestsalinity MS fluid inclusions; Fig. 7), similar to the range calculated for metamorphic fluids. These 'metamorphic fluids' have variable Br/Cl and I/Cl values and 36 Ar concentrations of 2.5–19 ppb. Although the data are limited to two pegmatite samples, they suggest a similar range of compositions, as seen in the ore-related quartz fluid inclusions (Figs. 3, 7 and 8).

It is worth noting that the ⁴⁰Ar/³⁶Ar value and ³⁶Ar concentration estimated for metamorphic fluids derived from metasedimentary host rocks, in this case, are very different from the values obtained for basement-derived metamorphic fluids in the Mt Isa Cu deposit (Kendrick et al. 2006b). Initially dry crystalline basement rocks typically contain an order of magnitude less ³⁶Ar than sedimentary rocks (Ozima and Podosek 2002), meaning basement-derived metamorphic fluids will have a much higher ⁴⁰Ar/³⁶Ar value and lower ³⁶Ar concentration (Kendrick et al. 2006b). Variable ³⁶Ar concentrations could be produced in a metamorphic volatilisation fluids at Osborne, depending on the initial ³⁶Ar content and previous Ar loss from the metasedimentary host rocks.

Sedimentary formation waters and evaporites

In addition to metamorphic volatilisation products, some of the fluids probably represent sedimentary formation waters which are also characterised by low 40 Ar/ 36 Ar values of <1,000–2,000 and variable Br/Cl and I/Cl (Torgersen et al. 1989; Turner and Bannon 1992; O'Nions and Ballentine 1993; Tolstikhin et al. 1996; Worden 1996; Kendrick et al. 2002). Sedimentary formation waters could have been (1) trapped in the protolith as a pore fluid or (2) introduced from an external reservoir at the time of mineralisation. The evolution of metamorphic fluids from protolith pore fluids has been suggested previously to explain the observation that metamorphic fluid salinity is more strongly related to the protolith than metamorphic grade (Yardley and Graham 2002). However, it is uncertain if such pore fluids could have remained in the (meta)sedimentary strata around Osborne where some pre-metamorphic albitisation had taken place (Rubenach et al. 2008).

Sedimentary formation waters have typical salinities of <30 wt% salts (Hanor 1994) and metamorphic volatilisation fluids produced from typical Cl-poor rocks are likely to be even less saline (Kendrick et al. 2006b). The extremely high salinity of fluids at Osborne (up to 65 wt% salts) and the lowest Br/Cl and I/Cl values (Fig. 3) are most easily explained by high-temperature fluid interaction with evaporites (Barton and Johnson 1996). Meta-evaporitic scapolite is common within the calc-silicate Corella Formation, equivalents of which could underlie the mine area. If sedimentary formation waters were inherited as a pore fluid, halite and sylvite in the protolith would have been easily mobilised at the onset of metamorphism. Alternatively, formation waters introduced after scapolitisation would acquire a high salinity if they equilibrated with Cl-rich scapolite (Mora and Valley 1989).

The low I/Cl values determined for the ore fluid are difficult to explain without the involvement of (meta) evaporites, as I is enriched in organic matter present in (meta)sedimentary rocks, meaning most other fluid–rock interactions would lead to high I/Cl values in the fluid (Worden 1996; cf. Fig. 3).

Mixed origins

The ore fluids at Osborne were present close to the 1,595-Ma metamorphic peak (Gautier et al. 2001) and are inferred to have had a high water–rock ratio. We interpret the fluids to represent a mixture of sedimentary formation waters and the products of metamorphic volatilisation.

The mineralised shear zone in the eastern part of the mine (Fig. 2; Adshead et al. 1998) could have been an important fluid conduit and fluids may have been sourced from both the host Soldiers Cap Group and the underlying calcite-scapolite-rich equivalents of the Corella Formation. These stratigraphic horizons probably contained sedimentary pore fluids with different Br/Cl and I/Cl values, and the metamorphic ore fluids inherited not only their high salinity (Yardley and Graham, 2002) but also their distinctive ranges of Br/Cl and I/Cl from these fluids. In addition, the consistently high salinities (up to 65 wt% salts) and variable Br/Cl and I/Cl of these fluids indicate that fluid interaction with evaporites (or scapolite) was a major process (Fig. 3).

The widespread occurrence of ore-related secondary fluid inclusions along annealed fractures and quartz veins demonstrates brittle behaviour during much of the mineralisation process. These faults were also fluid pathways and could have enabled infiltration of sedimentary formation waters from an upper crustal reservoir during mineralisation. The lowest fluid inclusion ⁴⁰Ar/³⁶Ar value of approximately 444 determined in a late (stage 3) quartz

vein (Osb22Av; Table 3) is fairly close to the atmospheric value of 296, compatible with an increased influx of surficial or upper crustal fluids during the waning stages of mineralisation.

The mixed origin interpreted for the Osborne ore fluids is compatible with a H_2O -dominated fluid, similar to that inferred by the relative abundance of CO_2 and H_2O fluid inclusions (Table 2). Although the XCO_2 of the metamorphic volatilisation products is unknown, sedimentary formation waters would initially have had a low CO_2 content. The inferred low XCO_2 of the ore fluids suggests that phase separation would have been a relatively minor process. Therefore fluid mixing was more significant than fluid unmixing.

Summary and implications

- Significant involvement of deeply derived magmatic fluids related to A-type magmatism is precluded at Osborne because fluid inclusions have (1) uniformly low ⁴⁰Ar/³⁶Ar values of less than approximately 2,200, (2) variable Br/Cl and I/Cl and (3) ³⁶Ar concentrations plus *F* values that do not favour significant phase separation or fluid overprinting.
- The data demonstrate that magmatic volatiles related to A-type magmatism are not an essential component of IOCG mineralising systems and that the CO₂ component can have a wholly metamorphic origin.
- The absence of magmatic fluids related to A-type magmatism is consistent with the preferred syn-metamorphic timing of mineralisation at Osborne, which preceded regional magmatism by approximately 60 Ma (Gauthier et al. 2001).
- The similarity of ore-related fluid inclusions and pegmatite fluid inclusions is compatible with a mixed origin for 'metamorphic' ore fluids by (1) host rock volatilisation and (2) either inheritance of sedimentary pore fluids or influx of sedimentary formation waters.
- The ultra-high salinities and the lowest Br/Cl and I/Cl values favour fluid interaction with evaporites or metaevaporites present in equivalents of the Corella Formation.
- The spread in Br/Cl and I/Cl compositions of ultrahigh-salinity brines indicate that fluids had different Br/ Cl and I/Cl compositions before evaporite dissolution, consistent with sourcing fluids from multiple aquifers and indicating that fluid mixing could have been a trigger for mineralisation.
- The involvement of upper crustal sedimentary formation waters is unproven but the data is compatible with an influx of upper crustal fluids during the final stages of mineralisation.

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