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Australian Zn-Pb-Ag Ore-Forming Systems: A Review and Analysis

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Abstract

Zn-Pb-Ag mineral deposits are the products of hydrothermal ore-forming systems, which are restricted in time and space. In Australia, these deposits formed during three main periods at ~2.95, 1.69 to 1.58, and 0.50 to 0.35 Ga. The 1.69 to 1.58 Ga event, which accounts for over 65 percent of Australia's Zn, was triggered by accretion and rifting along the southern margin of Rodinia.

Over 93 percent of Australia's Zn-Pb-Ag resources were produced by four ore-forming system types: Mount Isa (56% of Zn), Broken Hill (19%), volcanic-hosted massive sulfide (VHMS; 12%), and Mississippi Valley (8%). Moreover, just 4 percent of Australia's land mass produced over 80 percent of its Zn. The four main types of ore-forming systems can be divided into two "clans," based on fluid composition, temperature, and redox state. The Broken Hill- and VHMS–type deposits formed from high-temperature (>200°C) reduced fluids, whereas the Mount Isa- and Mississippi Valley-type deposits formed from low-temperature (<200°C), H_2S-poor, and/or oxidized fluids. The tectonic setting and composition of the basins that host the ore-forming systems determine these fluid compositions and, therefore, the mineralization style.

Basins that produce higher temperature fluids form in active tectonic environments, generally rifts, where high heat flow produced by magmatism drives convective fluid circulation. These basins are dominated by immature siliciclastic and volcanic rocks with a high overall abundance of Fe^{2+}. The high temperature of the convective fluids combined with the abundance of Fe^{2+} in the basin allow inorganic sulfate reduction and leaching of sulfide from the country rock, producing reduced, H_2S-rich fluids.

Basins that produce low-temperature fluids are tectonically less active, generally intracratonic, extensional basins dominated by carbonate and variably mature siliciclastic facies with a relatively low Fe^{2+} abundance. In these basins, sediment maturity depends on the paleogeography and stratigraphic position in an accommodation cycle. Volcanic units, if present, occur in the basal parts of the basins. Because these basins have relatively low heat flow, convective fluid flow is less important, and fluid migration is dominated by expulsion of basinal brines in response to local and/or regional tectonic events. Low temperatures and the lack of Fe^{2+} prevent inorganic sulfate reduction during regional fluid flow, producing H_2S-poor fluids that are commonly oxidized (i.e., $\Sigma SO_4 > \Sigma H_2S$).

Fluid flow in the two basin types produces contrasting regional alteration systems. High-temperature fluid-rock reactions in siliciclastic-volcanic–dominated basins produce semiconformable albite-hematite-epidote assemblages, but low-temperature reactions in carbonate-siliciclastic–dominated basins produce regional K-feldspar-hematite assemblages. The difference in feldspar mineralogy is mostly a function of temperature. In both basin types, regional alteration zones have lost, and probably were the source of, Zn and Pb.

The contrasting fluid types require different depositional mechanisms and traps to accumulate metals. The higher temperature, reduced VHMS- and Broken Hill-type fluids deposit metals as a consequence of mixing with cold seawater. Mineralization occurs at or near the sea floor, with trapping efficiencies enhanced by subsurface replacement or deposition in a brine pool. In contrast, the low-temperature, oxidized Mount Isa- and Mississippi Valley-type fluids precipitate metals through thermochemical sulfate reduction facilitated by hydrocarbons or organic matter. This process can occur at depth in the rock pile, for instance in failed petroleum traps, or just below the sea floor in pyritic, organic-rich muds.

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Introduction

IN 2005 AUSTRALIA was the second largest producer of Pb and Zn and the fourth largest producer of Ag. With the commissioning of the HYC, Century and Cannington mines in the 1990s, Australia's position as an important producer of these commodities will be maintained for the medium term. Australia's Zn-Pb-Ag endowment stems from mineralizing processes that accompanied the formation of the Australian continent. Spatial and temporal differences in Zn-Pb-Ag prospectivity in Australia can be traced back to the evolution of the continent. In this contribution we examine processes that formed these deposits using a systems approach and then relate the deposits back to the tectonic and geodynamic setting of Australia to better understand global, regional, and local controls on Zn-Pb-Ag mineralization.

The Temporal and Spatial Distribution of Zn-Pb-Ag Deposits in Australia

Many mineral deposit types have restricted temporal and spatial distributions across the globe. For example, Woodall (1990) showed that most Australian gold mineralization occurred in two geologic periods: a 2.6 to 2.7 Ga event in the Yilgarn craton and a 0.35 to 0.45 Ga event in the Tasmanides. Although recent exploration success has shown the importance of gold introduced at 1.85 to 1.59 Ga (e.g., in the Pine Creek, Tanami, and Gawler regions), the fundamental observation of Woodall (1990) of the periodicity of gold mineralization prevails. This periodicity stems from many geologic factors including the tectonic environment and preservation potential of individual deposits.

Zn-Pb-Ag deposits also display temporal and spatial concentrations owing to the evolution of tectonic and depositional environments through time. Seventy-two deposits in Australia (Table 1) contain(ed) geologic resources in excess of 0.1 million metric tons (Mt) zinc and lead. Based on these deposits, over 80 percent of Australian Zn resources occur in just seven areas—the Eastern and Western successions of the Mount Isa inlier, the McArthur region, the Broken Hill region, the Lennard shelf, the Broome platform, and the Dundas region—which comprise only 3.9 percent of Australia's land mass (Table 2, Fig. 1). When normalized to the land area, these regions have the highest Zn endowment in Australia—in all cases over 100 t/km². The Western succession of the Mount Isa inlier has an endowment of 1,800 t/km², 100 times more than the continental endowment of 18 t/km². Over 80 percent of the rest of the Australian continent has Zn endowment below 1.0 t/km² (Fig. 1). Variations in Pb and Ag endowments are similar, indicating a strong provinciality in the formation of Zn-Pb-Ag resources.

Like Au deposits, Zn-Pb-Ag deposits have a periodic distribution through geologic time (Table 3; Figs. 2–3). Most of Australia's Zn resources were deposited during two periods: 1.5 to 1.7 and 0.3 to 0.5 Ga, with a third, small event at 2.9 to 3.0 Ga. The majority (75%) of Australia's Zn mineralization formed between 1.69 to 1.58 Ga, a period characterized by

TABLE 1. Australian Mineral Deposits with Total Endowment Exceeding 0.1 Mt Combined Zn and Pb[1]

Deposit	Type	Age (Ga)	Size (Mt)	Zn (%)	Pb (%)	Ag (g/t)	Cu (%)	Au (g/t)	Zn (Mt)	Pb (Mt)	Ag (t)	100 Zn / Zn + Pb	100 Cu / Cu + Zn
Adelaide region													
Beltana-Aroona	?	0.49	1.0	37					0.37	0.00		100	0
Ediacara	MVT	?	29.0		1.07					0.31		0	
Arunta region													
Oonagalabi	?	1.73	25	1.0			0.5		0.25			100	33
Balcooma-Thalanga province													
Handcuff	VHMS	0.48	1	10.0	0.4	8	0.6	0.2	0.10	0.00	8	96	6
Liontown	VHMS	0.48	1.8	6.2	2.2	29	0.5	0.9	0.11	0.04	52	74	7
Balcooma	VHMS	0.48	3.841	3.04	1.44	33	2.72	0.43	0.12	0.06	127	68	47
Dry River South-Surveyor	VHMS	0.48	2.732	8.84	3.05	80	1.05	0.76	0.24	0.08	219	74	11
Thalanga	VHMS	0.48	6.6	8.4	2.6	69	1.8	0.4	0.55	0.17	455	76	18
Bangemall region													
Abra	?	1.64	200		1.8	6	0.2	0.09		3.60	1200	0	
Bonaparte region													
Sandy Creek	MVT	0.34	3.2	2.5	4.4	15			0.08	0.14	48	36	0
Sorby Hills	MVT	0.34	16.24	0.6	5.3	56			0.10	0.85	909	10	0
Broken Hill region													
Broken Hill[2]	BHT	1.69	280	8.5	10.0	148	0.14	0.47	23.80	28.00	41400	46	2
The Pinnacles	BHT	1.70	0.8	2.5	10.0	420			0.02	0.08	336	20	0
Broome platform													
Admiral Bay	MVT	0.41	120	6.4	2.3	32			7.38	2.76	3840	74	
Cairns region													
Mt. Garnet	Skarn	0.31	2.045	6.73		16	0.36		0.14		33	100	5
King Vol	Skarn	0.31	0.825	20.30	1.00	38	0.90		0.17	0.01	31	95	4
Dundas region													
Oceana	Irish	0.47	4.13	3.9	19.2	107			0.16	0.79	442	17	0
Sylvester	Skarn	0.35	6.1	5.5	3.3	40			0.34	0.20	244	63	0
Zeehan field	Vein	0.35	1.44		8.9	421			0.00	0.13	606	0	
Que River	VHMS	0.50	3.3	13.3	7.4	195	0.7	3.3	0.44	0.24	644	64	5
Hercules	VHMS	0.50	3.33	17.3	5.5	171	0.4	2.8	0.58	0.18	569	76	2
Hellyer	VHMS	0.50	16.5	13.9	7.2	169	0.38	2.55	2.29	1.19	2790	66	3
Rosebery	VHMS	0.50	31.7	14.3	4.4	146	0.58	2.3	4.53	1.39	4630	76	4

TABLE 1. *(Cont.)*

Deposit	Type	Age (Ga)	Size (Mt)	Zn (%)	Pb (%)	Ag (g/t)	Cu (%)	Au (g/t)	Zn (Mt)	Pb (Mt)	Ag (t)	100 Zn / Zn + Pb	100 Cu / Cu + Zn
Eastern Goldfields province													
Jaguar	VHMS	2.69	1.64	14.7		140	3.5		0.24		230	100	
Teutonic Bore	VHMS	2.69	2.15	11.35	0.79	150	3.54		0.24	0.02	323	93	24
Einasleigh province													
Mt. Misery	BHT	1.70	3.6	5.54	2.45	50			0.20	0.09	180	69	0
Gawler region													
Menninnie Dam	Manto	1.59	1.7	8.0	5.0	100			0.14	0.09	170	62	0
Halls Creek region													
Onedin	VHMS	1.84	3.02	3.2	1.5	31	0.9	0.3	0.10	0.05	94	68	22
Sandiego	VHMS	1.84	2.2	5.8	0.8	47	1.6	0.4	0.13	0.02	103	88	22
Kanmantoo region													
Angas	?	0.51	1.0	10	4.0	60		1.0	0.10	0.04	60	71	0
Lachlan region													
Browns Reef	?	0.41	12.6	2.3	1.3	9	0.11		0.29	0.16	107	65	5
Bowdens	Epithermal	0.07	18.8	0.37	0.32	99			0.07	0.06	1860	54	0
CSA	EWT	0.40	35	1.37	0.42		2.91		0.48	0.15		77	68
Elura	EWT	0.40	51.4	8.7	5.7	66			4.47	2.93	3390	60	0
Extended Workings	Skarn	0.28	1.78	6.7	0.25	41	0.08		0.12	0.00	73	96	1
Toms zone	VHMS	0.42	1	7.90	5.36	214	0.30	1.95	0.08	0.05	214	60	4
Wet Lagoon	VHMS	0.42	1.5	5.5	3.0	33	0.5		0.08	0.05	50	65	8
East Currawang	VHMS	0.42	0.8	13.0	2.2	33	1.6		0.10	0.02	26	86	11
Cow Flat	VHMS	0.42	27.2	0.7			0.3		0.19			100	30
Wilga	VHMS	0.42	4.0	5.5	0.4	30	4.3	0.5	0.22	0.02	120	93	44
Lewis Ponds	VHMS	0.42	4.8	4.94	3.02	116	0.19	3.52	0.24	0.14	557	62	4
Kempfield	VHMS	0.42	32.9	0.7	0.4	37			0.24	0.14	1220	63	0
Currawong	VHMS	0.42	9.0	4.2	0.9	39	2.0	1.2	0.38	0.08	351	82	32
Captains Flat	VHMS	0.42	4.0	10.0	6.0	56	0.7	1.7	0.40	0.24	224	63	7
Woodlawn	VHMS	0.42	18.4	9.9	3.8	80	1.4		1.82	0.70	1470	72	12
Lennard shelf													
Kutarta (Prices Creek)	MVT	0.36	2.34	7.2	0.5	39			0.17	0.01	91	94	0
Fossil Downs	MVT	0.36	2.15	9.5	2.1				0.20	0.04		82	0
Goongewa (Twelve Mile bore)	MVT	0.36	2.3	9.7	2.7				0.22	0.06		78	0
Kapok	MVT	0.36	5.21	8.0	7.9				0.42	0.41		50	0
Cadjebut	MVT	0.36	5.0	11.4	3.2				0.57	0.16		78	0
Pillara (Blendevale)	MVT	0.36	19.5	7.9	2.4				1.54	0.47		77	0
McArthur region													
HYC	MIT	1.64	227	9.2	4.1	40	0.2	0.0051	20.88	9.31	9080	69	2
Mount Isa inlier—Eastern succession													
Pegmont	BHT	1.68	8.6	3.5	7.8	10			0.30	0.67	86	31	0
Cannington	BHT	1.68	43.8	4.4	11.6	538			1.93	5.08	23600	28	0
Dugald River	MIT	1.67	50	12.1	1.9	41			6.05	0.95	2050	86	0
Mount Isa inlier—Western succession													
Lady Loretta	MIT	1.65	13.6	17.1	5.9	97		0.0022	2.33	0.80	1320	74	0
Mount Isa	MIT	1.65	150	7.0	6.0	150	0.1	0.0020	10.50	9.00	22500	54	1
Century	MIT	1.57	105	12.1	1.8	46			12.71	1.84	4830	87	0
Hilton-George Fisher	MIT	1.65	228	10.8	5.5	97			24.62	12.54	22100	66	0
Silver King	Veins	1.69	0.965	4.14	6.60	64			0.04	0.06	62	39	0
Murchison province													
Gossan Hill (Golden Grove)[3]	VHMS	2.95	15.7	6.7	0.18	22	1.8	1.3	1.05	0.03	340	97	21
Scuddles[4]	VHMS	2.95	12.3	8.2	0.58	63	1.8	0.9	1.01	0.07	780	93	18
Nabberu basin													
Magellan	MVT		12.6		5.4					0.68		0	
Pilbara region													
Lennons Find	VHMS	3.47	1.2	7.60	1.94	100	0.43	0.3	0.09	0.02	120	80	5
Kangaroo Caves	VHMS	3.24	1.7	9.8	0.6	18	0.6	0.1	0.17	0.01	31	94	6
Sulphur Springs	VHMS	3.24	5.3	6.2	0.3	26	2.2	0.2	0.33	0.02	138	95	26
Pine Creek region													
Browns	?		70		2.6	10	0.8			1.81	700	0	100
Woodcutters	EWT		4.65	12.3	5.7	82			0.57	0.26	381	68	0
Southern Cross province													
Pincher Well	VHMS	2.96	20.7	2.16			0.2		0.45	0.00	3840	100	8

[1] Endowment is defined as total production and geologic resources; data from Ozmin (Ewers and Ryburn, 1997) supplemented by New South Wales Department of Mineral Resources database and company annual reports and announcements; BHT = Broken Hill-type, EWT = Elura-Woodcutters-type, MIT = Mount Isa-type, MVT = Mississippi Valley-type

[2] Gold grade based on total endowment reported by Woodall (1990)

[3] Includes Catalpa, Ethel, Xantho, Hougoumont, and Amity lenses

[4] Includes Zeewijk lens

Table 2. Endowment of Zn, Pb, and Ag for Geologic Areas in Australia[1]

Region	Area (km²)	Zn (Mt)	Zn endowment (t/km²)	Pb (Mt)	Pb endowment (t/km²)	Ag (t)	Ag endowment (kg/km²)
Mount Isa inlier—Western succession	27,300	50.19	1840	24.24	888	50800	1860
Broken Hill	20,000	23.82	1190	28.08	1400	41800	2090
Dundas	11,000	8.34	758	4.13	376	9920	902
Mount Isa inlier—Eastern succession	19,400	8.28	427	6.70	345	25600	1320
Broome platform	39,200	7.38	188	2.76	70.4	3840	98.0
McArthur	154,000	20.88	136	9.31	60.4	9080	59.0
Lennard shelf	25,100	3.12	124	1.15	45.8	91	3.66
Thalanga-Balcooma province	9,500	1.12	118	0.35	37.3	861	90.6
Lachlan	299,000	9.19	30.7	4.74	15.9	9670	32.3
Murchison province	152,000	2.06	13.6	0.10	0.63	1120	7.37
Pine Creek	45,000	0.57	12.7	2.08	46.1	1081	24.0
Kanmantoo	8,000	0.10	12.5	0.04	5.00	60	7.50
Pilbara	52,000	0.59	11.3	0.05	0.95	288	5.55
Bonaparte	18,000	0.18	10.0	0.99	55.0	957	53.2
Einasleigh province	27,000	0.20	7.39	0.09	3.27	180	6.67
Cairns	50,000	0.31	6.10	0.01	0.17	64	1.28
Halls Creek	39,000	0.22	5.73	0.06	1.61	197	5.05
Adelaide	69,000	0.37	5.36	0.31	4.50	0	0.00
Southern Cross province	117,000	0.45	3.81	0.00	0.00	0	0.00
Eastern Goldfields province	191,000	0.48	2.56	0.02	0.09	553	4.06
Arunta	196,000	0.25	1.28	0.00	0.00	0	0.00
Gawler	144,000	0.14	0.94	0.09	0.59	170	1.18
Bangemall	75,000	0.00	0.00	3.60	48.00	1200	16.0
Nabberu	58,000	0.00	0.00	0.68	11.73	0	0.00
Australia total	7,682,300	138.32	18.0	89.56	11.7	157600	20.5

Note: Names incorporating "region" correspond to Geoscience Australia's geologic regions of Australia; other names are subdivisions of these regions where appropriate

[1] Endowment is defined as total production and geologic resources

the development of rift and rift-sag basins in northern and central Australia. Deposits in the Western succession of the Mount Isa inlier and the McArthur basin are hosted in variably dolomitic and organic matter-rich siltstones associated with aggradational and early progradational highstand deposits of second-order supersequences where minimal coeval volcanism and plutonism are found (Southgate et al., 2000a). The geologic setting of the Broken Hill and Cannington deposits, although of broadly similar age, is more active, characterized by penecontemporaneous volcanism and plutonism within a dominantly sedimentary sequence consisting of sandstone, siltstone, and shale (Stevens et al., 1988).

The other major period of Australian Zn mineralization, the Paleozoic, is characterized by active tectonism and magmatism, particularly in eastern Australia. The deposits of the Dundas trough and Lachlan fold belt are mostly associated with volcanism and formed as a consequence of subduction, but in the Ordovician to Carboniferous Canning basin of Western Australia, Mississippi Valley-type deposits formed during the Early Devonian (McCracken et al., 1996) and the Early Carboniferou (Christensen et al., 1995), a period lacking volcanism in that region. Zn-Pb-Ag ores occur both in environments that lack significant igneous activity and in those that have contemporaneous volcanism and plutonism.

Ore-Forming Systems in Australia

In Australia, over 93 percent of the known Zn endowment is accounted by four deposit types, including VHMS, Broken Hill, Mississippi Valley, and Mount Isa-type deposits (Table 4). In this paper we describe these deposits and their ore-forming systems according to the basin that hosts the system, the heat source that drove the system, the "plumbing system," including mechanisms that drive fluid flow, the sources of ore-fluid components (water, chloride, sulfur, and metals), the site of metal deposition, and the outflow zone.

VHMS Ore-Forming Systems

VHMS deposits, which form during volcanism and related sedimentation within submarine volcanic belts, are the most common Zn-Pb-Ag deposits in Australia, accounting for 32 of the deposits listed in Table 1. These deposits tend to be small; the median VHMS deposit in Table 1 contains only 0.24 Mt Zn. Compared to other Zn-Pb-Ag ore-forming systems, the VHMS system is well understood, partly through extensive research on ancient systems, particularly in Canada and Australia, but also through the discovery of modern analogues on the sea floor (i.e., "black smoker" deposits).

In general, VHMS deposits consist of Zn-Pb-Cu–bearing massive sulfide lenses underlain by chlorite- and/or sericite-bearing alteration zones that commonly contain Cu. The presence of significant Cu (and Au) in the ore assemblage distinguishes these deposits from Mount Isa- and Mississippi Valley-type deposits. The scale of VHMS systems also differs from that of other Zn-Pb-Ag ore-forming systems. Ore-forming systems that form VHMS deposits operate on scales of, at most, several tens of kilometers, whereas Mississippi Valley-type systems, for example, operate at scales of hundreds to thousands of kilometers (Anderson and Macqueen, 1987). Figure 4 schematically illustrates important components of the VHMS ore-forming system.

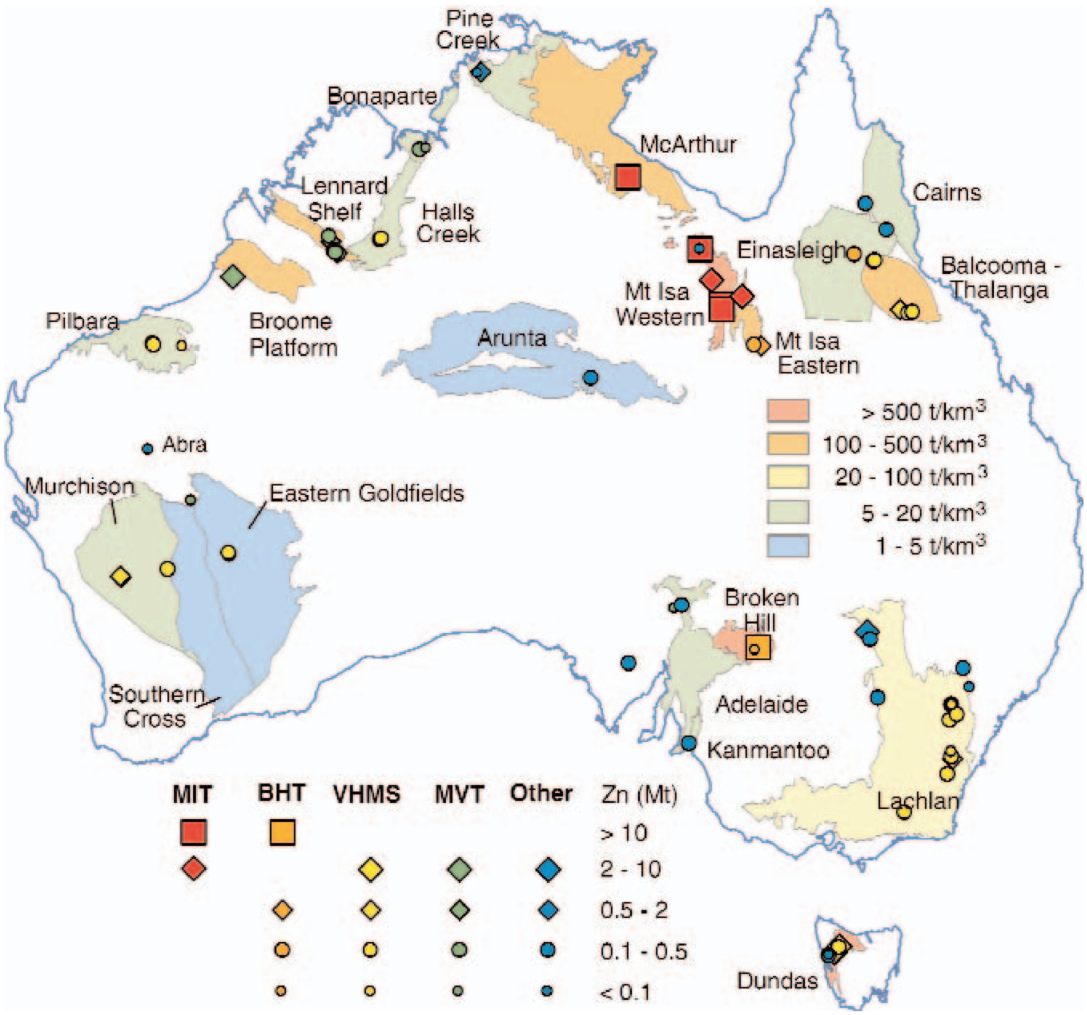

FIG. 1. Spatial distribution of Zn resources in Australia (based on Table 2). Abbreviations: BHT = Broken Hill-type, MIT = Mount Isa-type, MVT = Mississippi Valley-type, VHMS = volcanic-hosted massive sulfide.

The basin

VHMS deposits occur only in submarine volcanic settings, most commonly in back-arc basins, including ophiolites and ensialic rifts. Many of the largest VHMS deposits occur in ensialic rifts, including the Bathurst district in New Brunswick (van Staal et al., 2003) and the Iberian Pyrite Belt (Tornos, 2006). The Mount Read volcanic belt in Tasmania, host to several world-class VHMS deposits, also developed on continental crust (Crawford and Berry, 1992). Black smoker deposits, modern analogues of ancient VHMS deposits, have been discovered in medial rift valleys of mid-ocean ridges, in back-arc rift zones and in the summit calderas of arc volcanos (Hannington et al., 2005). Black smoker and VHMS deposits form rift settings, albeit oceanic, back-arc, or ensialic environments. Rifts are characterized by high heat flow and extensive magmatism, which drive convective fluid flow within the crust.

The heat source

Fluid inclusion data and measurements of modern venting fluids indicate that the ore fluids that formed VHMS deposits were 200° to 350°C (de Ronde, 1995). The production of such hot fluids in the upper part of the crust requires high heat flow. Subvolcanic intrusions are inferred as the heat source that drove fluid circulation in many VHMS systems (Galley, 2003). Figure 5 illustrates the relationship between a subvolcanic intrusive complex, regional-scale alteration zonation, and mineral deposits in the 3.24 Ga Panorama district in the Pilbara. A similar relationship between subvolcanic intrusions and regional alteration patterns exists in other districts around the world, and, in may cases, a temporal link between VHMS ore-forming systems and subvolcanic intrusions has been established (Galley, 2003; Franklin et al., 2005). Where links between VHMS systems and subvolcanic intrusions have been established, the intrusions generally have a trondhjemitic or tonalitic composition and a sill-like shape. Granitic (e.g., Panorama) and dioritic intrusions are the heat source in some districts. In most districts, the intrusion is polyphase, has a thickness of 1 to 3 km, and intrudes 1.5 to 3 km below the ore position. However, a genetic link to intrusions has not been demonstrated in many of the world's largest VHMS districts, including the Mount Read Volcanics of Tasmania.

TABLE 3. Endowment of Zn, Pb, and Ag with Geologic Time in Australia[1]

Age (Ga)	Zn (Mt)	Pb (Mt)	Ag (t)
3.4–3.5	0.09	0.02	120
3.3–3.4			
3.2–3.3	0.50	0.03	169
3.1–3.2			
3.0–3.1			
2.9–3.0	2.51	0.10	4,960
2.8–2.9			
2.7–2.8			
2.6–2.7	0.48	0.02	553
2.5–2.6			
2.4–2.5			
2.3–2.4			
2.2–2.3			
2.1–2.2			
2.0–2.1			
1.9–2.0			
1.8–1.9	0.22	0.06	197
1.7–1.8	0.25	0.00	0
1.6–1.7	90.67	70.18	123,900
1.5–1.6	12.85	1.93	5,000
1.4–1.5			
1.3–1.4			
1.2–1.3			
1.1–1.2			
1.0–1.1			
0.9–1.0			
0.8–0.9			
0.7–0.8			
0.6–0.7			
0.5–0.6	0.10	0.04	60
0.4–0.5	20.91	8.50	18,100
0.3-0.4	8.90	5.56	5,350
0.2-0.3	0.12	0.00	73
0.1-0.2			
0.0–0.1	0.07	0.06	1,860
Total known	137.68	86.51	160,400
Unknown	0.57	3.06	1,080

[1] Endowment is defined as total production and geologic resources

The "plumbing" system

District-scale alteration zones in VHMS districts tend to be semiconformable, although high-temperature semiconformable zones become transgressive, where they define fluid pathways to the site of mineral deposition (Galley, 1993; Brauhart et al., 1998). Table 5 summarizes the characteristics of regional alteration facies for well-described districts. Of the assemblages described, albitic zones in the volcanic pile just above the magma chambers, K-feldspar-bearing zones near the top of the volcanic pile, and epidote- and/or hematite-bearing zones near the base of volcanic pile are consistently developed, whereas feldspar-destructive zones and intensely silicified zones are less common. In the Snow Lake and Panorama districts, alteration assemblages near the base of the volcanic pile are associated with an increase in Fe_2O_3/FeO. Huston et al. (2001) suggested this change could be related to inorganic sulfate reduction and that the development of epidote- and/or hematite-bearing assemblages may reflect this process. Metal leaching has been recorded at depth in the volcanic pile (Fig. 5c) in five districts. However, variations in Fe_2O_3/FeO and base metal abundances have not been measured in most districts, so they may be more common than indicated in Table 5.

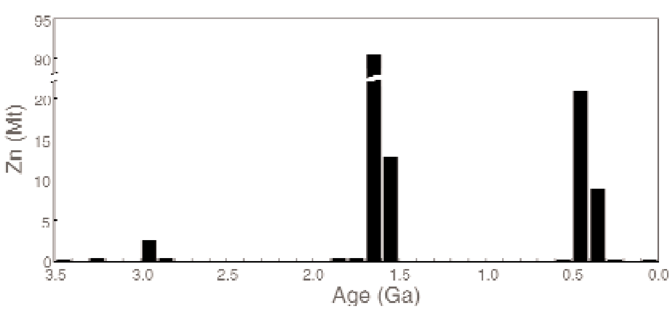

FIG. 2. Temporal distribution of Zn resources in Australia (based on Table 3).

District-scale alteration zones in VHMS districts also can be mapped using oxygen isotopes. In districts where regional $\delta^{18}O$ variations have been mapped there is an ^{18}O-depleted zone at or near the base of the volcanic pile (where defined), commonly above a subvolcanic intrusion. In some cases, ^{18}O is enriched at the top of the volcanic pile or in the hanging wall to individual VHMS deposits (cf. Huston, 1999; Brauhart et al., 2000).

Brauhart et al. (2000) estimated the temperature of hydrothermal alteration in the Panorama district by assuming a value for $\delta^{18}O$ of the altering fluids. These calculations indicate that regional variations in $\delta^{18}O$ data result from an increase in temperature from the top to the base of the volcanic pile as a consequence of heating by the subvolcanic intrusion. Hence, $\delta^{18}O$ variations can be used as a proxy for alteration temperatures, with high values indicating low alteration temperatures and low values indicating high temperatures.

Deposit-scale alteration zones are transgressive, texturally destructive, contain feldspar-destructive assemblages of chlorite, sericite, and quartz, and are characterized by Na and ^{18}O depletions and Fe and Mg enrichments. The morphology of these proximal zones is variable (Franklin et al., 1981). Where the substrate to the deposit is coherent, these zones tend to be narrow. For example, at the Hellyer deposit in Tasmania (Gemmell and Large, 1992), which is underlain by massive andesite, the proximal zone is only 150 m wide (Fig. 6a) and extends to a depth at least 500 m below the ore lens. In contrast, at the nearby Rosebery deposit, the ore lenses are underlain by pumice breccia (Large et al., 2001), which has been altered in a zone that extends at least 500 m laterally beyond the boundaries of the ore lenses (Fig. 6b). Many VHMS deposits in Australia are characterized by volcaniclastic substrates and laterally extensive proximal alteration zones.

The regional and proximal distribution of alteration facies in VHMS districts defines flow paths of hydrothermal fluids through the ore-forming system. As chloritic alteration assemblages generally form by interaction of the rocks with high-temperature ore fluids (Franklin et al., 1981; Ohmoto et al., 1983), the distribution of this facies records the passage of such fluids. The presence of semiconformable chloritic zones at the base of the volcanic pile in the Panorama district (Brauhart et al., 1998) suggests that high-temperature fluid flow was subhorizontal through much of the Panorama district. Franklin et al. (1981) termed this part of the ore-forming system the "reaction" zone, noting that many important

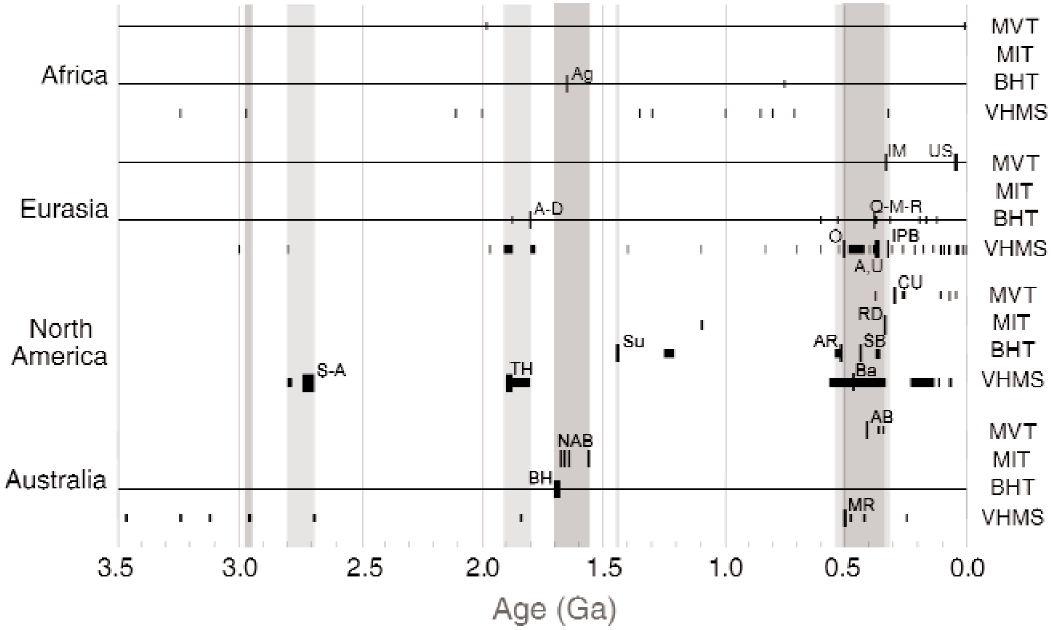

FIG. 3. The timing of major Zn mineralizing events in Australia compared to events in North America, Europe, Asia and Africa. The dark-gray shaded columns indicate important periods of Zn-Pb-Ag mineralization in Australia; the light-gray shaded columns indicate important periods of global Zn-Pb-Ag mineralization. Thick bars indicate mineralizing events that resulted in Zn and Pb resources of 10 Mt or more. Thin bars indicate smaller mineralizing events. Major mineralizing events are labeled as follows: A = Altaides, AB = Admiral Bay, Ag = Aggeneys, AR = Anvil Range, A-D = Aravalli-Delhi, Ba = Bathurst, BH = Broken Hill, CU = Central United States, IM = Irish Midlands, IPB = Iberian Pyrite Belt, MR = Mount Read, NAB = North Australian basins, O = Ozerovnoe, Q-M-R = Qingling-Meggan-Rammelsburg, RD = Red Dog, SB = Selwyn basin, Su = Sullivan, S-A = Superior province (Abitibi subprovince), TH = Trans-Hudson, U = Uralides, and US = Upper Silesia. BHT = Broken Hill-, MIT = Mount Isa-, MVT = Mississippi Valley-type, VHMS = VHMS deposits. Data are from Leach et al. (2005), Franklin et al. (2005), and this study, with data for the Perkoa deposit from Schwartz and Melcher (2003). Following Leach et al. (2005), the Irish Midlands deposits are grouped with Mississippi Valley-type deposits.

chemical reactions occur within this zone. Because of the large quantity of fluid reacting with rocks, the reaction zone approaches equilibrium with the altering fluid. Phase separation is also an important process within the reaction zone. This process, which is interpreted to occur hundreds to thousands of meters below the sea floor, appears to be common in modern systems (e.g., Butterfield et al., 1990; Von Damm, 1990). Condensation of brine as a result of supercritical phase separation is an important mechanism causing variable salinity in VHMS ore fluids (e.g., de Ronde, 1995).

At a point determined partly by permeable zones related to synvolcanic faults (e.g., Vearncombe et al., 1998), fluids in the reaction zone flow up stratigraphy, forming transgressive high-temperature alteration (or “discharge”) zones that extend to deposits at or near the sea floor. Although semiconformable reaction and transgressive discharge zones are mapped in a number of ways, the lower temperature “recharge” zone (Franklin et al., 1981) is difficult to map. Alteration, geochemical, and oxygen isotope mapping do not define zones consistent with downward moving, low-temperature fluid flow in the Panorama and other districts. Hence, recharge may be diffuse and not involve narrow zones of high fluid flux.

The interpreted flow pattern is that of convection cells developed below the sea floor in permeable volcano-sedimentary rocks heated by a subvolcanic, sill-like intrusion. For homogeneous permeability, the surface spacing of upflow zones associated with cells is 3.8 times the depth to intrusion (Lapwood, 1948), which is the approximate spacing of transgressive alteration zones observed at Panorama. This geometric relationship may explain the systematic spacing of deposits in many VHMS districts (Solomon, 1976).

Due to complex interrelationships of rock units and the occurrence of synvolcanic faults, the permeability structure of subaqueous volcano-sedimentary complexes is highly heterogeneous. Fluid flow and ore deposition may be controlled by local structures and volcanic facies changes (Doyle and Huston, 1999). Systematic variations in thicknesses of the host unit or massive sulfide, or in metal zonation may indicate locations of these faults. The permeability of the units underlying VHMS deposits controls the morphology of deposits in addition to the morphology of the underlying proximal alteration zones. Moundlike deposits with pipelike stringer zones develop over impermeable lavas (e.g., Hellyer); whereas blan-

TABLE 4. Endowment of Zn, Pb, and Ag by Deposit Type in Australia[1]

Deposit type	Zn (Mt)	Pb (Mt)	Ag (t)
MIT	77.09	34.44	61,890
BHT	26.25	33.92	65,600
VHMS	16.52	5.03	19,730
MVT	10.68	5.89	4,888
Other	7.71	10.29	9,359

Abbreviations: BHT = Broken Hill type, MIT = Mount Isa type, MVT = Mississippi Valley-type

[1] Endowment is defined as total production and geologic resources

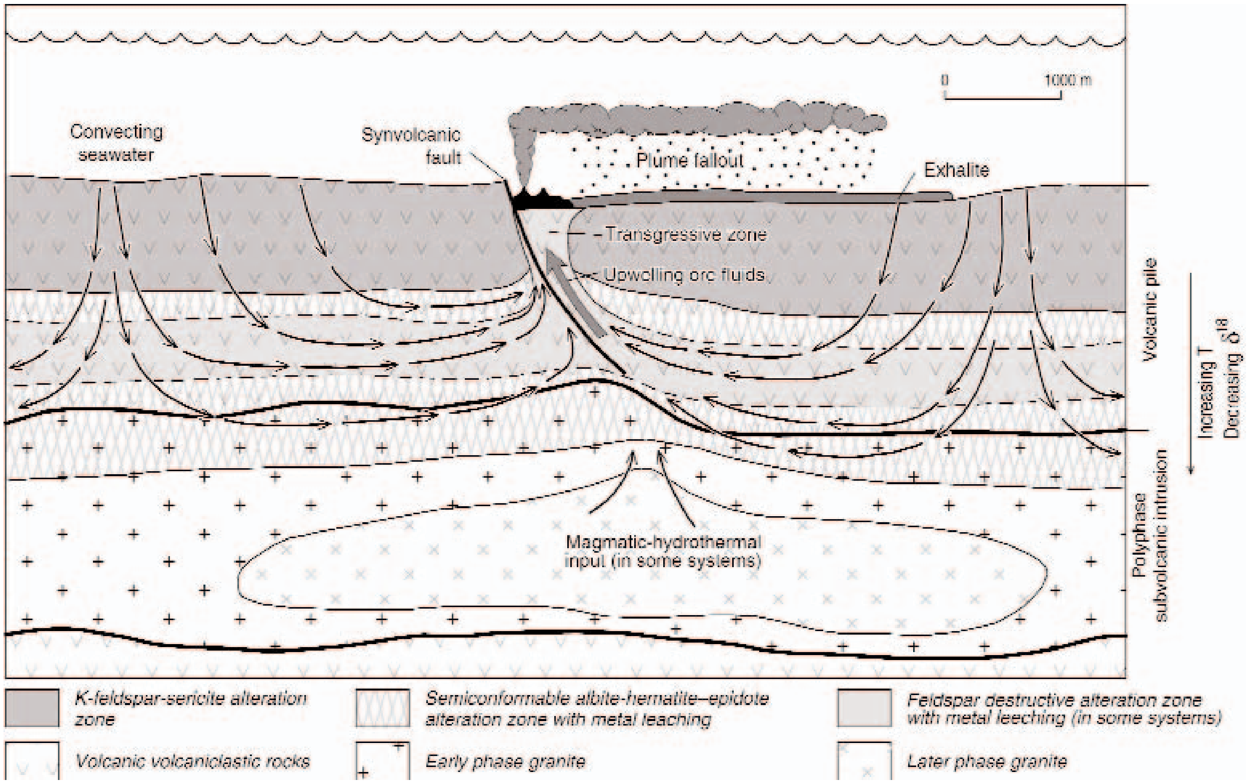

FIG. 4. Schematic illustration of the VHMS ore-forming system. Key illustrated components include the host basin (extensional volcanic basin), the heat source (subvolcanic intrusion), the plumbing system (extensional faults and aquifers), the nature of fluid flow (convection), the source of fluid components (seawater and volcanic pile; possibly the subvolcanic intrusion in some systems), the site of metal deposition (at or near the sea floor), and the outflow zone (water column).

ketlike deposits with laterally extensive alteration zones form over permeable volcaniclastic units (e.g., Rosebery; Fig. 6).

The sources of ore-fluid components

In most models of VHMS systems, ore fluids and chloride derive from circulating modified seawater, ore metals are leached from the rocks through which the seawater circulates, and sulfur originates from both sources (e.g., Franklin et al., 1981). In a number of cases, a significant magmatic-hydrothermal input has been inferred from geologic relationships (e.g., Large et al., 1996a), melt inclusions in associated volcanic rocks (Yang and Scott, 1996), and local occurrence of advanced argillic alteration assemblages (Sillitoe et al., 1996). The importance of magmatic-hydrothermal water in VHMS ore-forming systems is not constrained and may vary from district to district.

Source of water: The $\delta^{18}O$ of VHMS ore fluids varies from –2 to 4 per mil and δD varies from –40 to 5 per mil (Huston, 1999). These compositions do not correspond uniquely to a particular fluid but have compositions that are intermediate between seawater (δD ~0‰, $\delta^{18}O$ ~0‰) and magmatic waters (δD = –30 to –60‰, $\delta^{18}O$ = 5.5–9.5‰: Taylor, 1986). The shifts in $\delta^{18}O$ away from seawater can be accounted for by water-rock interactions in the circulation cell, but such reactions cannot account for variations in δD. The δD data could indicate up to 25 percent magmatic-hydrothermal fluid in some systems (i.e., those with low δD), but these same variations could also be caused by phase separation in the reaction zone.

Source of chloride: The chlorinity of VHMS fluids is typically elevated relative to seawater (e.g., de Ronde, 1995). This implies that unmodified seawater is not the sole source of chloride in VHMS fluids; either phase separation occurred in the reaction zone or high-salinity magmatic-hydrothermal fluids were incorporated into a seawater-dominated ore fluid.

Source of sulfur: The $\delta^{34}S$ values of sulfide minerals from Phanerozoic VHMS deposits are generally between those of coeval seawater sulfate and juvenile or magmatic sulfur. This has been interpreted to indicate that the sulfur was a mixture from these two sources (e.g., Solomon et al., 1988), with the seawater inorganically reduced in the reaction zone and juvenile or magmatic sulfur leached from the volcanic rocks or contributed directly from a subvolcanic magma. In euxinic basins, biogenically reduced seawater sulfate may also be important. In contrast, $\delta^{34}S$ values of sulfide minerals from Proterozoic and Archean deposits are always close to the magmatic value of 0 per mil (Huston, 1999). This has been interpreted to indicate that magmatic sulfur (either dissolved from volcanic rock or derived from magmatic outgasing) is the major source of sulfur in these older deposits (cf. Eastoe et al., 1990), although Archean seawater sulfate also had low $\delta^{34}S$ values (Huston, 1999).

Sources of metals: In the 1970s and 1980s a consensus grew that metals were leached from the underlying volcanic strata with minimal magmatic contribution (cf. Franklin et al., 1981; Ohmoto et al., 1983). This model was supported by Pb isotope data and limited geochemical evidence for leaching

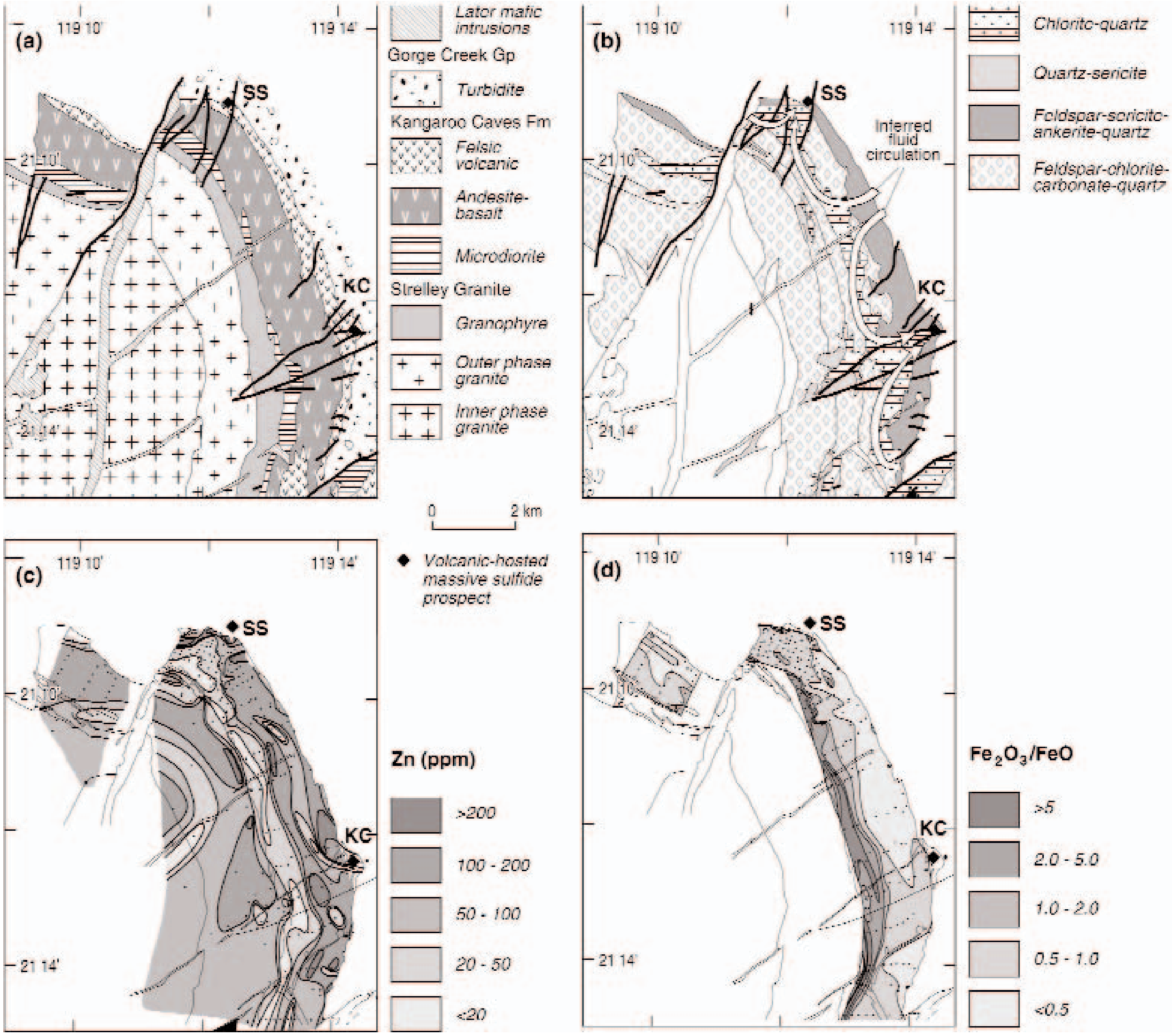

FIG. 5. Regional maps of the Panorama volcanic-hosted massive sulifde deposits, showing the distributions of (a) lithology, (b) alteration facies, (c) Zn abundances established from whole-rock analyses, and (d) whole-rock Fe_2O_3/FeO ratios (modified after Brauhart et al., 1998, 2001; Huston et al., 2001). KC = Kangaroo Caves, SS = Sulphur Springs. Dots in parts (c) and (d) indicate location of samples.

(Table 5) but was challenged by a number of workers (e.g., Sawkins, 1982; Stanton, 1990) who advocated derivation of metals from crystallizing magmas. Data from regional alteration studies (Table 5) indicate that large quantities of metals were stripped from volcanic rocks in some districts. Brauhart et al. (2001) showed that the amount of Zn stripped from the underlying rocks exceeded the amount of Zn present in deposits of the Panorama district by nearly an order of magnitude, with excess metal interpreted to have been lost to seawater. It is likely that in most districts, a large, if not predominant, portion of the metal was stripped from volcanic rocks, although there is evidence to suggest a magmatic-hydrothermal component in some districts.

The site of metal deposition

The primary mechanism of ore deposition in VHMS deposits is rapid cooling when ore fluids mix with seawater at or near the sea floor. Consequently, VHMS deposits commonly form at specific stratigraphic horizons during periods of volcanic quiescence that allow accumulation of sulfide at or near the sea floor.

Trapping of metals: The term "black smoker" stems from very fine grained hydrothermal minerals in buoyant hydrothermal plumes that precipitate when venting fluids rapidly cool upon mixing with seawater (Fig. 7a). Although sulfides precipitate, they do not accumulate efficiently on the sea floor. Less than 10 percent of the metals in the venting fluid are retained in the growing sulfide mound (Converse et al., 1984); the rest are dispersed in the buoyant plume. Because of this poor depositional efficiency, black smoker venting does not appear to be the most efficient mechanism for forming large VHMS deposits. Two possible, more efficient, mechanisms include the formation of a brine pool (Fig. 7b) and mineral precipitation below the sea floor (Fig. 7c).

TABLE 5. Characteristics of Regional Alteration Zones in Volcanic-Hosted Massive Sulfide Deposits (based partly on compilation of Galley, 1993)

District	K-feldspar–bearing zones	Albite-bearing zones	Feldspar-destructive zones	Epidote ± hematite-bearing zones	Silicified zones	Primary references
Troodos, Cyprus	Present in upper part of sheeted dike swarn	Present in lower part of sheeted dike swarm	Not reported	Extensive epidote-quartz-chlorite zones underlie and crosscut overlying feldspar-bearing zones; depleted in base metals	Not reported	Schiffman and Smith (1988)
Iberian Pyrite Belt	Erratically developed near top of volcanic sequence	Not pervasive; concentrated in permeable zones lower in volcanic sequence	Not reported	Epidote present in albitic zones down section	Not reported	Munha and Kerrich (1980)
Bergslagen, Sweden	Present at top of volcanic pile	Present toward base of volcanic pile; chloritic toward top; depleted in Fe, Mn, Zn, Pb, and Ba	Not reported	Not reported	Not reported	Lagerblad and Gorbatschev (1985)
Snow Lake, Manitoba	Not reported	Silicified zones commonly albitized	Semiconformable quartz-biotite ± staurolite ± chlorite zones with local loss of Zn, Pb, Cu, and Mo and increase in Fe_2O_3/FeO	Conformable epidote zones associated with Zn loss and increase in Fe_2O_3/FeO; discrete epidote-hematite zones in Sneath Lake pluton below Cu-rich Anderson Lake and Stall Lake deposits	Extensive semi-conformable zones with local loss of Zn, Pb, and Mo and increase in Fe_2O_3/FeO	Bailes and Galley (1991, 1996); Skirrow and Franklin (1994); D. Huston, unpub. data
Noranda, Quebec	Not reported	Broad, regional semiconformable zone	Not reported	Epidote-quartz assemblages overprint silicified zones and increase toward center and base of volcanic complex in association with major dike swarm	Semiconformable zones at several stratigraphic positions	Gibson (1989)
Matagami, Quebec	Not reported	Extensively developed in footwall basalt	Not reported	Epidote in veinlets and as patches in footwall basalt	Silicification accompanies albite alteration	MacGeehan (1978)
Manitouwadge, Ontario	Presence is indicated in alkali geochemistry but spatial distribution not described	Presence is indicated in alkali geochemistry but spatial distribution not described; trondhjemite is Na enriched	Semiconformable orthoamphibole-cordierite-garnet gneiss in volcanic pile just above the contact with trondhjemite intrusion	Not reported	Not reported	Zaleski and Peterson (1995)
Panorama, Western Australia	Semiconformable zone at top of volcanic pile	Semiconformable zone near base of volcanic pile that extends down into the subvolcanic intrusion; loss of Zn, Pb, Cu, and S, and increase in Fe_2O_3/FeO	0.5 km thick, semiconformable zone just above the base of the volcanic pile; loss of Zn, Pb, Cu, Mo, and S, and increase in Fe_2O_3/FeO	Local epidote-hematite zones toward base of volcanic pile	Not reported	Brauhart et al. (1998, 2001); Huston et al. (2001)

Work at the Rosebery (Allen, 1994) and Kidd Creek (Bleeker, 1999; Hannington et al., 1999) deposits suggests that these large deposits formed, at least in part, by replacement of the host units (Doyle and Allen, 2003). Hydrothermal-seawater mixing occurred in clastic rocks (e.g., coarse volcaniclastic rocks or sandstones) that formed permeable zones below the sea floor, more effectively trapping precipitated sulfides.

Alternatively, Solomon and Khin Zaw (1997) suggested that the Hellyer deposit formed in a brine pool. They argued that initially buoyant fluids, which formed by mixing of saline (to 15% NaCl) ore fluid with seawater, became more dense than

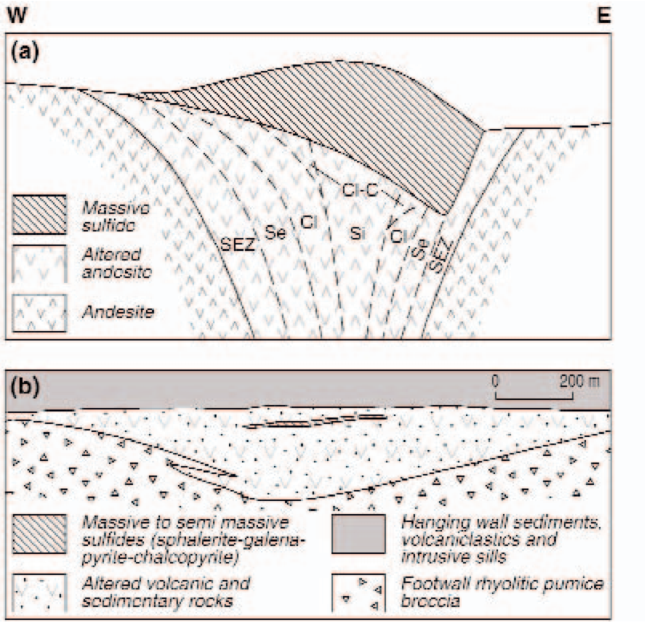

FIG. 6. Schematic diagrams, showing the morphology of proximal alteration zones underlying the (a) Hellyer and (b) Rosebery volcanic-hosted massive sulifde deposits (modified after Gemmell and Large, 1992, and Large et al., 2001). In (a) SEZ = the stringer envelope zone, Se = the sericitic alteration zone, Cl = the chloritic alteration zone, Cl-C = the chlorite-carbonate alteration zone, and Si = the siliceous alteration zone.

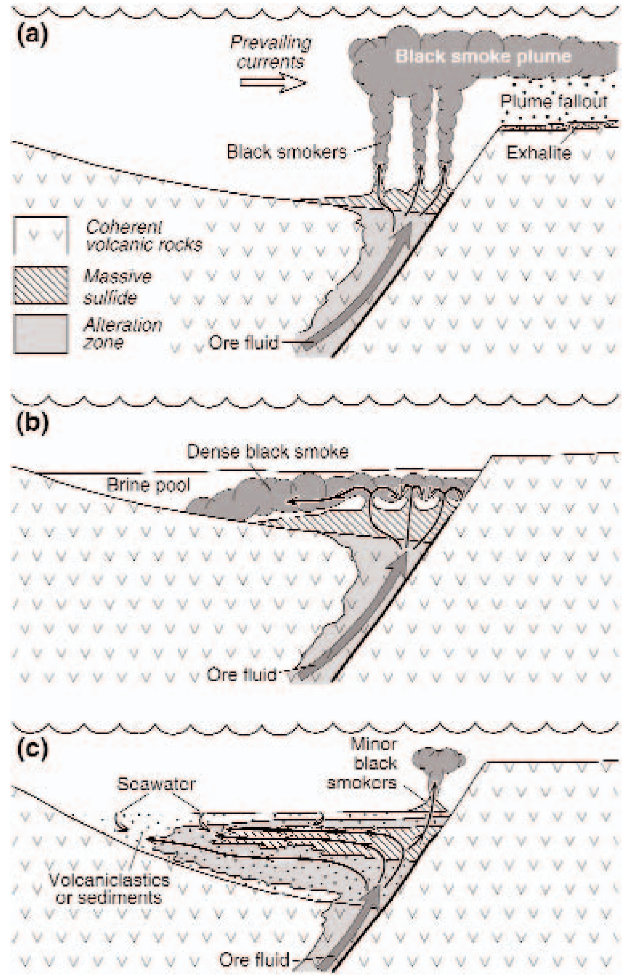

FIG. 7. Possible fluid behavior and sulfide depositional mechanisms for volcanic-hosted massive and Broken Hill-type deposits: (a) black smoker plume, (b) brine pool, and (c) subsea-floor replacement.

seawater upon cooling. Such a fluid would then form a brine pool, trapping all metal from the original venting fluid. Although this mechanism is controversial and buoyancy reversal has not been observed in modern systems, it is potentially an efficient method of trapping sulfides.

Zone refining: Within the massive sulfide lens ore deposition is complex and dominated by "zone refining" (Eldridge et al., 1983). In this process, progressively hotter fluids replace the base of the sulfide lens with higher temperature mineral assemblages. Zn-rich ore formed at low temperature is progressively replaced by Cu-rich and then pyritic ores to produce the pyrite → Cu → Zn-Pb ± Ba zonation characteristic of these deposits. Metals removed in this process move upward, where they are either trapped or lost via black smoker-type venting. In this manner a massive sulfide lens grows from the base and from the top. Fluid inclusion data suggest that Zn, Pb, and Ag are precipitated in the range of 200° to 300°C (e.g., Pisutha-Arnond and Ohmoto, 1983). If the fluid temperature exceeds 300°C, Cu-bearing ores form at the base of the sulfide lens. Sustained high-temperature fluid flux can actually move Zn, Pb, and even Cu out of the sulfide lens, leaving a massive pyrite body (cf., Hannington et al., 1998).

Water depth: Morton and Franklin (1987) classified VHMS deposits into two types based on morphology and the character of the host sequence. Moundlike deposits with pipelike alteration zones overlying a coherent substrate were termed Noranda-type (similar to Hellyer) and inferred to form in deep water. Blanketlike deposits with diffuse alteration zones overlying a fragmental substrate were termed Mattabi-type and inferred to form in shallow (i.e., <500 m) water depths. Cas (1992), on the other hand, argued that all VHMS deposits must have formed in relatively deep (i.e., >500 m) water to prevent boiling of the hydrothermal fluids.

In situ boiling changes the dynamics of ore deposition, and the depth of boiling changes with the temperature and gas content of the ore-forming fluid. For instance, a 200°C fluid of seawater salinity boils at a depth of about 200 m, whereas at 350°C fluid boils at a depth of 1,700 m (Huston and Cas, 2000). Hence, for a low-temperature deposit, depths in excess of 200 m might be considered deep, whereas for a high-temperature deposit, a depth of 1,700 m might be considered shallow. Most modern black smokers occur at water depths that are sufficient to prevent boiling (e.g., >1,300 m: Huston and Cas, 2000; Hannington et al., 2005), although some occurrences in shallow volcanic arcs are boiling. Some of these may be the sea-floor manifestation of VHMS-related epithermal vein deposits below the sea floor. Deposition in shallow-water parts of the VHMS system may not have typical VHMS characteristics (i.e., stratiform massive sulfide) but may be more akin to epithermal deposits in form and, possibly, in metal assemblages and zonation.

The outflow zone

Depositional environments and mechanisms also affect how and where spent fluids interact external to the depositional environment. For instance, fluids from black smoker venting can form exhalites that extend for tens of kilometers along mineralized horizons lateral to black smoker deposits (Fig. 7a; Spry et al., 2001). However, if the fluids were sufficiently saline to form a brine pool, all hydrothermal precipitates will be trapped in a restricted area. Although "exhalites" should be less extensive (Fig. 7b), metalliferous sediments in the Atlantis II brine pool extend many kilometers (Pottorf and Barnes, 1983). If deposits form below the sea floor, exhalite, if formed, will develop on the sea floor at a higher stratigraphic position (Fig. 7c).

According to Spry et al. (2001), and references therein, the most common form of exhalite in VHMS deposits is iron formation. Another less common type of exhalite is tourmalinite. These exhalites commonly mark the stratigraphic position of VHMS deposits and geochemical variations within them can be used as a vector to ore. However, exhalites do not appear to be common in Australia. In many Australian deposits spent fluids have interacted with the overlying rocks to form hanging-wall alteration zones. These zones tend to be more subtle than the footwall zones and can be enriched in more volatile elements. An extensive zone of Hg and Sb enrichment has been demonstrated in the hanging wall to the Rosebery deposit (Smith and Huston, 1992; Large et al., 2001), and enrichment of Sb and As also has been demonstrated in the hanging wall of the Kangaroo Caves deposit in the Panorama district (Hill, 1997).

If a sulfide lens is buried, continued hydrothermal activity may lead to the formation of stacked ore lenses. In Australia, this relationship is best illustrated at the Que River deposit, where the S lens was overprinted by hydrothermal fluids that formed the P lens, some 130 m higher up in the stratigraphy (Large et al., 1988).

Postdepositional modifications

One of the most important postdepositional processes that can affect preservation of VHMS deposits is sea-floor weathering. This process, which has been documented in extinct black smokers (Hannington et al., 1995), destroys sulfide accumulations unless these accumulations are protected either by rapid covering by later sediments or by an anoxic water column (Goodfellow et al., 1986). Deposition either below the sea floor or in a brine pool may also prevent weathering when ore formation ceases.

Broken Hill-Type Ore-Forming Systems

Although not as common as VHMS deposits, Broken Hill-type deposits are more important due to their large size. Of the five deposits in Table 1, two (Broken Hill and Cannington) are world-class. The Broken Hill deposit is the largest Zn-Pb-Ag accumulation on Earth. However, Broken Hill-type districts are also characterized by numerous small occurrences. The Broken Hill district contains an abundance of such showings (Fig. 8); the second largest deposit in the district, the Pinnacles deposit, contains two to three orders of magnitude less Zn, Pb, and Ag than Broken Hill. The proposed origins of Broken Hill-type deposits include syngenetic or diagenetic deposition (King and Thomson, 1953; Laing et al., 1978; Haydon and McConachy, 1987; Stevens, 2003) and syn- or posttectonic replacement (Ehlers et al., 1996; Hobbs et al., 1998; Gibson and Nutman, 2004). As the Broken Hill ores underwent folding and high-grade metamorphism (Lawrence, 1973), we consider the only viable origins to be pretectonic and prefer deposition at or just below the sea floor (Fig. 9). However, Gibson and Nutman (2004) inferred that the Broken Hill deposit formed in the lower plate of an extensional detachment surface that developed no more than 10 m.y. after deposition of the host rocks. Many of the features described here, which are based on the Broken Hill and Cannington districts, are also relevant to the alternative syn- or posttectonic models, particularly that of Gibson and Nutman (2004).

Broken Hill-type deposits have many similarities to VHMS deposits, including associations with volcanic rocks, the presence of Ag, Sb, Cu, As, Bi, and Au in the ores (Table 6) and an association with rocks interpreted as exhalites, features that set them apart from Mount Isa- and Mississippi Valley-type deposits. The main characteristic that defines Broken Hill-type deposits as a class is high metamorphic

TABLE 6. Geochemical Characteristics of Ore Lenses from Broken Hill-Type Deposits

Lens	Pb (%)	Zn (%)	Ag (ppm)	Cu (%)	Au (ppm)	Bi (ppm)	Sb (ppm)	F (%)	100 Zn / Zn + Pb	100 Cu / Cu + Zn + Pb
Broken Hill										
No. 3	7.8	11.9	169	0.14		2	418	1.10	60	0.71
No. 2	16.4	12.4	118	0.14		10	413	1.35	43	0.48
No. 1	9.6	22.4	53	0.09		28	372	0.34	70	0.28
A lode	4.3	10.4	31	0.12		48	67	0.06	71	0.81
B lode	4.3	12.5	33	0.20		37	113	0.11	74	1.18
C lode	2.4	5.0	34	0.13					68	1.73
Cannington										
Broadlands	11.5	1.7	430	0.018	0.03		505	1.53	13	0.14
Burnham-Nithsdale	14.8	2.3	820	0.051	0.08		680	5.06	14	0.30
Colwell	2.0	12.4	84	0.110	0.27		58	0.28	86	0.76

Notes: Data from Johnson and Klingner (1975), and Walters and Bailey (1998); data for Burnham-Nithsdale is average of data quoted for the Burnham and Nithsdale lenses

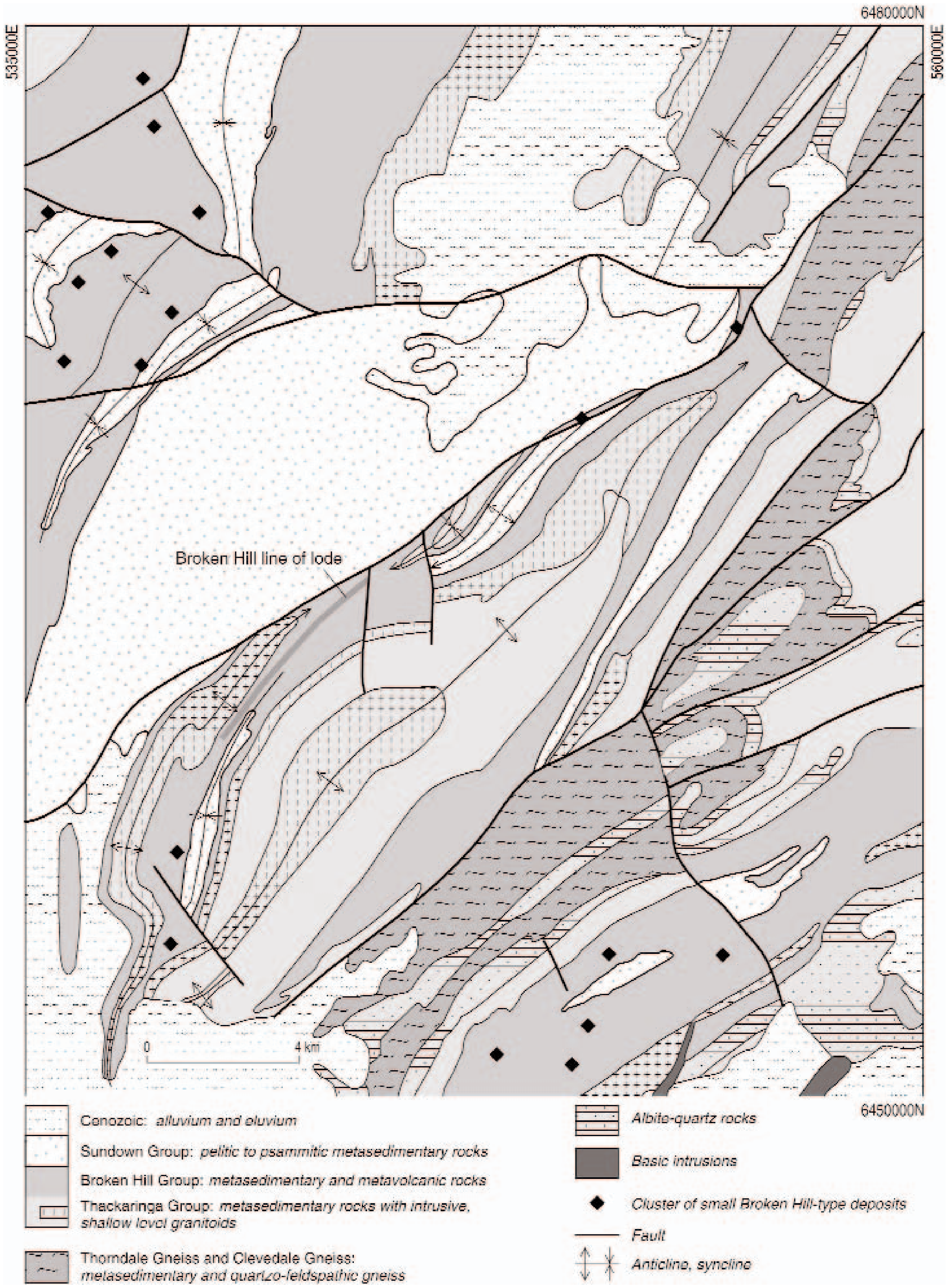

FIG. 8. Regional geology of the Broken Hill district (simplified from Willis, 1989), showing the location of the Broken Hill deposit, minor Zn-Pb-Ag occurrences, and albite-rich rocks.

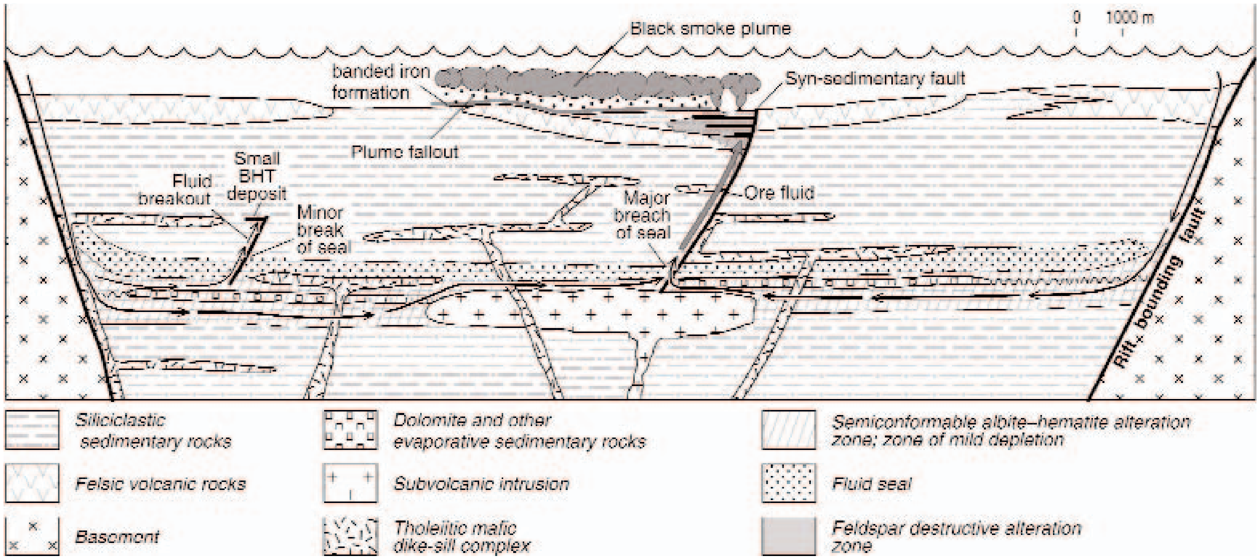

FIG. 9. Schematic illustration of the Broken Hill-type ore-forming system. Key illustrated components include the host basin (ensialic rift), the heat source (subvolcanic intrusion), the plumbing system (extensional faults and aquifers), the nature of fluid flow (convection), the source of fluid components (seawater and volcanic pile), the site of metal deposition (at or near the sea floor), and the outflow zone (water column).

grade (amphibolite or higher). Walters (1996) identified a number of Broken Hill-type characteristics, including (1) "skarnlike" mineralogies, (2) stacked ore lenses with low aspect ratios, (3) large-scale, unfocused proximal alteration halos, and (4) S-poor iron mineralogy.

The basin

In Australia, Broken Hill-type deposits occur in dominantly sedimentary basins that have been overprinted by high-grade (upper amphibolite to granulite) metamorphism. These basins, which include the Broken Hill block and the Eastern succession of the Mount Isa inlier, are dominated by siliciclastic sedimentary rocks, with minor but genetically important felsic volcanic rocks, granites, and tholeiitic mafic sills (Willis et al., 1983; Beardsmore et al., 1988). Carbonate rocks in these packages are rare. The Willyama Supergroup, which hosts Broken Hill, and the Maronan Supergroup, which hosts Cannington, was deposited in rifts, with an ensialic setting proposed at Broken Hill (Willis et al., 1983; Beardsmore et al., 1988). The geochemistry of mafic sills at Broken Hill led James et al. (1987) to infer a depleted mantle source, possibly in a propagating rift setting. James et al. (1987) also suggested that the presence of felsic rocks required significant crustal involvement in the rift.

The heat source

Although not as extensive as in VHMS systems, active volcanism and magmatism were present during ore formation and were probably essential to form Broken Hill-type deposits. The Broken Hill orebody is hosted by nonvolcanic metasedimentary rock within the 1686 ± 3 Ma Hores Gneiss, which is interpreted from petrographic studies to be mainly volcanic in origin (Page and Laing, 1992; Page et al., 2000a; Stevens and Barron, 2002). Moreover, felsic sills such as the Rasp Ridge Gneiss (1682 ± 3 Ma: Page et al., 2000a) were emplaced at about the same time as the Hores Gneiss and the orebody. Extensive tholeiitic amphibolite and mafic granulite occur stratigraphically below the Broken Hill deposit but do not extend into the overlying Sundown Group. The ages of these mafic bodies (1690–1670 Ma: Donaghy et al., 1998; Nutman and Ehlers, 1998) overlap with the emplacement ages of the felsic sill rocks, the volcanic rocks, and the orebody, and some intrude the Rasp Ridge Gneiss.

The ca. 1676 Ma Soldiers Cap Group (Page and Sun, 1998), which hosts the Cannington deposit, contains significant amphibolite and metabasalt along with minor felsic volcaniclastic units, within a sequence dominated by metapelite and metapsammite (Beardsmore et al., 1988). Although volumetrically minor, volcanic rocks and their subvolcanic equivalents appear to be an important component of the Broken Hill-type system. Paired felsic-tholeiitic magmatism, together with an inferred basin deepening (Stevens et al. 1988), suggest a rift environment with a high geothermal gradient, possibly associated with a deep-seated heat source that may have driven Broken Hill-type ore-forming systems.

The plumbing system

Although high-grade metamorphism and complex structural histories have obscured regional evidence of plumbing systems at Broken Hill and Cannington, stratiform, albite-rich rocks are known in both areas. At Broken Hill, regionally extensive, stratiform albite-rich zones with high Fe_2O_3/FeO occur about 500 to 2,000 m stratigraphically below the ore position (Huston et al., 1998). Although these rocks have been interpreted as metamorphosed evaporitic tuffs (Plimer, 1977), the detrital character and age range of their contained zircons indicate a probable origin as detrital sediments. The distribution and mineralogy of these rocks are similar to regional albite-bearing zones that form high-temperature reaction zones in VHMS ore-forming systems, and Vernon (1969) interpreted them as metasomatic products. Extensive albite-bearing alteration zones are also present in the Cannington region, where they overprint rocks of the Fullarton River Group that occur stratigraphically below the ore position. Although most of this alteration appears to be syntectonic or related to the intrusion of the Williams batholith (Wyborn, 1998), de Jong and Williams (1995) noted that some of the albitic alteration cannot be related to ductile structures, and Rubenach and Barker (1998) observed early albitite veins overprinted by S_2 fabrics. Although not definitive, these relationships raise the possibility that some of this alteration could be an early albitization event associated with the Cannington ore-forming system.

Cartwright (1999) presented whole-rock $\delta^{18}O$ data for the Broken Hill block that showed a regional decrease in $\delta^{18}O$, with the lowest values broadly associated with Pb-Zn mineralized zones. Similarities with whole-rock $\delta^{18}O$ patterns in VHMS districts led Cartwright (1999) to infer a model whereby circulating seawater, driven by granites, caused the isotopic variations and mineralization in the Broken Hill Block.

Like VHMS deposits, changes in sedimentological or volcanic facies appear to localize ore. At Broken Hill there is a major facies change across the Broken Hill antiform and a substantial stratigraphic thickness change in the immediate vicinity of the orebody (Fig. 10). These changes may relate to the presence of a growth fault. As in VHMS systems, the localization of ore is largely controlled by structures that were active during mineralization.

Focusing of the ore fluids at Broken Hill may also have been aided by aquicludes at depth. The Broken Hill Group is predominantly pelitic, and the sillimanite-biotite-rich pelites were probably originally chloritic, clay-rich sediments. These sediments could have constrained fluid flow to the Thackaringa Group, where the albite-rich zones are best developed. The presence of a growth fault would have focused fluid flow upward from this inferred aquifer. The small occurrences characteristic of Broken Hill-type districts may represent breakouts where minor faults have breached the impermeable sediments at the base of the Broken Hill Group.

In the footwall of the Broken Hill deposit, Plimer (1979) recognized an extensive proximal alteration zone that is characterized by siliceous rock, such as garnet quartzite, and encloses all ore lenses except three lenses (Fig. 10). Chemical changes associated with this zone, which can extend up to 500 m from ore zones, include losses of Na, Ca, Sr, and Mg and gains in K, Rb, Mn, Pb, and S (Plimer, 1979). Quartzose biotite-sillimanite schist and feldspathic psammite with abundant almandine garnet, which extend up to 250 m from the lodes, are interpreted as the proximal alteration zone at Cannington (Walters and Bailey, 1998). Chapman and Williams (1998) indicated that these rocks have lost Na, K, and Rb but gained Ca, P, Mn, Fe, Pb, and Zn. The geochemistry and form of these zones are similar to the more diffuse, sericitic alteration zones characteristic of Rosebery-type VHMS deposits.

The sources of ore-fluid components

Although high-grade metamorphic overprints make it difficult to establish the composition of Broken Hill-type ore fluids, Pb and S isotopes constrain the sources of ore-fluid components. $\delta^{34}S$ values are in the range of 0 ± 4 per mil

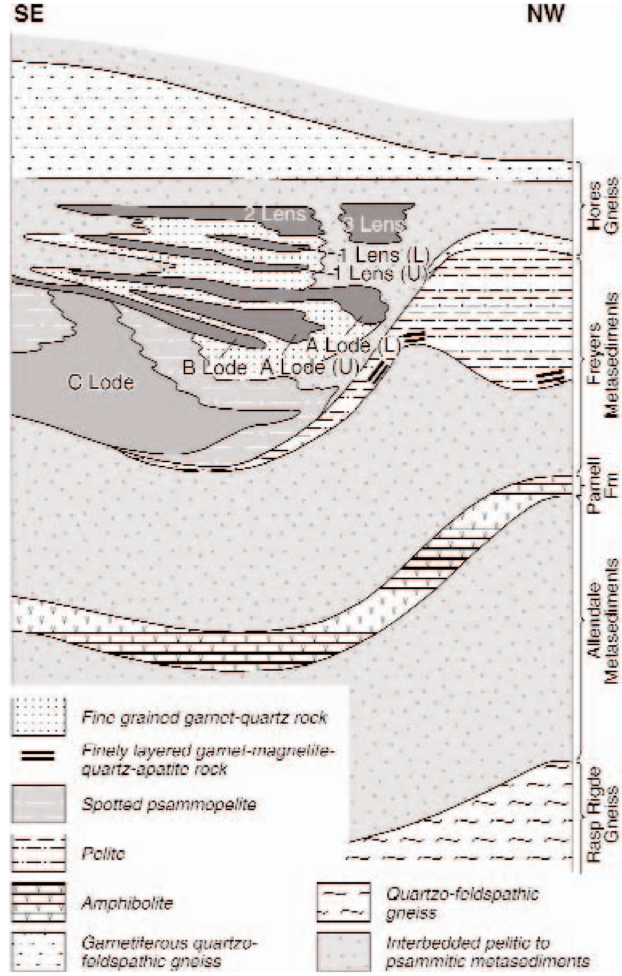

FIG. 10. Unfolded cross section of the Broken Hill deposit, showing the inferred relationship of ore lenses to changes in thickness of stratigraphic units and proximal alteration zones.

(Parr and Plimer, 1993), which could reflect mixtures from several sources, including reduced seawater sulfate and organic S. However, the simplest explanation would be derivation of S from magmatic emanations (Parr and Plimer, 1993) or indirectly via leaching of magmatic rocks, including dolerite sills and dikes.

Figure 11 shows the Pb isotope composition of the Broken Hill and Cannington ores compared to ores from Mount Isa-type deposits in north Australia. The Broken Hill-type deposits fall on a growth curve that is more primitive than Mount Isa-type deposits, which can be interpreted as resulting from an unusually primitive source of Pb with a large mantle input (e.g., Hobbs et al., 1998) or a highly evolved source of Pb for Mount Isa-type deposits. Figure 11 incorporates a number of Proterozoic VHMS deposits that have similar or more primitive Pb isotope compositions. This suggests that the source of Pb in Broken Hill-type deposits may be intermediate between the evolved crustal source seen in Mount Isa-type deposits and the primitive signature observed in some VHMS deposits, consistent with tectonic models invoking an ensialic-rift setting.

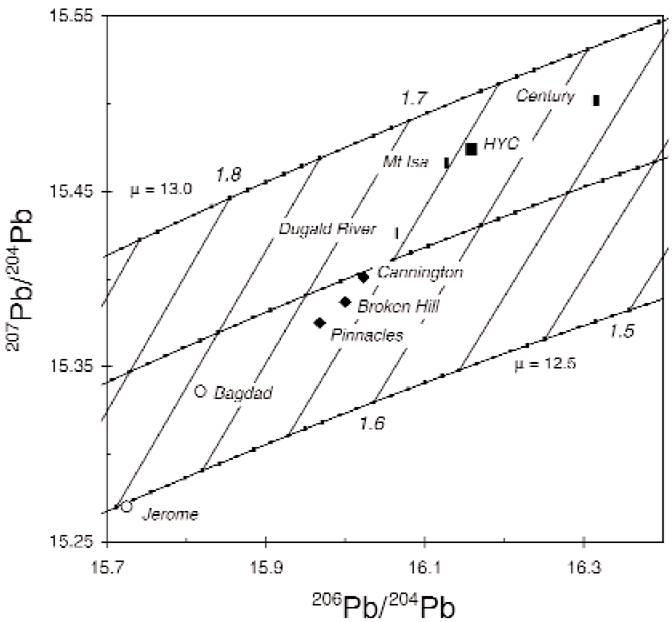

FIG. 11. $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ diagram contrasting the lead isotope characteristics of galena from Proterozoic Broken Hill-type (solid diamonds), Mount Isa-type (solid squares), and VHMS deposits (from North America). Data are from Wooden and DeWitt (1991), Sun et al. (1996), and Parr et al. (2004). Evolution curves are based on the AGSO-CSIRO lead evolution model (Sun et al., 1996). $\mu = {}^{238}U/^{204}Pb$ integrated to present.

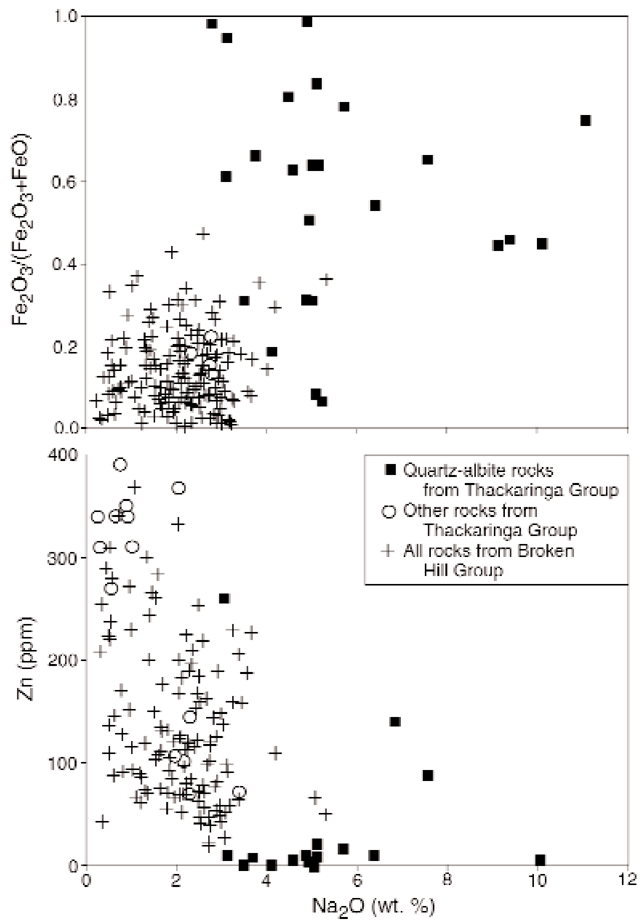

FIG. 12. Plots of Zn concentrations and $Fe_2O_3/(Fe_2O_3 + FeO)$ vs. Na_2O abundances, showing decreases in Zn concentrations and increases in $Fe_2O_3/(Fe_2O_3 + FeO)$ in quartz-albite rocks relative to other rocks in the Broken Hill district.

Regionally, many rock units in the Broken Hill region have elevated Zn and Pb concentrations relative to average crustal abundances. The only rocks with low base metals (<10 ppm Cu, Pb, and Zn) are albite-rich rocks in the Lady Brassey and Himalaya Formations (Huston et al., 1998: Fig. 12), making them a potential leached source rock for metals in the Broken Hill orebody. As these rocks also have high Fe_2O_3/FeO, they may be analogous to the high-temperature reaction and leaching zones observed in VHMS ore-forming systems. The model of Gibson and Nutman (2004) also highlights these rocks as potential source rocks.

In the Broken Hill block and nearby Olary block, calc-silicate rocks are known stratigraphically below the Broken Hill ore position (Willis et al., 1983; Page et al., 2000a). These units have been interpreted as a metamorphosed evaporite sequence (Cook and Ashley, 1992), which may have been a source of chloride for the Broken Hill system.

The site of metal deposition

Both major Broken Hill-type deposits in Australia consist of a series of stacked lenses with Ag, Sb, and F abundances increasing stratigraphically upward, and Au, Bi, and Cu abundances decreasing (Table 6; Johnson and Klingner, 1975; Walters and Bailey, 1998). These patterns are similar to those in VHMS deposits (Eldridge et al., 1983; Smith and Huston, 1992), so zone refining also may have been important in Broken Hill-type deposits.

Stacking of ore lenses suggests that Broken Hill and Cannington were the sites of long-lived and episodic hydrothermal vents. Major Broken Hill-type deposits probably formed either in a brine pool or by subsea-floor replacement (Fig. 7b-c; Stevens et al., 2004), both of which retain metal efficiently. A modern analogue for Broken Hill-type deposits may be the Atlantis II Deep in which metalliferous sediments are accumulating in a brine pool (Pottorf and Barnes, 1983).

Based on the relatively S poor nature of the ores, Large et al. (1996b) proposed that Broken Hill-type deposits formed when oxidized, H_2S-poor ore fluids exhaled into a reduced basin. However, the narrow range of $\delta^{34}S$ values is inconsistent with oxidized ore fluids. The S-poor character of the ores may relate to other processes, including metamorphism (see below).

The outflow zone

Broken Hill-type deposits are commonly associated with rock types, including quartz-gahnite rock, banded iron formation (BIF), and tourmalinite, which have been interpreted as exhalites (e.g., Plimer, 1984). These rocks are present throughout the Broken Hill Group and do not have a specific association with the ore horizon (e.g., BIF is present both stratigraphically above and below, but not at, the Broken Hill ore horizon). However, the BIF are characterized by elevated base metals proximal to lodes (Stanton, 1976).

In the Cannington region, the Pegmont deposit is associated with a finely laminated Fe-rich metasedimentary unit.

Studies by Vaughan and Stanton (1986) indicated that base metal and magnetite abundances in this unit increase toward ore, with garnet and Fe sulfides becoming more important laterally away from ore.

Postdepositional modifications

As with VHMS deposits, the presence of a local anoxic environment may have been required to prevent sea-floor oxidation of Broken Hill-type ores (Goodfellow et al., 1986). Moreover, high-grade metamorphism (amphibolite to granulite facies), metasomatism, and deformation have affected the morphology and architecture of Broken Hill-type deposits, coarsening the ores, converting original alteration assemblages to metamorphic mineral assemblages, partially melting ore minerals (i.e., to produce Pb-rich "droppers:" Lawrence, 1967; Mavrogenes et al., 2001), and remobilizing and upgrading ore into high-grade zones (e.g., Plimer, 1987; Bodon, 1998). Breakdown of pyrite to pyrrhotite and liquid sulfur above 743°C (Kullerud and Yoder, 1959) may account for the predominance of pyrrhotite over pyrite as the main Fe sulfide and the S-poor character of granulite-facies Broken Hill-type ores.

Mississippi Valley-Type Ore-Forming Systems

Mississippi Valley-type deposits are epigenetic but generally strata-bound deposits hosted mainly by marine carbonate successions in platform sequences overlying continental crust as in the intracratonic sag basins of North America (e.g., Viburnum Trend and the Old Lead Belt: Sangster, 1990; Leach et al., 2005) and in the intracratonic rifts of the Paleozoic Canning basin of Western Australia. These deposits are mostly found along the southern flanks of the Lennard shelf and the Broome platform adjacent to basinal sediments of the Fitzroy trough and Willara subbasin. The other principal deposits lie in time-equivalent rocks of the Bonaparte basin.

Although individual Mississippi Valley-type deposits worldwide tend to be small (generally <1 Mt Pb + Zn), some districts contain up to 10 Mt of metal (Sangster, 1990). In the Lennard shelf all deposits except one contain less than 1 Mt metal, with a total of 4.5 Mt of metal in the entire district (Tables 1–2). The Admiral Bay deposit on the southern flank of the Broome platform may have a total resource exceeding 10 Mt Pb + Zn (McCracken et al., 1996), but this is poorly constrained.

Figure 13 illustrates a system model for Mississippi Valley-type deposits based on the Canning basin. This model differs

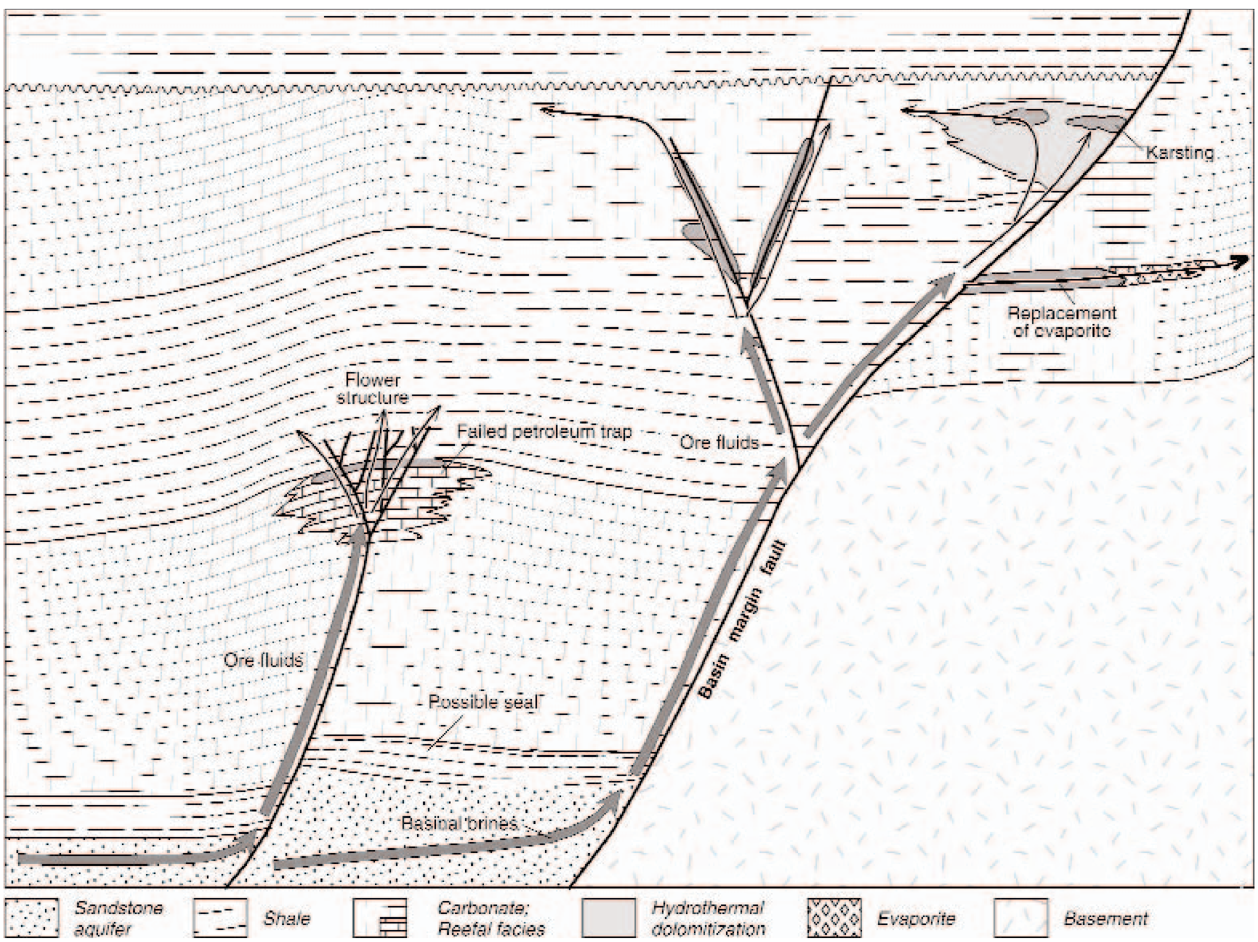

FIG. 13. Schematic illustration of the Mississippi Valley-type ore-forming system. Key illustrated components include the host basin (subbasin associated with synbasin faults), the heat source (normal geothermal gradient), the plumbing system (basin faults and aquifers), the nature of fluid flow (overpressuring of fluid source; other alternatives possible), the source of fluid components (basinal brines), the site of metal deposition (platform-margin carbonates near basinal faults), and the outflow zone (faults and aquifers).

from analogous systems in North America because of the importance placed on fluid migration along faults.

The basin

The links between Mississippi Valley-type mineralization and their source rocks are usually poorly defined, owing to the difficulty in determining the stratigraphic, structural, and timing relationships between host rocks in intracratonic settings far from the possible depocenters of the source rocks. This is further complicated by the presence of multiple basins and their long and complex geologic histories.

Deposits on the edge of basins that contain significant gray to white carbonate and mostly green to gray or black mudrocks with quartz sandstone (e.g., Canning and Bonaparte basins) show the closest links to possible source rocks. Iron in these basins is present mostly in pyrite. Evaporites deposited in a marine environment are also common, whereas red beds are subordinate and tend to be deposited in shallow, mostly marine environments fringing the basin. Hence the basin packages could be loosely classified as weakly reducing.

Wallace et al. (1991) linked the deposits of the Canning basin to the evolution of the adjoining depocenters. The Canning basin, which flanks the southwest edge of the Proterozoic Kimberley block, consists of three northwest-trending platforms separated by two subbasins (Fitzroy trough and Willara subbasin: Fig. 14: Kennard et al., 1994). The boundaries between the subbasins and platforms are marked by syndepositional normal faults. The subbasins are half grabens, with the thickest accumulations of sediments on northeast margins. These accumulations are controlled by extensional

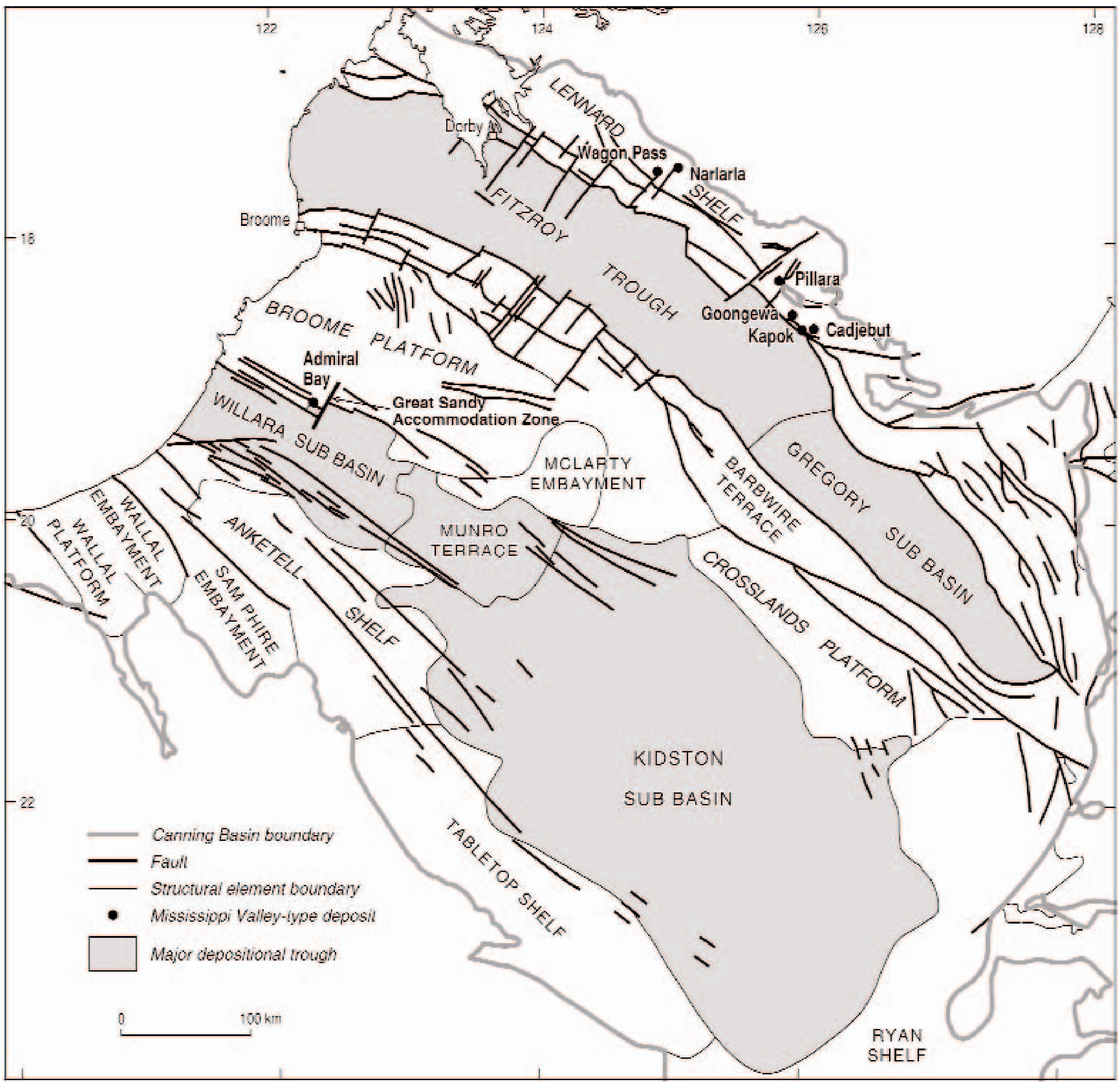

FIG. 14. Map of the Canning basin, showing the distribution of Mississippi Valley-type deposits in relationship to depocenters and important structural components (modified after Kennard et al., 1994).

faults (Drummond et al., 1991), which are offset by northeast-trending transfer zones. Spatial variations in Pb isotope systematics (Vaasjoki and Gulson, 1986) and in hydrocarbon biomarkers in fluid inclusions (Etminan and Hoffman, 1989) suggest that the transfer zones compartmentalized fluid flow (Dörling et al., 1996). The Mississippi Valley-type deposits of the Canning basin are localized on the edge of carbonate platforms along or near these basin-bounding faults or transfer zones (Fig. 14), which also controlled paleohighs adjacent to the deepest parts of the adjoining subbasins. The paleohighs lie on the upthrown leading edge of extensional tilt blocks of basement (Dörling et al., 1996).

Extension to form the Paleozoic Canning basin began at ~490 Ma, with sedimentation in three tectonically driven megasequence cycles. Rocks of the basal megasequence (490–410 Ma) are dominated by carbonates, mudstones, and lesser evaporites in areas of low accommodation rates (shelves and platforms: Kennard et al., 1994; Romine et al., 1994). In areas of high-accommodation rates (half-graben depocenters), shales and siltstones with variable carbonate and organic carbon contents dominate. The Admiral Bay deposit is hosted by the platform facies (McCracken et al., 1996) that forms part of the basal megasequence which was terminated by the 410 to 400 Ma Prices Creek compression.

Deposits on the Lennard shelf are hosted by the Pillara and Nullara Limestones in the second megasequence, which was deposited between 400 and 326 Ma and was terminated by the Meda transpression at 326 to 320 Ma. In areas of low-accommodation rates (Lennard shelf and Broome platform), carbonate deposition dominated this megasequence, but fine-grained turbiditic siliciclastic units, up to 6 km thick, dominated the high-accommodation Fitzroy trough (Kennard et al., 1994).

The Bonaparte basin (Fig. 1) comprises a major rift-sag sequence between the Kimberley and the Proterozoic Sturt blocks. The southern end laps onto the Proterozoic Halls Creek mobile zone, which provided a basement of major strike-slip fault zones that influenced local basin geometry. After an initial Cambrian-Ordovician intracratonic sag phase, which included deposition of evaporites, northwest-oriented rifting occurred in the Late Devonian-early Carboniferous followed by thermal subsidence in the late Carboniferous-Early Triassic (O'Brien et al., 1996). Most extension and sedimentation occurred offshore with up to 15,000 m of Cambrian to Cretaceous sediments in the Petrel subbasin to the north (Gunn and Ly, 1989). Only the southern tip of the basin lies onshore where carbonate and coarse clastic rocks of Late Devonian to early Carboniferous age (375–325 Ma) were deposited in continental, shelf, and reef environments (Mory and Beere, 1988) coeval with up to 3,000 m of fine-grained siliciclastic marine sediments in the adjoining Petrel subbasin. Carbonates of the shelf and reef complex (~350 Ma) lie on a paleohigh controlled by an arch in the basement, and they host the Sorby Hills Pb-Zn deposits (Lee and Rowley, 1990).

The Mississippi Valley-type deposits in the Canning and Bonaparte basins are up to 55 m.y. younger than their host rocks. On the Lennard shelf, Rb-Sr dating of sphalerite indicates an age of 357 ± 3 Ma (Christensen et al., 1995), 5 to 15 m.y. younger than the host rocks. The paragenetic relationship of base metal sulfides to diagenetic carbonate cements indicates that mineralization occurred during the first period of burial diagenesis, which corresponds to maximum subsidence during late extension prior to initial unroofing (McManus and Wallace, 1992). At the Admiral Bay deposit, McCracken et al. (1996) indicated an age for mineralization of 425 to 410 Ma based on the relationship of the sulfides to cement chronology. This age, which is 40 to 55 m.y. younger than the host carbonates, corresponds to the final stages of the main subsidence in the Willara subbasin, just prior to exhumation during the Prices Creek compression. Although the timing of mineralization in the Bonaparte basin is not precisely defined, it overlaps with saddle dolomite (Ringrose, 1989) indicating temperatures characteristic of deep burial. It appears to be coeval with development of a local basin edge unconformity during the maximum rate of rifting in the early Carboniferous (cf. Mory and Beere, 1988). This unconformity may have been a response to movement in the Halls Creek mobile zone (Mory and Beere, 1988). In all three areas in Australia where significant Mississippi Valley-type deposits are known, mineralization is tied to the advanced stages of rifting, just before a change in structural regime that reactivated basinal faults, opening structural and stratigraphic seals to allow fluid escape toward paleohighs near the basin edge.

The heat source

The formation of Mississippi Valley-type deposits is not associated with contemporaneous magmatism. Volcanism and plutonism are not known at ca. 410 to 355 Ma in the Canning or Bonaparte basins. Low-temperature Mississippi Valley-type ore fluids (80°–200°C: Etminan and Hoffman, 1989) could be produced by normal geothermal gradients during basin evolution (Garven et al., 1993).

The plumbing system

In the Canning basin, stratal architecture probably constrained horizontal fluid migration within depocenters followed by vertical fluid flow along both the subbasin-bounding normal faults and transfer zones onto the shelf areas, where fluid flow was concentrated in faults (Rasmussen et al., 1997). The largest deposits are concentrated in the eastern Lennard shelf where the major mineralized fault systems coincide with the major boundary between the shelf and the Fitzroy trough. In contrast, only minor deposits are known inboard of the shelf-trough boundary within the western Lennard shelf (Muhling, 1994). Deposits in the Lennard shelf are localized in or near these faults (Fig. 14: Dörling et al., 1996), and subeconomic base metal deposits also occur in these faults (Vearncombe et al., 1995), indicating that ore fluids passed along them. At the Pillara (Blendevale) deposit the ores are concentrated in fault and crackle breccias along two synthetic normal faults that form a small graben (Fig. 15a: Vearncombe et al., 1996). At Goongewa (Twelve Mile bore), the ore lenses are within dolomitized limestone in the hanging wall of the Cadjebut fault (Fig. 15b: Murphy, 1990; Bradley, 1994). Even the stratiform Cadjebut (Fig. 15c) orebody is located within 2 km of the Pinnacle fault, which forms the boundary between the Lennard shelf and Fitzroy trough (Fig. 14). The Kapok deposit is hosted within the Cadjebut fault, a major splay from the Pinnacles fault that passes close to the Cadjebut deposit, and Tompkins et al. (1997) indicated that this fault

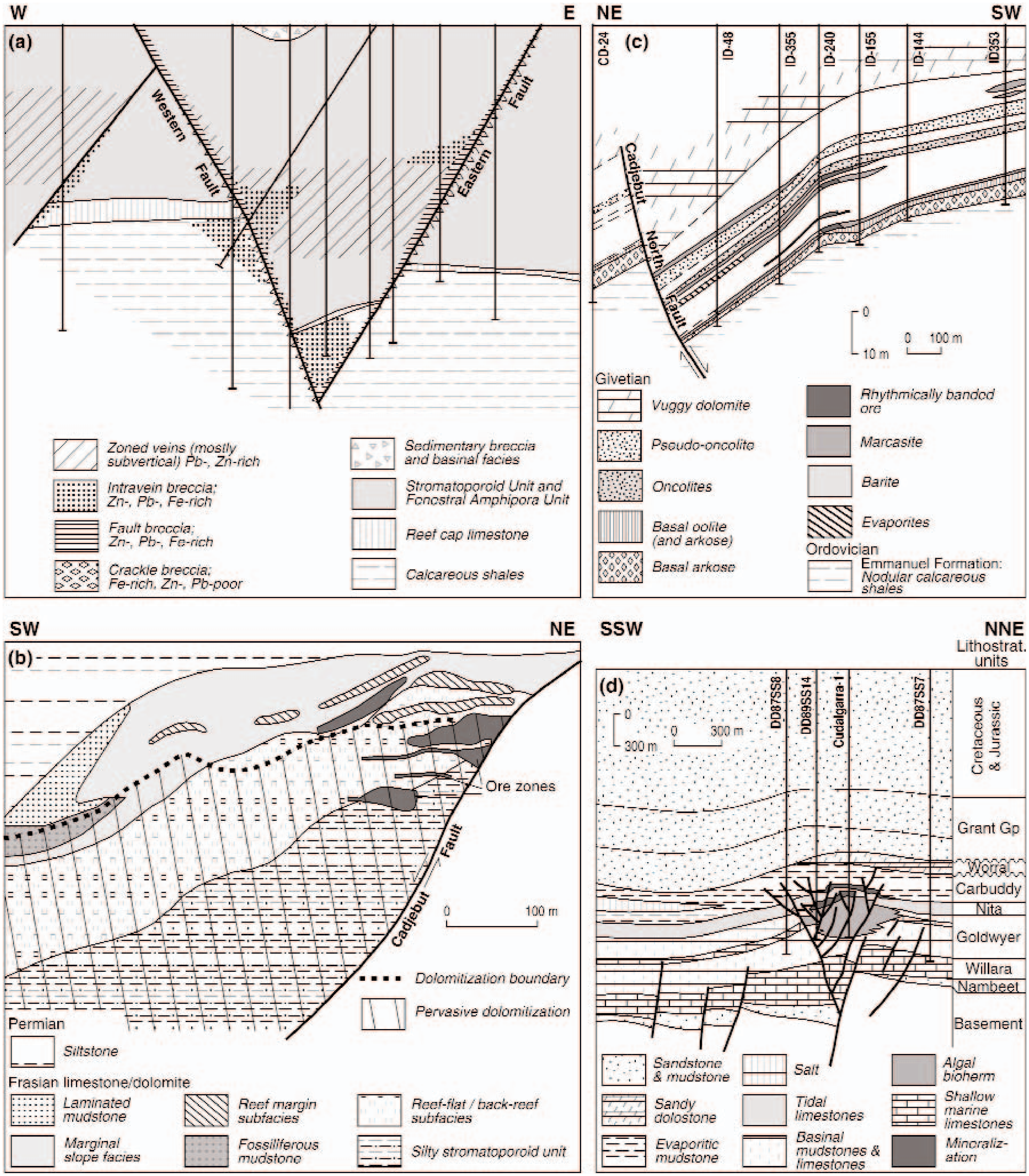

FIG. 15. Cross sections, showing the geology of Mississippi Valley-type deposits in the Canning basin: (a) Pillara (Blendevale) deposit (modified after Vearncombe et al., 1995), (b) Goongewa (Twelve Mile Bore) deposit (modified after Bradley, 1994), (c) Cadjebut deposit (modified after Tompkins et al., 1997), and (d) Admiral Bay deposit (modified after McCracken et al., 1996).

channeled ore fluids into the Cadjebut deposit. Structural and carbonate cement studies show that all of the economic deposits in the Lennard shelf formed during reactivation of synsedimentary basin rift faults and transfer zones.

A strong structural control on mineralization is also present at the Admiral Bay deposit. The mineralized lenses are localized about the Great Sandy accommodation zone, which is orthogonal to the main Admiral Bay fault, and separates the Broome platform from the Willara subbasin (Fig. 15d: McCracken et al., 1996). Changes in unit thickness confirm that the Admiral Bay fault and the accommodation zone were active during sedimentation and controlled the development of the algal bioherm upon which the Admiral Bay deposit is centered. The bioherm was also the focus for basin fluids that produced footwall alteration (quartz, siderite, gypsum, magnetite, hydrocarbons, fluorite, dolomite, and barite) in primary and fracture porosity (McCracken et al., 1996).

Although there is an association between Mississippi Valley-type deposits and syndepositonal structures in the Canning basin, timing constraints indicate that mineralization postdated deposition of the host rocks and was controlled by the reactivation of these faults. The Admiral Bay deposit is located where the Admiral Bay fault has been displaced by the Great Sandy accommodation zone (Fig. 14). This intersection produced a relay ramp which has controlled the geometry of permeable facies. The combination of the fault and the relay ramp has focused migrating basinal fluids. The accommodation zone offsets the Admiral Bay fault and leads back into the Willara subbasin where it lies on one edge of a major depocenter within the basin (Romine et al., 1994; McCracken et al., 1996). This position in the basin framework is analogous to that of the Pillara deposit, which also lies in an accommodation zone linked to a major depocenter, supporting the concept that ore fluids passed along faults from thick sediment packages in nearby depocenters (Dörling et al., 1998). The role of regional structures in controlling fluid flow distinguishes Mississippi Valley-type systems in the Canning basin from most others in the world. In other systems, stratigraphic aquifers, particularly basal sandstones, are inferred as fluid pathways (Sverjensky, 1984; Garven, 1995) and regional faults are not generally considered as fluid pathways. The mineralization in the Bonaparte basin also occurs close to faults, some of which are synsedimentary (Rowley and Lee, 1986), however there is little information on the role of regional faults or stratigraphy during mineralization.

Four mechanisms have been proposed as drivers of fluid flow in Mississippi Valley-type systems: (1) overpressuring caused by compaction of sediments (e.g., Sharp, 1978), (2) hydraulic forcing caused by tectonic uplift in a foreland basin (e.g., Garven and Freeze, 1984), (3) orogenic compression of the source basin (e.g., Oliver, 1986), and (4) gas expulsion (Eisenlohr et al., 1994). Vearncombe et al. (1996) reviewed alternative drivers for the Lennard shelf deposits and concluded that overpressuring caused by sediment compaction was the only viable mechanism. They argued that topographic relief and basin compression are not likely as the Alice Springs orogeny, the only local or regional orogenic event of similar age to mineralization, was centered over 1,500 km to the east-southeast and could not have driven fluid flow north from subbasins onto shelves in the Canning basin. Eisenlohr et al. (1994) suggested that a drop in sea level triggered gas expulsion that may have driven fluid flow, but the timing of this event postdates both mineralizing events in the Canning basin.

Overpressuring probably occurred during the Pillara extension (ca. 375 Ma), which caused major rifting, rapid subsidence, and sedimentation in the Fitzroy trough. This event would have depressed source sediments (including evaporites) into higher temperature regimes creating warm saline brines trapped under regional stratigraphic and structural seals. The age of mineralization determined by Christensen et al. (1995) for the Lennard shelf deposits corresponds to the ca. 354 Ma Red Bluff extensional event, which was developed along the southern margin of the Fitzroy trough (Kennard et al., 1994). Block tilting associated with this event could have breached regional seals and expelled basinal brines from the Fitzroy trough along reactivated faults onto the Lennard shelf. The formation of the Lennard shelf Mississippi Valley-type deposits most likely were triggered by relatively short-lived regional stress changes during a period of overall thermal subsidence.

The Admiral Bay deposit was formed during the last stages of thermal subsidence (McCracken et al., 1996) just prior to and overlapping the transpressional Prices Creek event, at 410 to 400 Ma. The change in regional stress regime opened the synsedimentary faults allowing the overpressured fluids to reach the trap site.

The source(s) of ore-fluid components

Fluid inclusion data from the Canning basin and Sorby Hills deposits indicate that, like worldwide Mississippi Valley-type deposits, the ore fluids were low-temperature (70°–110°C) and highly saline (5–25 wt % NaCl equiv: Etminan and Hoffman, 1989; Lee and Rowley, 1990; Dörling et al., 1998). Because of similarities in temperature and composition with oil field brines, it is now generally accepted that Mississippi Valley-type ore fluids are expelled basinal brines (cf. Anderson and Macqueen, 1987). Studies of diagenetic cement stratigraphy, Pb-Zn mineralization, and hydrocarbons in the Canning basin show that Pb-Zn mineralization was an integral part of the burial history of the carbonate host and development of the basin, entering the Lennard shelf contemporaneously with hydrocarbons (McManus and Wallace, 1992; Wallace et al., 2002).

Basinal brines form during diagenesis from seawater or evaporative brines buried with sediments. Seawater, evaporative brines, and dissolved halite provide the chloride for metal complexing (Hanor, 1996), and clastic basinal sediments provide Zn, Pb, Fe, and other ore metals. Hanor (1996) showed that in basinal brines Zn abundances increase with chlorinity, particularly above 10 to 20 percent, where Zn abundances rise exponentially from <1 to >>100 ppm.

Zinc concentrations decrease with increasing H_2S concentrations in basinal brines (Kharaka et al., 1987; Moldovanyi and Walter, 1992; Hanor, 1996). Therefore, it is likely that Mississippi Valley-type ore metals were derived from siliciclastic units (Hanor, 1994), rather than carbonate units as siliciclastic rocks contain much higher abundances of base metals than do carbonates (Table 7), and Fe in siliciclastic rocks fixes H_2S (Hanor, 1996). In brines derived from Fe-poor carbonates, H_2S concentrations can approach 1,000 ppm

TABLE 7. Abundances of Zn and Pb in Common Rock Types

Rock type	Zn (ppm)	Pb (ppm)
Gabbro-basalt	80–120 (100)	1.4–8.8 (3.2)
Diorite-andesite	40–100 (100)	3.5–12 (5.8)
Rhyolite	40–120 (100)	13–40 (24)
Graywacke	70–120	5–25 (10)
Quartzose sandstone	25-50	
Shale	70–200 (110)	18–28 (22)
Black shale	70–170	14–39 (24)
Limestone	3–31 (20)	1–9 (5)

Notes: Data from Wedepohl (1972a, b, 1974a, b); quoted ranges exclude outliers; numbers in brackets indicate average values

(Wade et al., 1989), which limits the solubilities of base metal, particularly at low temperature.

Although data for basinal brines suggest that Mississippi Valley-type ore fluids must have been H_2S poor, the amount of sulfate in the fluid does not affect Zn concentrations. Hanor (1996) suggested that Zn-rich brines can carry up to 250 ppm SO_4^{2-}. However, the common presence of barite in the Canning and Bonaparte basin deposits suggest that the mineralizing fluids must also have been sulfate poor as the very low solubility of barite precludes the transport of Ba and SO_4^{2-} in the same fluid. This suggests that in most deposits, sulfur was acquired at the depositional site, either from evaporites or a second fluid.

Unlike VHMS, Broken Hill- and even Mount Isa-type deposits, Mississippi Valley-type deposits in the Canning and Bonaparte basins, and many elsewhere in the world, are characterized by highly radiogenic Pb (Vaasjoki and Gulson, 1986; Dörling et al., 1996). Moreover, in the Lennard shelf, Pb isotope ratios vary systematically from southeast to northwest, with the northwestern deposits, which are smaller and located farther away from the margin of the Fitzroy trough (Vaasjoki and Gulson, 1986), characterized by more heterogeneous and radiogenic Pb (Dörling et al., 1996). Vaasjoki and Gulson (1986) interpreted that the less radiogenic Pb in the Pillara deposit was derived from feldspar-rich sediments in the Fitzroy trough produced by erosion of the Paleoproterozoic Kimberley block, whereas the more radiogenic Pb from the northwestern deposits was derived locally from the Proterozoic hinterland of the Kimberley. Alternatively, the highly radiogenic Pb in these latter deposits could have been derived from loosely held Pb in Paleozoic sediments.

Three major models have been developed to account for the movement of metals and sulfur in Mississippi Valley-type systems: (1) transport of metals and H_2S together in a basinal brine (Sverjensky, 1984); (2) transport of metals and sulfate together in a basinal brine (Anderson, 1975; Beales, 1975); and (3) transport of metals in a basinal brine with sulfur derived from sources at the site of deposition, either local rocks or a second fluid (Beales and Jackson, 1968). Data from the oil field brines (Hanor, 1996) and the presence of barite in the Australian Mississippi Valley-type ores are most consistent with the last model.

The site of metal deposition

In general, mineralization in the Canning and Bonaparte basins occurs in or close to splays from major basin faults that lead onto paleohighs, distinguished by thinning of sedimentary sequences onto underlying basinal sequences or crystalline basement. The host carbonate is commonly covered by an aquiclude of siltstone or shale and underlain by an impermeable layer. Both these features are present in other Mississippi Valley-type districts (e.g., Viburnum Trend: Hayes and Palmer, 1989).

At the orebody scale, Australian Mississippi Valley-type deposits occur in (hydrothermal) karsts (Goongewa: Bradley, 1994), by replacement of evaporative sulfate (Cadjebut: Tompkins et al., 1994), and in hydrothermal solution breccias in dilatant faults (Pillara: Vearncombe et al., 1996). The common feature to all depositional environments is open space. In general, the open space is located in a carbonate wedge between impermeable zones. Pillara lies in faulted carbonate enclosed between impermeable granite and basinal shale, the Cadjebut host is evaporite-dissolution breccia that overlies impermeable Emanuel Shale (Tompkins et al., 1994; Warren and Kempton, 1997), and the Goongewa hydrothermal karsts lie within an upward-converging wedge of slope-facies carbonate capped by a silty carbonate and faulted against impermeable shale in the footwall of the Cadjebut fault. The Admiral Bay deposit is concentrated in permeable bioclastic carbonates between silty horizons or in veins. The most important hosts for the Sorby Hills deposits are breccias on a local unconformity underlying a siltstone cap (Rowley and Lee, 1986).

Based on synmineralization stratigraphic reconstructions and on carbonate cement characteristics, Mississippi Valley-type deposits in the Canning basin and elsewhere are interpreted to have formed at depths of several hundred meters to 2 km (Anderson and Macqueen, 1987; McManus and Wallace, 1992; McCracken et al., 1996). Arne (1996) indicates that Cadjebut formed at peak burial temperatures for the host sequence, which is consistent with a depth of 1 to 2 km.

Many Mississippi Valley-type deposits are closely associated with organic matter in the host rocks or hydrocarbons in fluid inclusions (Anderson and Macqueen, 1987). Etminan and Hoffmann (1989) observed hydrocarbons in fluid inclusions in all deposits studied in the Canning basin. Variability in hydrocarbon contents, from 0 to 100 percent, suggests that the ores formed in the presence of immiscible aqueous brines and hydrocarbons. Analysis of steranes and hopanes in the inclusions indicates that hydrocarbons were too mature for their host units, that the hydrocarbons were not sourced from local oils, and that the hydrocarbon sources differed between deposits. From these data, Etminan and Hoffman (1989) concluded that hydrocarbons in Mississippi Valley-type deposits of the Canning basin were sourced deep in the basin. At the Admiral Bay deposit, bitumen was introduced paragenetically just prior to base metal sulfides (McCracken et al., 1996), and hydrocarbons are closely associated with paragenetically early sphalerite at the Cadjebut deposit (Tompkins et al., 1994). The presence of hydrocarbons and/or organic matter during mineralization in most, if not all, of the deposits suggests these materials may have been important for ore deposition.

Wallace et al. (2002) suggested that sulfate reduction occurred in association with migrated hydrocarbons to produce reservoirs with H_2S within the carbonates which then reacted with metalliferous brines. A similar model has been suggested for the Viburnum Trend deposits by Anderson (1991), who made the important suggestion that carbonate is essential as a host rock because it provides a nonoxidizing package which preserves the reducing properties of the hydrocarbons.

Hydrocarbons and/or organic matter may provide reduced sulfur directly to the ore system or act as a reductant facilitating sulfate reduction. Similarities in $\delta^{34}S$ of ore minerals and local oils led Kesler et al. (1994) to infer that these oils, which contain up to 1.8 percent sulfur, provided reduced sulfur in Mississippi Valley-type districts from central Kentucky and central Tennessee. However, the $\delta^{34}S$ values of these districts are much lower than in other Mississippi Valley-type districts in North America, and Kesler et al. (1994) inferred that the sulfide in the high $\delta^{34}S$ districts was produced by sulfate reduction. Limited data suggest that sulfides in Mississippi Valley-type deposits from the Canning basin are also characterized by relatively high $\delta^{34}S$ values. These values, which are only slightly lower than sulfate minerals in regional evaporites, led Tompkins et al. (1994) to conclude that the sulfur in the ores was produced by sulfate reduction.

At low temperatures, sulfate reduction can occur by biogenic sulfate reduction (BSR) or thermochemical sulfate reduction (TSR). As BSR only occurs at temperatures below 80°C (cf. Machel, 2001), below the likely temperature of Mississippi Valley-type ore fluids, it is not likely to have occurred at the site of metal deposition. Thermochemical sulfate reduction occurs at temperatures above 127°C (Machel, 2001), and therefore it is potentially a significant process at the site of ore deposition. It is a kinetically controlled process in which aqueous sulfate is reduced by reaction with reduced carbon or other reductants. Reaction rates increase with increasing temperature and decreasing pH, and the reaction may be catalyzed by a number of species, including H_2S and Mn^{2+} (Goldhaber and Orr, 1994; Machel, 2001), which may be present at the site of deposition. In the absence of catalytic H_2S, Goldhaber and Orr (1994) indicated that TSR is too slow at low temperatures to be geologically important.

Tompkins et al. (1994) and Warren and Kempton (1997) suggested that the stratiform, banded ores at the Cadjebut deposit formed by replacement of evaporites including sulfate minerals. Evidence cited includes evaporite dissolution breccias, halite molds (Warren and Kempton, 1997), calcite pseudomorphs after evaporite minerals, and structures in the ores similar to those in evaporites (Tompkins et al., 1994). Ringrose (1989) reported pseudomorphs of gypsum at the Wagon Pass prospect to the northwest. Tompkins et al. (1994) and Warren and Kempton (1997) documented regional evaporites at the stratigraphic position of the Cadjebut ore lenses and interpreted the ore textures and similarities in $\delta^{34}S$ of the ores and evaporites along strike to indicate that H_2S was provided by TSR of sulfates present in the evaporite horizon that the ores replaced. Similarly, McCracken et al. (1996) inferred that the Admiral Bay deposit formed where the ore fluids interacted with evaporitic sulfates in the host Cudalgara Member. However, many of the other deposits in the Canning basin are not associated with evaporative horizons, which suggest that a local evaporative source of sulfur is not essential for ore deposition. In these cases, it is likely that most or all of the ore sulfur was either provided by a second fluid or was carried as sulfate in the ore fluids. H_2S in a second fluid may have been produced prior to reaching the site of ore deposition (e.g., by BSR in distal reservoirs, as suggested by Goodfellow et al., 1993). Alternatively, sulfate in the ore fluid was reduced by thermal sulfate reduction where the ore fluid interacted with hydrocarbons either in failed traps or migrating along fault zones.

The outflow zone

Wall-rock alteration marking the outflow zones of Canning basin deposits occurs in rocks that vary from silty layers with evaporite dissolution breccias (e.g. Cadjebut: Tompkins et al., 1994), to grainstone units dolomitized during diagenesis and burial (Admiral Bay: McCracken et al., 1996), to reef flat (limestone) and back reef (silty dolomitised) units (Goongewa: Middleton and Wallace, 2003). The alteration halo at Cadjebut occurs within the same parts of the stratigraphic units that host the zones of mineralization, mimicking the banded style of the sulfides (Tompkins et al., 1994). The alteration halo is asymmetrical and zoned laterally with barite present adjacent to the ore zones and marcasite ± calcite assemblages more distal up to 450 m from the ore. Ferroan dolomite has been documented along mineralization-stage faults and a regional marcasite halo occurs in fractures and joints in the hanging wall to the Cadjebut deposit. Middleton and Wallace (2003) indicated that alteration assemblages were synchronous or postdated mineralization.

Alteration at Admiral Bay contrasts with that of other Mississippi Valley-type deposits (McCracken et al., 1996), comprising early, strata-bound siderite-hematite-jasper-magnetite-quartz overprinted by a later stage of ore-related barite-(saddle) dolomite-fluorite-calcite. The main assemblage that may define an outflow zone comprises laterally extensive hydrothermal (saddle) dolomite which has invaded carbonates between the lower Pb-rich zone and the upper Zn-rich zone. Dolomite extends farthest in the permeable grainstones but the precise extent is not known. This dolomite extends farthest laterally in the permeable grainstones but the precise extent is not known. It was emplaced during and after sulfide mineralization (McCracken et al 1996).

At the Pillara deposit, barite ± calcite occurs on top of the deposit at the contact with the impermeable Gogo Formation, and marcasite ± calcite occurs in a halo of fractures in limestone around the main mineralized fault zones (Ringrose, 1989). The outflow zone for Pillara thus may have been where the faults in the host carbonate reached the topographically highest zone, under a cap of impermeable Gogo Formation at the south end of the deposit; however, this contact has been removed by erosion. According to Ringrose (1989) the barite, calcite and marcasite were deposited during and after mineralization.

Mount Isa-Type Ore-Forming Systems

Paleo- to Mesoproterozoic basins of the North Australian craton contain five world-class Mount Isa-type deposits (Zn + Pb >7 Mt), making it the richest Zn-Pb mineral province in the world. Although, Mount Isa-type deposits are large, with a median size of 17 Mt Zn + Pb, they differ from similarly sized Broken Hill-type (and VHMS) deposits in the lack of proximal coeval volcanism, the presence of extensive carbonates in the time-equivalent basin fill, and the low abundances of Cu and, particularly, Au in the ores. However, the Mount Isa-type ore-forming system (Fig. 16) has a number of similarities with the Mississippi Valley-type ore-forming system.

The basin

Mount Isa-type deposits are hosted by pyritic and carbonaceous dolomitic siltstones in the uppermost of three ~1790 to 1575 Ma superbasins in northwestern Queensland and in the Northern Territory. Siliciclastic sedimentation, bimodal volcanism, and felsic magmatism dominate the lower two superbasins. Shallow-water platform and ramp carbonate rocks, deeper water and variably dolomitic siltstone and shale, and organic matter-rich shale dominate the upper superbasin (Jackson et al., 1987, 2000; Southgate et al., 2000a: Fig. 17).

Southgate et al. (2000b) suggested that the Mount Isa and Hilton-George Fisher deposits are located in the depocenter of the Isa superbasin. This superbasin, which was dominated by relatively deep water, laminated dolomitic siltstone facies during sedimentation, shallows to the west and north, changing to lithofacies dominated by quartzose sandy dolomite and sandstone. They concluded that the Isa depocenter formed as a dilational jog in a north-trending strike-slip structural regime. The HYC deposit is also hosted by dolomitic siltstone (Bull, 1998) within the deepest part of a small pull-apart basin associated with the Emu fault, which, during mineralization, was a sinistral strike-slip fault (Korsch et al., 2004). These observations suggest that Mount Isa-type deposits formed in subbasins or basins developed in dilational jogs or pull-aparts associated with major strike-slip faults.

These intracratonic, extensional basins are thought to have initiated and evolved in response to far-field tectonic events along the southern margin the North Australian craton. In detail, however, the local geometry of the subbasins that host the ore deposits are controlled by wrench tectonics (Southgate et al., 2000b). Although volcanic rocks are present at depth, their absence from the ore-hosting Isa superbasin suggests that Mount Isa-type systems were not driven by coeval magmatism.

The heat source

Fluid inclusion data (Muir et al., 1985; Rohrlach et al., 1996; Cooke et al., 1998; Polito et al., 2006a, b) suggested that the temperatures of ore fluids were low, between 70° and 240°C. Hydrological modeling of the McArthur basin (Garven et al., 2001) suggests that fluids with temperatures in excess of 110°C can be produced by a heat flow of 70 m W/m^2, which is typical for continental crust. If so, this suggests that ambient or slightly elevated heat flow is sufficient to form Mount Isa-type deposits and that a specific heat source, such as a granite intrusion, is not needed.

The plumbing system

At the HYC (Williams, 1978a) and Century (Broadbent et al., 1998) deposits, major synmineralization faults are thought to have channeled fluids into the ore environment. However, the sizes of Mount Isa-type deposits suggest that ore fluids drained deep reservoirs in the underlying basins. Hiatt et al. (2003) and Polito et al. (2006b, c) have shown that during deep burial unstable mineral grains present in proximal fluvial facies interact with basinal fluids to generate secondary porosity and fertile basinal brines. Determining flow paths of the ore fluids is difficult, as the fluids were probably in chemical equilibrium with, and buffered by, rocks within the host basins.

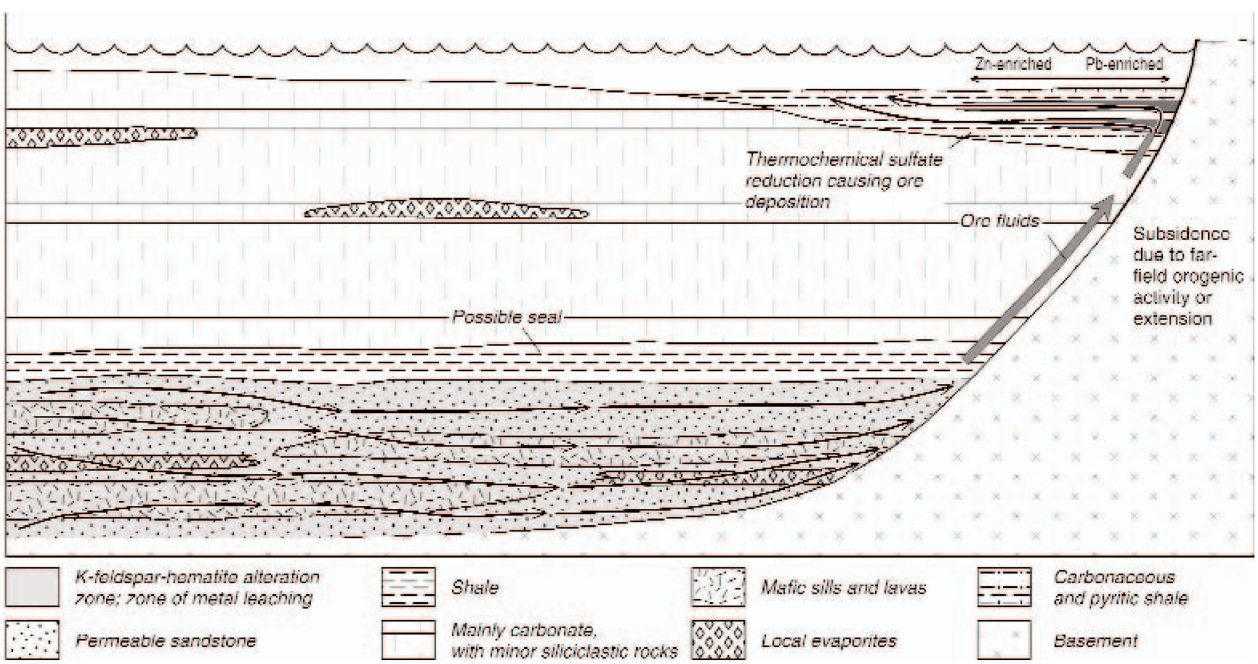

FIG. 16. Schematic illustration of the Mount Isa-type ore-forming system. Key illustrated components include the host basin (sedimentary basin), the heat source (normal geothermal gradient), the plumbing system (basin faults and aquifers), the nature of fluid flow (overpressuring of fluid source or convection triggered by tectonic disturbances), the source of fluid components (basinal brines), the site of metal deposition (diagenetic or epigenetic replacement of organic-rich, dolomitic siltstone deposited in the deepest part of the subbasin), and the outflow zone (overlying sedimentary pile).

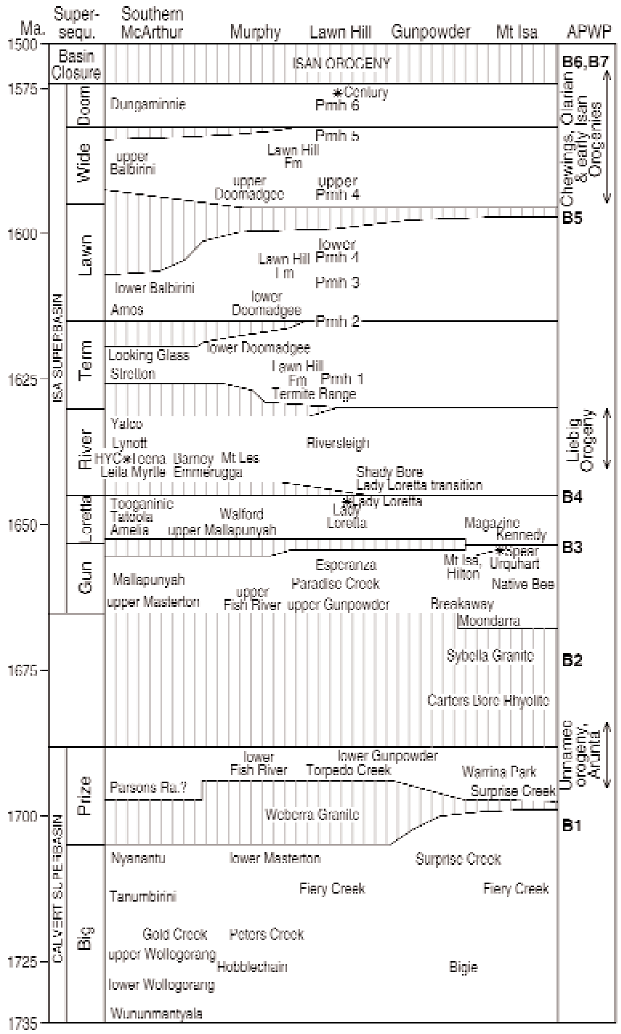

FIG. 17. Correlation between sequence stratigraphy, tectonic events, and mineralizing events in the North Australian craton. APWP = Australian polar wander path. Modified after Southgate et al. (2000a).

Because of their unusual chemical and mineralogical composition relative to the sedimentary rocks that make up most of the basins, volcanic rocks that may be present are more likely to be altered during the passage of the ore fluids. Cooke et al. (1998) documented widespread potassic metasomatism in dolerite from the Settlement Creek and Gold Greek Volcanics in the Mallapunya dome area (~50 km south of HYC). These units are located near the top of the Tawallah Group, which underlies the McArthur Group, host to the HYC deposit. Paleomagnetic data indicate that this alteration occurred at 1640 Ma (M. Idnurm *in* Cooke et al., 1998), coincident with the HYC deposit. Two mineral assemblages are present, the first characterized by orthoclase-quartz ± sericite ± hematite ± dolomite ± anatase ± barite. In addition to K enrichment, an important characteristic of this assemblage is very high Fe_2O_3/FeO. The second assemblage is characterized by chlorite-orthoclase-quartz but not by high Fe_2O_3/FeO (Cooke et al., 1998). Similar alteration assemblages affect the volcanic rocks in the Tawallah Ranges, the Scrutton Ranges, and the Bauhina Downs region (all west of HYC: Jackson et al., 1987; Pietsch et al., 1991; Haines et al., 1993), suggesting that this potassic alteration is regionally extensive. D. Rawlings (pers. commun., 2002) suggested that many of these zones are fault controlled, as indicated by hand-held γ-ray spectrometric data from the Mount Isa and McArthur regions. This alteration is the most obvious manifestation of regional fluid flow associated with Zn-Pb-Ag metallogenesis in the Batten trough. In the Mount Isa Western succession, the Fiery Creek and Peters Creek Volcanics also have been extensively altered by potassic alteration assemblages with high Fe_2O_3/FeO (Hutton and Wilson, 1984).

As noted above, hydrological modeling of the McArthur region (Garven et al., 2001) and the Lawn Hill platform (Yang et al., 2006) suggests that fluid flow responsible for the HYC and Century deposits could have been driven by normal heat flow. Yang et al. (2006) suggested that fluid flowed within sandstone/volcanic packages and along the Termite Range fault to the Century deposit. Similarly, Garven et al. (2001) modeled fluid flow down the Tawallah fault zone, along an aquifer at the top of the Tawallah Group (including the Settlement and Gold Creek Volcanics) and then up the Emu fault to form the HYC deposit. Both studies highlighted the importance of deeply penetrating faults in promoting fluid flow, although recent seismic studies (Korsch et al., 2004) indicate that the Tawallah fault is a thrust fault with a geometry different from that used by Garven et al. (2001).

Alternatively, the flow of basinal brines may have been driven by overpressuring of brine reservoirs and triggered by extension (Vearncombe et al., 1996) or other tectonic disturbances (e.g., Scott et al., 2000), analogous with models of fluid flow in Mississippi Valley-type systems. For the Century deposit, Zhang et al. (2006) modeled brine flow associated with structural inversion of the Isa superbasin at ~1570 Ma. Their modeling indicated that fluid flow would occur in major aquifers and up basin-scale faults. The released brine could have produced the observed alteration of volcanic rocks, either during its residence in the reservoir or during expulsion. In such a model, fluid flow would be localized by extensional faults.

Both the buoyancy- and tectonic-driven models focus fluid flow through sandstone-dominated aquifers. Polito et al. (2006a, b) suggested that in both the McArthur and Isa basins, ore-related fluid flow occurred during peak diagenesis within "dirty" sandstones, whereas clean, quartzose sandstones that had been cemented by silica during early diagenesis were aquicludes at this time. The Settlement and Gold Creek Volcanics, which show extensive orthoclase-hematite alteration and base metal depletion (see below), are interbedded with "dirty" sandstone (Polito et al., 2006b).

The source(s) of ore-fluid components

Characterization of the fluids that formed Mount Isa-type deposits has been difficult, partly because of the fine-grained nature of the ores. Indirect studies of satellite deposits (e.g., Muir et al., 1985; Rohrlach et al., 1996) suggested low temperatures between 70° and 180°C. More recent fluid inclusion studies of regional alteration zones and aquifers suggest a temperature range of 100° to 240°C (Cooke et al., 1998; Polito et al., 2006b) and salinities higher than 20 wt percent NaCl equiv. These results have been confirmed by studies at the Century deposit (Polito et al., 2006a), where a pressure-corrected temperature of 120° to 160°C and a salinity of 22 wt percent NaCl equiv are indicated. These results contrast with the temperature of 250° to 400°C suggested from the maturity of polycyclic aromatic hydrocarbons by Chen et al. (2003). The lower temperature is supported by the general lack of Cu in the ores.

Mount Isa-type ore fluids are generally thought to be basinal brines because the ores occur in major sedimentary basins that lack significant synore magmatism and because of the low temperatures of the ore fluids and analogies with Mississippi Valley-type ore-forming systems (e.g., Sangster, 1990; Rohrlach et al., 1996; Broadbent et al., 1998). The most likely source of sulfur and chloride are evaporitic units that are present through much of the McArthur basin and the Western succession of the Mount Isa inlier (Neudert and Russell, 1982; Jackson et al., 1987; Sami et al., 2000). Derivation of sulfur from evaporitic sources would suggest that the ore fluids carried the sulfur as sulfate (cf. Williams, 1978b; Cooke et al., 1998).

Lead isotope data indicate that Pb in the HYC, Century, Hilton-George Fisher, and Mount Isa deposits was derived from a homogeneous source (Fig. 11). Each deposit is characterized by tightly constrained isotopic ratios, and all four deposits plot on an evolution curve with a μ value ~12.9 (μ = $^{238}U/^{204}Pb$ integrated to present), which is significantly higher than that of Broken Hill-type deposits.

In the McArthur basin, Cooke et al. (1998) showed that orthoclase-quartz ± hematite–altered rocks from the Settlement Creek and Gold Creek Volcanics have lost Zn (110–230 ppm), Pb (37–78 ppm), and locally Cu (to 35 ppm). Although absolute mass losses cannot be calculated, both mafic and felsic rocks from potassically altered Fiery Creek Volcanics in the Western succession of the Mount Isa inlier also lost significant Zn and Pb (Hutton and Wilson, 1984). Although these volcanic units are relatively thin (commonly <100 m), they are laterally extensive, and evidence of metal leaching and alteration is widespread, making them good candidates for source rocks. Other potential, but untested source rocks, include the "dirty" sandstones, which Polito et al. (2006b, c) interpreted as aquifers for peak diagenetic hydrothermal fluid flow.

The site of metal deposition

Before 1960, Mount Isa-type deposits were interpreted as having formed by replacement of beds during deformation (Grondjis and Schouten, 1937). However, after the development of syngenetic models for Broken Hill-type and VHMS deposits, similar models were applied to Mount Isa-type deposits (e.g., Solomon, 1965; Lambert and Scott, 1973). Williams (1978a, b) suggested that the HYC deposit formed by diagenetic replacement just beneath the sea floor, and Broadbent et al. (1998) suggested that the Century deposit formed by replacement during the early stages of basin inversion. More recently other workers have revisited both syndeformational (Perkins, 1998) and syngenetic models (Large et al., 1998) for these deposits.

Table 8 summarizes observations considered by recent workers to indicate the timing of Zn-Pb-Ag mineralization in Mount Isa-type deposits. Evidence to support a syngenetic timing include the fine layering of the ores, particularly at HYC (e.g., Large et al., 1998), and the presence of ore clasts within intra-ore mass-flow units at HYC (Ireland et al., 2004a). Ore banding is a characteristic of all Mount Isa-type deposits; at the HYC and Century deposits, limited postore deformation has preserved these textures. Although age constraints at HYC are consistent with a syngenetic origin, timing constraints on the origin of the finely laminated Century ores suggest that they were emplaced well after deposition of the sediments. Broadbent et al. (1998) showed that, although stratiform at the local scale, overall the orebodies are transgressive. Moreover, Pb isotope model ages calculated using the AGSO-CSIRO model for north Australian basins (Sun et al., 1996) indicated an age of ca. 1567 Ma based on least radiogenic (i.e., oldest) analysis from Broadbent et al. (1998), which is 28 m.y. younger than the ~1595 Ma (Page et al., 2000b) age of the host unit of the ores. These constraints suggest that the fine laminations that characterize Mount Isa-type ores may not necessarily indicate a syngenetic origin. Hinman (1996) and Chen et al. (2003) proposed that HYC ores formed by styolitic replacement, a mechanism that would account for the preservation of finely laminated textures in Mount Isa-type ores. Ireland et al. (2004a) documented the presence of ore clasts within intra-ore mass-flow units and suggested that the ores were emplaced within 1 m of the sea floor. However, they also documented scouring by the mass-flow units of up to 4-m depth (their fig. 8), which suggests that the clasts could have been derived from several meters below the sea floor.

In order for saline brines to migrate laterally through unconsolidated muds just below the sea floor, a mechanism for such migration is required. Fisher et al. (2003) and Barnicoat et al. (2005) suggested that in semiconsolidated sediment, fault permeabilities decrease dramatically near surface. When upwardly migrating fluids encounter these zones of low permeability, they are forced to migrate laterally into the wall rock.

Textural evidence, indicating that the ore sulfides were deposited during or, mostly, after early pyrite and after the formation of nodular carbonate, has been cited to indicate a diagenetic and/or epigenetic origin of mineralization. Most workers (Williams, 1978a; Eldridge et al., 1993; Large et al., 1998; Ireland et al., 2004a) agreed on the relationship between pyrite and base metal sulfides, although there is disagreement as to the origin of the pyrite. Williams (1978a) and Eldridge et al. (1993) interpreted the textures and sulfur isotope characteristics of this pyrite to indicate a diagenetic origin and, therefore, a diagenetic timing for base metal introduction. Ireland et al. (2004b, fig. 11) show that this early pyrite paragenetically postdates nodular carbonate that displaces siltstone laminae. This timing relationship requires that the early pyrite was emplaced after deposition of the host sediments and not syngenetically. Thus, critical evidence in support of a diagenetic and/or epigenetic origin includes textures which indicate that base metal mineralization was synchronous with or postdated diagenetic pyrite and nodular dolomite (Williams, 1978a; Eldridge et al., 1993; Hinman, 1995, 1996; Chen et al., 2003; Ireland et al., 2004b), mineralized zones that transgress stratigraphy, and, in the case of the Century deposit, geochronological evidence that mineralization postdates the age of the host rock by ~30 m.y. We do not

TABLE 8. Observational and Theoretical Constraints on Genetic Models of Mount Isa-Type Deposits

	Syngenetic model	Diagenetic/epigenetic model
Observational constraints		
Ore lenses crosscut stratigraphy at Century (Broadbent et al.,, 1998)	Broadly crosscutting relationship of ores could be explained by movement of vent during the life of the ore-forming system	Broadly crosscutting ore lenses to stratigraphy most simply interpreted to indicate emplacement after sedimentation
Geochemical halos at HYC (Large et al., 2000)	Enrichment of Tl up to 200 m above ore zones could result from low-temperature fluid flow after main-stage mineralization	Thallium anomalies up to 200 m above ore zones indicate fluid flow well after deposition of ore-hosting sediments
Mass-balance limitations: alteration mass changes at HYC	Comparison of siltstone bands interlayered with ore laminates indicates insignificant loss of carbonate within ore zone (Irelend et al., 2004b)	Comparison with average, unmineralized Barney Creek Formation indicates significant carbonate dissolution within ore zones (Hinman, 2001)
Ore-bearing sedimentary breccias and sedimentary scouring at HYC (Ireland et al., 2004a)	Reworking of ore clasts into sedimentary breccias indicates mineralization occurred at or near sea floor	Scouring of sediments to a depth of 4 m could incorporate ore clasts formed in a shallow diagenetic environment into sedimentary breccias; this places maximum depth of mineralization
Lead isotope model age for mineralization at Century	Not consistent	Lead model age of ~1566 Ma (calculated from least radiogenic data of Broadbent et al. [1998] using AGSO-CSIRO model [Sun et al., 1996]) is ~30 m.y. younger than age of host sedimentary rocks (~1595 Ma: Page et al., 2000)
Laminated sulfide textures at HYC and Century (Broadbent et al., 1998; Large et al., 1998)	Finely laminated, ore-bearing sediments are consistent with deposition from water column	Laminated ores can be produced by replacement of sedimentary layering; Hinman (1996) suggested the ores are stylolaminated; laminated ores at the Century deposit are ~30 m.y. younger than their hosts
Timing of sphalerite and galena deposition at HYC (Williams, 1978a; Eldridge et al., 1993; Large et al., 1998)	Not consistent	Deposition of base metal sulfides after diagenetic pyrite indicates ore formation after sediment was deposited
Theoretical constraints		
Pyrite abundance in ores (W. Goodfellow, pers. commun., 2005)	Model consistent with high abundances of pyrite in ores	Preserved amount of organic matter insufficient to produce observed quantities of pyrite in some ores if pyrite formed diagenetically; however, high abundances of pyrite are also present several kms lateral from Mount Isa ore zones in Urquhart Shale, and the amount of organic matter presently in host rocks probably do not reflect total amount available during mineralization
Fluid behavior at trap site (W. Goodfellow, pers. commun., 2005)	Likelihood of brine reaching neutral buoyancy at seaf loor is low; neutral and then negative buoyancy may be achieved by double-diffusive splitting (cf. Turner and Gustafson, 1978)	Likelihood of brine reaching neutral buoyancy just below seaf loor is low; however, modeling by Fisher et al. (2003) suggests that the very upper portions of faults are highly impermeable, which would force fluid flow laterally into consolidating sediments

Notes: Observations and data that we consider not to constrain models include stable isotopes and the distribution of carbonate nodules (Eldridge et al., 1995; Chen et al., 2003; Ireland et al., 2004b).

consider that the advanced evidence supports a definitive syngenetic model and that the presence of ores which predate deformation. For example, Chapman, 2004, precludes a syntectonic timing. Mount Isa-type ores most likely formed at depths ranging from a few meters (Hinman, 1996) to a few kilometers (Polito et al., 2006a) below the surface.

The pyritic and/or pyrobitumen-bearing dolomitic siltstones and shales that host Mount Isa-type deposits (Broadbent et al., 1998; Painter et al., 1999) are now considered to represent the deepest parts of sedimentary basins (Large et al., 1998; Southgate et al., 2000a), although earlier workers (Williams and Logan, 1981; Neudert and Russell, 1982) inferred a shallower, locally emergent environment. A euxinic environment for the deposition of these fine-grained rocks is required for the deposition of base metals from oxidized, H_2S-poor ore fluids.

As in Mississippi Valley-type systems, low-temperature fluids responsible for Mount Isa-type deposits can only transport significant metals if they are H_2S poor and saline, and a source of H_2S at the site of ore deposition is required to precipitate base metals. The H_2S can be from reduction of sulfate carried by the ore fluid or H_2S already at the depositional site, either in the rocks or in a second fluid. Although most evidence suggests that fluids responsible for Mount Isa-type deposits lacked H_2S (cf. Cooke et al., 2000), small amounts of H_2S at the depositional site can catalyze TSR. Sources of catalytic H_2S include H_2S in reduced pore fluids in shallow diagenetic environments (e.g., HYC) and sour gas in deeper environments (e.g., Century). In shallow environments, BSR may have contributed catalytic H_2S. Alternatively, Mn^{2+}, which is highly enriched in shales underlying the HYC deposit (Large et al., 2000), may have catalyzed thermal sulfate reduction. Logan et al. (2001) argued that biogenic and thermal sulfate reduction may have been important at different parts of the brine pathway.

Diagenetic pyrite also may have been a source of reduced sulfur. All Mount Isa-type deposits are characterized by variable $\delta^{34}S$ (Broadbent et al., 1998; Painter et al., 1999), with the HYC deposit having a range in excess of 50 per mil (Smith and Croxford, 1973; Eldridge et al., 1993). In contrast, at HYC sphalerite and galena have a $\delta^{34}S$ range of only –5 to +8 per mil, leading Eldridge et al. (1993) to conclude that base metal sulfides did not acquire sulfur from earlier pyrite. Broadbent et al. (1998) indicated that pyrite was cogenetic with base metal sulfides and, therefore, could not have been a source of sulfur for ore sulfides. Painter et al. (1999) suggested that early-formed pyrite and base metal sulfides at Mount Isa have a similar sulfur source, which they interpreted to be marine sulfate reduced by theremal sulfate reduction. Both at HYC and Century, $\delta^{34}S$ of base metal sulfides are 5 to 25 per mil lower than those of evaporitic sulfates in the McArthur basin (Muir et al., 1985; Eldridge et al., 1993; Broadbent et al., 1998). This fractionation is consistent with that expected from open-system theremal sulfate reduction (cf. Williams, 1978b; Broadbent et al., 1998). Pyrobitumen is present throughout the paragenesis of the Century deposit (Broadbent et al., 1998), and Machel (2001) noted that high-temperature bitumens are common products of theremal sulfate reduction. Therefore, it seems likely that theremal sulfate reduction probably produced H_2S for base metal deposition from sulfate in the ore fluids.

If thermal sulfate reduction of hydrothermal sulfate was the main source of H_2S, a large amount of reductant was needed at the site of ore deposition. Based on a broad correlation between Zn and S (Croxford and Jephcott, 1972), the HYC deposit contains about 28 Mt of sulfur, of which more than 8 Mt occurs in base metal sulfides. To reduce enough sulfate to form the base metal sulfides, at least 3 Mt of organic carbon would be required, assuming the sulfate reduction is caused by oxidation of carbon from the -4 to the +4 valence state. It is difficult to envisage this amount of carbon being available in the water column, particularly in a restricted brine pool as suggested by Large et al. (1998). This amount of carbon would be readily available in an organic-rich mud and/or siltstone. These calculations illustrate the importance of a large reservoir of organic carbon at the trap site.

The outflow zone

Outflow zones associated with Mount Isa-type deposits are extensive. Lambert and Scott (1973), Smith (1973), and Large et al. (2000) have shown that the HYC deposit is characterized by halos of Zn, Pb, Cu, Ag, Tl, Hg, and Mn enrichment, with anomalous Zn, Pb, and Tl observed 15 km and Mn-rich carbonates present 23 km laterally from the deposit. Anomalous Tl extends 200 m above and 100 m below the ore lenses. Large et al. (2000) interpreted the anomalies lateral as “leakage” of metals from a brine pool into the overlying water column with deposition into laterally equivalent sediments. The Mn in carbonate is interpreted as the result of interaction of the ore brines with the underlying muds. Alternatively, the base metal enrichment could result from either lateral fluid flow (e.g., in a diagenetic model: Williams, 1978a, b) or mark the position of a condensed section and sediment starvation. Thallium anomalies in overlying sediments suggest that expulsion of fluid continued well after deposition of the ore hosts.

Comparison with Global Ore-Forming Systems

Although Australian VHMS and Mississippi Valley-type deposits are broadly similar to these types of deposits around the world, Broken Hill- and Mount Isa-type deposits are largely an Australian phenomenon. Broken Hill-type deposits are known in southern Africa and Scandinavia, but recognized Mount Isa-type deposits are restricted to Proterozoic basins of northern Australia. Traditionally both Broken Hill- and Mount Isa-type deposits have been grouped as SEDEX deposits (Leach et al., 2005).

Analogues to Broken Hill-type deposits are present in the Aggeneys district, South Africa, and Bergslagen district, Sweden (Walters, 1996), both of which are hosted by siliciclastic-dominated basins that have undergone high-grade (amphibolite to granulite facies) metamorphism. Possible, although controversial, low-metamorphic grade analogues of Broken Hill-type deposits are the SEDEX deposits of western Canada, including those in the Selwyn basin and the Sullivan deposit. The host basins to these deposits are dominated by siliciclastic rocks and lack carbonates, and the basin hosting the Sullivan deposit is intruded by syn-ore tholeiitic sills and dikes (Turner et al., 1996). Anderson and Goodfellow (2000) inferred an ensialic rift setting for this basin. Aside from metamorphic grade, the main difference between Australian Broken Hill-type deposits and western Canadian SEDEX deposits is the abundance and type of Fe-S minerals. This difference may reflect the high grade of metamorphism, which stabilizes S-poor Fe-bearing minerals such as pyrrhotite and magnetite over S-rich pyrite.

In the Bergslagen district, Broken Hill-type deposits coexist with VHMS deposits (Walters, 1996), raising the possibility that these two classes are part (end members) of a continuum. In the Iberian Pyrite Belt, VHMS deposits are hosted by an ensialic rift dominated by siliciclastic rocks with subordinate volcanic rocks (Tornos, 2006), a setting that is similar to that inferred for Broken Hill-type deposits.

Until recently, direct analogues to Mount Isa-type deposits outside of northern Australia have not been identified (cf. Cooke et al., 2000). However, the geologic setting and genetic model for deposits in the 320 Ma (Werdon et al., 2004) Red Dog district of Alaska are similar to those of Mount Isa-type deposits. These deposits, which are hosted by black shale and carbonate turbidites of the Middle Devonian-early Carboniferous Kuna basin, formed below the sea floor when H_2S, produced by BSR, was incorporated into relatively saline (14–19 wt % NaCl equiv), oxidized, and low-temperature (110°–180°C) ore fluids (Leach et al., 2004) to cause sulfide deposition (Kelley et al., 2004). This model is very similar to our favored model for Mount Isa-type deposits, suggesting that these deposits are not unique to Australia or Proterozoic basins.

Some Australian Zn-Pb-Ag mineralizing events do not correspond to global events (Fig. 3). The 2.65 to 2.75 and 1.80 to 1.90 Ga VHMS events of North America and Scandinavia are represented in Australia by small deposits in the Eastern Goldfields province and by small deposits in the Halls Creek, Pine Creek, and Arunta regions. In contrast, mineralizing events that correlate with the time of the 1.57 to 1.69 Ga Mount Isa- and Broken Hill-type events are not as strongly developed elsewhere. Rather, events that produced these types of deposits were best developed at ~1.45 and 0.3 to 0.5 Ga. The latter was also a period of extensive global Mississippi Valley-type and VHMS mineralization, which is represented in Australia by VHMS deposits of the Tasmanides and Mississippi Valley-type deposits in the Canning basin.

Relationships between Australian Zn-Pb-Ag Ore-Forming Systems

Comparison of the four major Australian ore-forming systems suggests that they can be grouped into two "clans," particularly when the tectonic setting and make-up of the host basins are compared. The first clan, which includes the VHMS and Broken Hill-type systems, occurs in active rifts with significant volcanism and magmatism. The second clan, which includes Mississippi Valley- and Mount Isa-type systems, occurs in cratonic extensional settings that lack significant coeval volcanism and magmatism. Basins that host VHMS and Broken Hill-type systems, which are dominated by volcanic rocks and clastic sedimentary rocks, contain minor, if any, carbonate, whereas basins that host Mississippi Valley- and Mount Isa-type systems contain abundant carbonate and siliciclastic rocks. These characteristics and others (Table 9) can be used to predict the likely type of ore-forming systems that can be found in a basin.

Effect of basin characteristics on ore fluids and water-rock reactions

In the VHMS and Broken Hill-type clan, ore fluids are moderate to high temperature (>200°C) and H_2S rich, whereas in the Mississippi Valley- and Mount Isa-type clan, ore fluids are low temperature (<200°C) and H_2S poor. In the latter clan, S, if present in the ore fluids, is carried as sulfate. These differences relate to the tectonic setting and composition of the host basin.

In submarine rift environments heat is lost to the hydrosphere by convective hydrothermal circulation of seawater. In the VHMS ore-forming system, the molar Na/K ratio of the evolving ore fluid decreases from 46 in seawater to between eight and 21 in high-temperature, venting black smoker fluids (data from de Ronde, 1995). Figure 18a shows that as the seawater begins to convect, low-temperature fluid-rock interaction converts albite (and other plagioclase feldspar) to K-feldspar, thereby increasing the Na/K ratio of the fluid. Together with increasing temperature, this stabilizes albite over K-feldspar in high-temperature (>250°–300°C) alteration zones (Fig. 18a). Thus, albitic zones present at depth in VHMS and Broken Hill-type systems are a consequence of high-temperature thermal convection in a rifted environment. K-feldspar-rich zones near the top of VHMS-bearing volcanic piles indicate the lower temperature parts of the convective cell.

Because of the high abundance of mafic volcanic rocks and derived turbidites in rift environments, the concentrations of Fe^{2+} in the system are high. At high temperature this iron reduces sulfate in the evolving fluid to H_2S but, as a consequence, is itself oxidized. This reaction and albitization break down mineral phases that host Zn and Pb, depleting the rocks in these and other metals and releasing them into the ore fluids. The three processes produce the regional Zn-Pb–depleted, albite-hematite and/or magneite ± epidote assemblages commonly observed in VHMS and Broken Hill-type systems.

In contrast, the lack of coeval magmatism and lower heat flows in basins hosting Mississippi Valley- and Mount Isa-type ore-forming systems produce low-temperature (70°–180°C) fluids. Goodfellow et al. (1993) and Leach et al. (2005) suggested that Mississippi Valley- and Mount Isa-type deposits formed preferentially in low paleolatitude basins, which allow the formation of high-salinity brines through evaporation. At these temperatures and in fluids with Na/K ratios characteristic of Mississippi Valley-type ore fluids (Sawkins, 1968), orthoclase is the stable feldspar (Fig. 18a). The presence of abundant carbonate rocks and the lack of mafic volcanic rocks and derived sediments suggest that basins have limited supplies of Fe^{2+}, thereby limiting sulfate reduction. However, where significant Fe^{2+} is present in volcanic rocks, these rocks are oxidized and metals stripped, producing the Zn-Pb–depleted, orthoclase-hematite assemblages in volcanic units that may be indicative of Mount Isa-type systems.

Chemistry of the ore fluids and the trap site

As a consequence of the differences in the compositions of the ore fluids, the sites of metal deposition differ between ore-forming systems. Figure 18b shows Zn solubility as a function of temperature and $\Sigma_{SO_4}/\Sigma_{H_2S}$. In this diagram pH, salinity, and $m_{\Sigma S}$ are constant. Although these parameters vary, their effect on Zn solubility is less than the effect of variable temperature or $\Sigma_{SO_4}/\Sigma_{H_2S}$.

Roedder (1968) suggested that to form a significant deposit, an ore fluid must contain 1 to 10 ppm Zn. Measurements of natural hydrothermal fluids extend the upper limit to 100 ppm (e.g., de Ronde, 1995). Using a range of 1 to 100 ppm to define a "solubility window" (Fig. 18b), Zn ore fluids can form under two conditions. At low temperature (T <200°C), such fluids have to be H_2S poor (i.e., high $\Sigma_{SO_4}/\Sigma_{H_2S}$). If the fluids are H_2S rich, temperatures above 200°C are required to form ore fluids. This latter fluid is similar to that formed in active rift environments as part of VHMS and Broken Hill-type systems, whereas the former is similar to the ore fluids present in Mississippi Valley- and Mount Isa-type ore-forming systems.

Evidence from ancient VHMS and modern black smoker deposits suggests that metal deposition in these, and probably Broken Hill-type, deposits was caused by rapid cooling of the ore fluids. Mixing with seawater is an effective way of cooling ore fluids, so VHMS and Broken Hill-type deposits form at, or just below the sea floor, leading to the stratiform character and strong stratigraphic control on these deposits. In contrast,

TABLE 9. Summary Characteristics of Zn-Pb-Ag Ore-Forming Systems in Australia

Ore-forming system	VHMS	Broken Hill-type	Mississippi Valley-type	Mount Isa-type
Tectonic setting	*Ensialic* rifts; back-arc rifts; ophiolites	*Ensialic rifts*	Margins of sedimentary basins	Extensional sedimentary basins
Boundaries	Determined by free convection, rift walls, synvolcanic faults	Rift walls (?)	(Sub)basin-bounding faults; unconformities with basement	(Sub)basin-bounding faults; unconformities with basement
Size	To 10 km horizontally, 2–3 km vertically	To 20 km horizontally, 2–3 km vertically.	Possibly hundreds of kilometers	Up to several tens of kilometers horizontally
Composition	Mainly volcanic and siliciclastic rocks *rich in* Fe^{2+}*; ores are usually associated with felsic volcanic rocks*	Mainly siliciclastics with *subordinate felsic volcanic rocks; basin is rich in* Fe^{2+}	Mixed carbonate and siliciclastic rocks	Dominantly carbonates in upper, ore-hosting stratigraphy; *siliciclastic and volcanic rocks in lower stratigraphy*
Heat source	Subvolcanic intrusions at depth of 1.5–3 km	High heat flow as indicated by *extensive mafic intrusions*	Normal geothermal gradients	Geothermal gradient possibly *enhanced by crust with high heat production*
Plumbing system				
Driver	Subvolcanic intrusion	High heat flow associated with rifting	*Basin dewatering driven by overpressuring and local tectonic events*	*Basin dewatering driven by far-field tectonic events*
Structural controls	*Synvolcanic faults*	Synsedimentary faults, as indicated by *sedimentary facies changes*	Basin-bounding and related faults; *possible intersection with transfer zones*	Basin-bounding and related faults; *possible association with wrench subbasins*
Aquifers	Not important	Specific units may not be important	*Siliciclastic units at base of stratigraphy*	*Dirty sandstone at base of stratigraphy*
Aquicludes and seals	Not important	*Possibly important to focus fluids in albitic reaction zone*	*Required to move fluids from source region to focusing faults*	*Required to transport and focus fluids in reaction zone*
Regional alteration	*Semiconformable albite ± epidote ± hematite zone at base of volcanic pile*	*Semiconformable albitites stratigraphically below ore position*	Unknown	*K-feldspar-hematite zones in volcanic and siliciclastic rocks at base of basin*
Deposit-scale alteration	Crosscutting	Crosscutting feldspar-destructive garnet-quartz zones	Minor dolomitization	Not extensive
Source(s) of ore-fluid components				
Ore-fluid characteristics	Reduced, H_2S-rich, moderate-high T (200°–350°C), moderate salinity (3–7% NaCl)	Reduced, H_2S-rich, moderate T (200°–300°C), variable salinity (3–25% NaCl)	Oxidized, H_2S-poor, low-T (70°–130°C), variable (high) salinity (5–25% NaCl)	Oxidized, H_2S-poor, low-T (100°–240°C), variable (high) salinity (15-25% NaCl)
Water	Seawater, possible magmatic contribution	Seawater, basinal brines	Basinal brines	Basinal brines
Chloride	Seawater, possible magmatic contribution	Seawater, basinal brines, evaporates	Basinal brines, evaporates	Basinal brines, evaporites
Sulfur	Seawater, leached from volcanic pile	Seawater, leached volcanic rocks	Basinal brines, evaporates	Basinal brines, evaporites
Metals	*Leached from volcanic pile*, possible magmatic contribution	*Leached from sedimentary pile*	Leached from basin depocenter, only loosely held metals may be leached	*Leached from volcanic and feldspathic units near base of basin stratigraphy*
Site of metal deposition				
Environment	At or just below sea-floor position, *commonly during quiescent sedimentation*	At or just below sea floor	*Within open space (faults, karsts, primary porosity) or replacing evaporate; possibly in degraded oil or gas traps*	*Carbonaceous, pyritic, carbonate-bearing siltstone and shale in depocenters of subbasins*
Fluid-focusing mechanisms	*Synvolcanic faults or changes in volcanic facies*	*Synsedimentary faults or changes in sedimentary facies*	*Extensional faults and transfer zones, or intersections of both (Canning basin)*	*Regional faults: extensional or wrench*
Depositional mechanisms	Quenching of fluids caused by mixing with seawater	Quenching of fluids caused by mixing with seawater	Thermochemical sulfate reduction by *remnant hydrocarbons* catalyzed by H_2S	Thermochemical sulfate reduction by organic matter catalyzed by H_2S
Factors favoring efficient trapping	*Fluid mixing below surface to form subsea-floor replacement* or brine pools	*Fluid mixing below surface to form subsea-floor replacement or brine pools*	Efficient focusing into depositional site (e.g., flower structures, aquicludes)	Deposition below sea floor in highly reactive sediment; aquicludes

Notes: Italics indicate characteristics that are critical in forming or localizing deposits or can be used to identify ore-forming systems

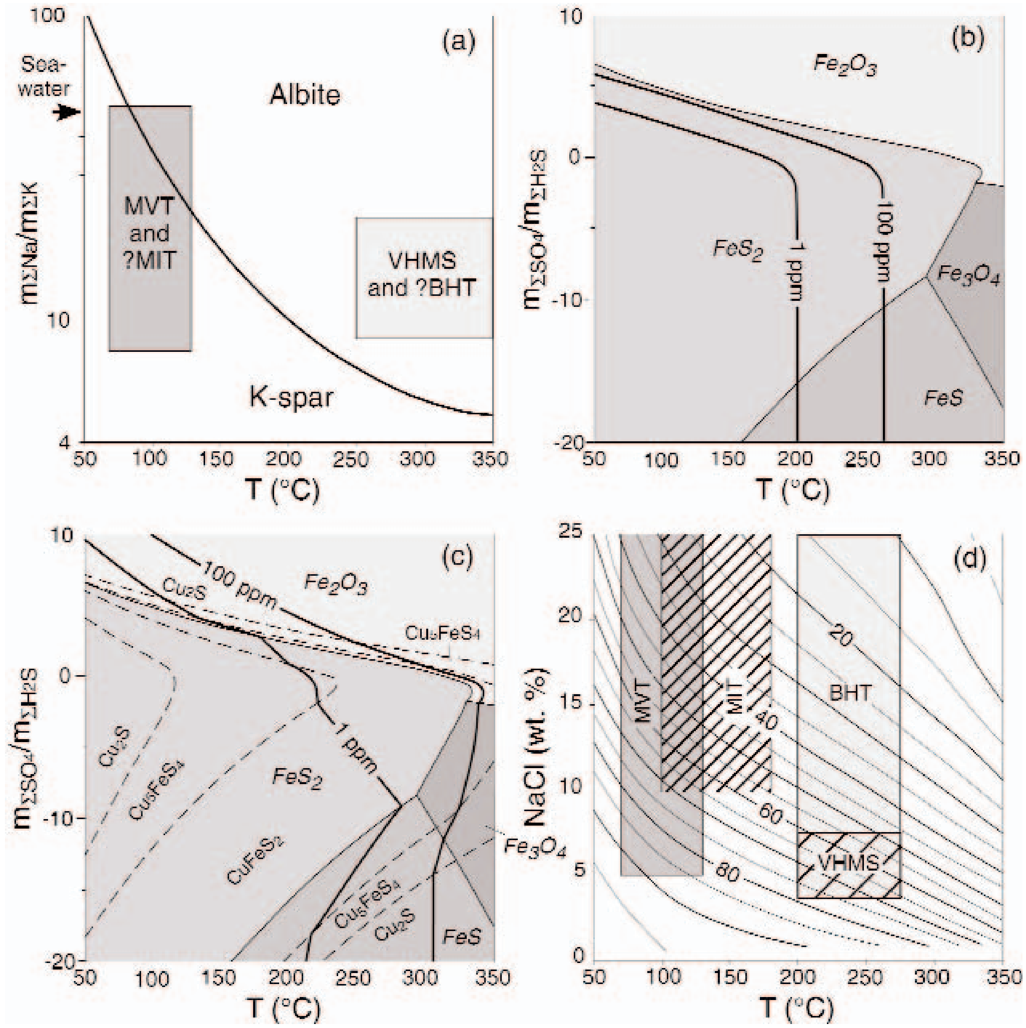

FIG. 18. Diagrams illustrating key aspects of ore-fluid geochemistry in Zn-Pb-Ag ore-forming systems. (a). m_{Na}/m_K-temperature diagram comparing the stabilities of albite and K-feldspar with the characteristics of high temperature (>300°C) black smoker fluids (data from de Ronde, 1995) and Mississippi Valley-type ore fluids (data from Sawkins, 1968). (b). $\Sigma_{SO_4}/\Sigma_{H_2S}$ -temperature diagram showing the solubility of Zn. (c) $\Sigma_{SO_4}/\Sigma_{H_2S}$ -temperature diagram showing the solubility of Cu. (d) Salinity-temperature diagram showing the variability of the Zn ratio (100Zn/[Zn + Pb]). Calculations to construct these diagrams were done using HCh (Shvarov and Bastrakov, 1999) and a database of thermochemical data provided by E. Bastrakov. Diagram (a) was calculated for a solution with $m_{\Sigma Cl}$ = 1.90, which for a pure NaCl solution corresponds to 10 percent NaCl. Diagrams (b) and (c) were calculated at pH = 4.5, $m_{\Sigma S} = 10^{-2.5}$ and 10 wt percent NaCl and assume chloride complexing. The likely concentrations of Zn and Cu in ore-forming fluids are bound by the 1 and 100 ppm contours. Dashed lines in (c) are stability field boundaries for Cu-Fe-S minerals. The arrow in diagram (d) indicates possible fluid evolution in time and space for the Mississippi Valley-type ore-forming system (see text).

metal deposition from low-temperature, H_2S-poor brines requires a supply of H_2S. The various ways in which H_2S can be supplied is the main reason for the range of depositional environments in the Mississippi Valley- and Mount Isa-type clan. Mississippi Valley- and Mount Isa-type deposits formed in sulfate-rich evaporites, along faults, in karsts or in organic matter-rich (dolomitic) siltstone. Metal deposition was mainly, if not entirely, diagenetic and epigenetic, with the depth of mineralization varying from a few meters to perhaps 2 km. Despite the range in depositional settings, the presence of hydrocarbons or organic matter which facilitated thermal sulfate reduction or, in some cases, directly provided H_2S is a common feature of these systems. A direct link to petroleum systems is indicated for some deposits (e.g., Etminan and Hoffman, 1989).

The effect of ore-fluid composition on minor metals

Although deposits discussed herein are largely mined for Zn, Pb, and Ag, Broken Hill-type and, particularly, VHMS deposits also produce by- and co-product Au and Cu. Although some Mississippi Valley- and Mount Isa-type deposits contain low levels of Cu, they invariably lack Au (Table 1). Like Zn, the abundances of these metals depend on ore-fluid characteristics, which are ultimately determined by the tectonic setting and composition of the host basin.

Figure 18c shows Cu solubility as a function of temperature and $\Sigma_{SO_4}/\Sigma_{H_2S}$ for the same conditions as shown in Figure 18b. For a solubility window of 1 to 100 ppm, two types of fluids carry enough Cu to form ore. At low to moderate temperatures (<250°C), the ore fluids must be H_2S poor but cannot be in equilibrium with pyrite. If pyrite is stable along the fluid pathways, Cu solubility is suppressed and this is the main reason for the low Cu contents of most Mississippi Valley- and Mount Isa-type deposits. If the fluids are too oxidized to stabilize pyrite, they can have high concentrations of Cu, possibly forming sediment-hosted Cu deposits. Such highly oxidized fluids could be produced in a basin with very low quantities of reductants such as Fe^{2+}.

Above 250°C, H_2S-rich ore fluids in equilibrium with pyrite and pyrrhotite can carry sufficient Cu for ore formation. The temperatures required for Cu transport are substantially higher than those required for Zn transport, and the calculations suggest that Broken Hill-type deposits, which are generally Cu-poor, formed at intermediate temperatures (200°–270°C).

One of the most striking differences between the VHMS and Broken Hill-type clan and the Mississippi Valley- and Mount Isa-type clan is their gold content. The gold contents of the Mount Isa- and Lady Loretta-type deposits are similar to those of unmineralized, background shales (Table 1; McGoldrick and Keays, 1990; Cooke et al., 2000). McGoldrick and Keays (1990) suggested that Mount Isa- (and probably Mississippi Valley-) type ore fluids were not hot enough and did not contain enough H_2S to transport Au. Conversely, the higher temperature, H_2S-rich VHMS (and probably Broken Hill-type) ore fluids transport significant Au.

Source rock, salinity, and Zn/Pb ratios

The relative abundances of Zn and Pb, usually expressed as simple ratios (e.g., Pb/Zn) have been extensively studied in Zn-Pb-Ag deposits (e.g., Stanton, 1962; Lydon, 1977). Huston and Large (1987) used 100Zn/(Zn + Pb), which they termed the "zinc ratio." Australian VHMS deposits have Zn ratios of 60 to 80 and 90 to 100 (Fig. 19), similar to global VHMS deposits (Huston and Large, 1987). Mount Isa-type deposits also have a limited range of Zn ratios, mostly between 66 and 87. However, there is a greater variability within individual systems, with Pb being enriched in zones proximal to inferred feeder faults at some Mount Isa-type deposits (Broadbent et al., 1998; Logan et al., 2001).

In contrast, Zn ratios of Broken Hill- and Mississippi Valley-type deposits vary between and within deposits. At the Cannington Broken Hill-type deposit, Zn ratios vary from 13 to 86 between lenses (Table 6). In Mississippi Valley-type deposits of the Canning basin, Pb-rich ores are commonly juxtaposed against Zn-rich ores, with Pb-rich ores close to feeder faults (e.g., McCracken et al., 1996; Vearncombe et al., 1996; Tompkins et al., 1997). At the Pillara deposit Zn ratios increase from values less than 60 along the footwall to values of 95 to 100 in the hanging wall of fault zones (Vearncombe et al., 1996).

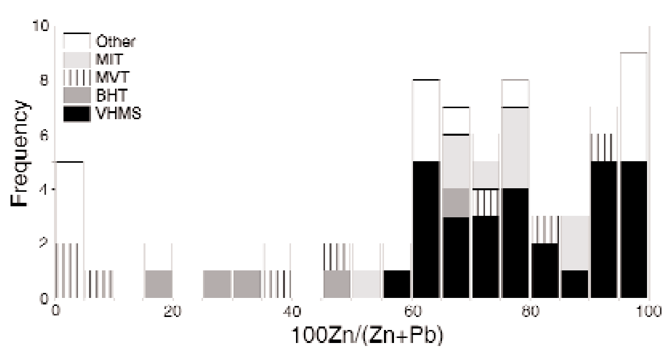

FIG. 19. Histogram showing the range of Zn ratios of the Zn-Pb-Ag deposits tabulated in Table 1.

Huston and Large (1987) argued that Zn ratios of VHMS deposits are controlled mostly by metal solubilities in the ore fluid and the metal content of the source rocks. They calculated that in a typical VHMS ore fluid (0.5–1.5 *m* NaCl, 150°–250°C) Zn ratios should vary between 58 and 85, values that match the lower mode in Figure 19. They suggested that Zn ratios above 90 were a consequence of low abundances of Pb in the source rocks. Figure 18d, which extends the original calculations of Huston and Large (1987) over larger ranges in temperature and salinity, confirms that for conditions typical of Zn-rich VHMS deposits, these deposits should have a narrow range of Zn ratios (55–75). However, the Zn ratio decreases with increasing temperature and, particularly, salinity of the ore fluids, which may account for the variable Zn ratios of Mississippi Valley- and Broken Hill-type deposits. Fluid inclusion data for Mississippi Valley-type deposits of the Canning basin suggest salinities of 5 to 25 wt percent NaCl equiv (Dörling et al., 1998), which corresponds to a Zn ratio range of 25 to 90, consistent with the range observed in the deposits. Variations in observed Zn ratios in Mount Isa-type systems are consistent with those estimated for fluids with salinities (10–25 wt % NaCl equiv) and temperatures (70–200°C) as indicated from fluid inclusion data. Zinc ratios for Broken Hill-type deposits suggest higher ore-fluid salinities than VHMS fluids, perhaps similar to those measured in the Atlantis II Deep (Pottorf and Barnes, 1983) and consistent with the formation of brine pools. Thus, most of the variation in Zn ratios of Zn-Pb-Ag deposits is caused by variations in salinities and temperatures of the ore fluids. In most cases, the metal abundances in the source regions are not important, except for the lack of Pb in mafic-rich greenstone belts that host some VHMS deposits. Zonation in Zn ratios observed in some deposits could be caused by decreases in temperature and/or salinity as ore fluids migrate laterally and mix with ambient fluids or by temporal changes in the salinity of the ore fluid as the ore-forming system evolves.

Other ore-forming systems

Although this review has concentrated on the characteristics of the four main ore-forming systems responsible for Zn-Pb-Ag deposits in Australia (Table 1), a number of other systems are recognized (Table 1). Of these only the Elura and Woodcutters-type deposits contribute more than 1 percent of Australia's Zn endowment. These deposits are epigenetic, occurring as pipelike bodies emplaced along the axial planes of anticlines (Fig. 20). At Elura, which is hosted within the turbidite-dominated Cobar basin, siltstone hosts the ores (Lawrie and Hinman, 1998), whereas at Woodcutters, which is located in the mixed siliciclastic and carbonate-dominated Pine Creek inlier, dolomitic mudstone hosts the ores (Fleming et al., 1994). Both deposits formed from moderate-temperature (220°–300°C), moderate-salinity (to 13 wt % NaCl equiv) fluids and at least locally contain significant gold.

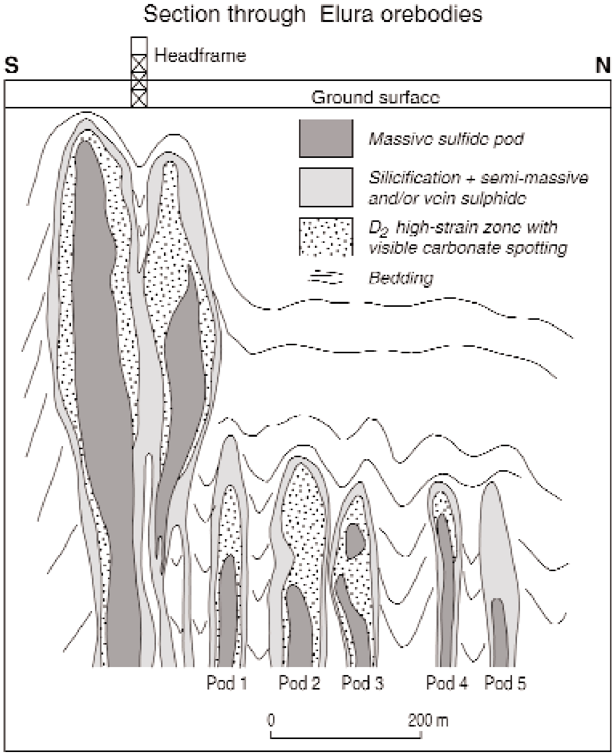

FIG. 20. Cross section of the Elura deposit, New South Wales (modified after Lawrie and Hinman, 1998).

Based on these characteristics, these deposits belong to the VHMS and Broken Hill-type clan.

Other minor Zn-Pb-Ag-bearing ore-forming systems in Australia include skarns, mantos, Irish-type deposits, veins, and epithermal deposits. With the probable exception of Irish-type deposits, these all belong to the VHMS and Broken Hill-type clan in that they formed from moderate- to high-temperature ore fluids and commonly contain significant Au.

Ore-Forming Systems: Consequences of the Tectonic Evolution of Australia

The main periods of Zn-Pb-Ag mineralization correspond closely to major periods of tectonism in Australia. Figure 21 synthesizes the relationship of important Zn-Pb-Ag mineral deposits and districts to tectonic elements of the Australian continent. Models of the tectonic assembly of Australia (e.g., Myers et al., 1996; Betts et al., 2002) point to possible tectonic drivers of Zn-Pb-Ag ore-forming systems.

Archean evolution

In a broad sense, the Australian continent youngs from west to east, with major Archean cratons located in Western Australia, Proterozoic blocks and fold belts in central and northern Australia, and Paleozoic fold belts along the eastern seaboard. Myers et al. (1996) inferred that Archean-early Proterozoic building blocks, the West, North, and South Australian cratons, were amalgamated in the Proterozoic. The West Australian craton, which contains the oldest Australian Zn-Pb-Ag deposits, consists of the 3.5 to 2.4 Ga Pilbara and the 3.8 to 2.6 Ga Yilgarn cratons. Although the oldest Zn-Pb-Ag deposit, the 3.47 Ga Lennons Find VHMS deposit, is in the Pilbara, the most significant districts, at Golden Grove (2.95 Ga) and Teutonic Bore (2.69 Ga), are located in the Yilgarn. Both of these districts are localized along the margins of rifts defined by Cassidy et al. (2005) and Huston et al. (2005), using variations in ε_{Nd} and Pb isotopes, respectively. High ε_{Nd} values and low μ values in the rift zones indicate primitive crust, a characteristic that is shared by the 2.75 to 2.64 Ga Abitibi subprovince, one of the world's richest Zn-Pb-Ag provinces.

Proterozoic evolution

The South Australian craton and highly mineralized North Australian craton formed mainly in the Paleoproterozoic around late Archean (~2.5 Ga) nuclei. With the possible exception of the Cannington and Dugald River deposits, all deposits in the North Australian craton formed in rift-sag basins in the northern part of the craton. This basin system and many of its contained deposits probably formed in response to tectonic events along the southern and, possibly, eastern margins of the North Australian craton (Idnurm, 2000; Scott et al., 2000). Southgate et al. (2000a) indicated that periods of Mount Isa-type mineralization correspond to changes in basin accommodation rates as indicated by regional unconformities and supersequence boundaries in the basin systems. Figure 17 suggests that the Mount Isa-type mineralization in the North Australian craton corresponds to bends in the Australian polar wander path (APWP), and that the timing of the two deposits in the western part of the basin system (HYC at ~1640 Ma and Century at ~1570 Ma) correspond to major orogenies along the southern margin of the North Australian craton (Liebig and Chewings orogenies, respectively: Scrimgeouer, 2003). This suggests that at least some Mount Isa-type mineralizing events were initiated or driven by far-field orogenies.

Although orogenies of similar age to the Mount Isa-Hilton (~1654 Ma) and Lady Loretta (~1648 Ma) deposits are unknown in Australia, these ages correspond to bends in the APWP (Fig. 17: Idnurm, 2000), suggesting coeval tectonic activity. The Mazatzal province in the southwestern United States, which may have been adjacent to Australia in the Proterozoic (e.g., Burrett and Berry, 2000; Karlstrom et al., 2001), underwent extensive magmatism (both felsic and mafic) and metamorphism at this time (Bauer and Williams, 1994; Eisele and Isachsen, 2001). Like Australia, this tectonism was driven by accretion from the south, possibly driving Mount Isa-type ore-forming systems in the eastern North Australian basin system and VHMS ore-forming systems (e.g., United Verde) in the southwestern United States.

The Broken Hill deposit is the only major Zn-Pb-Ag deposit in the South Australian craton. The possible age of this deposit (1.686–1.675 Ma: Page et al., 2000a; Parr et al., 2004) does not correspond to any major known orogenic event elsewhere in Australia, although Claoué-Long and Hoatson (2005) reported the presence of mafic intrusions and high-grade metamorphism of this age in the southern North Australian craton, and Daly et al. (1998) reported arc-related magmatism at this time in the western South Australian craton. Laing (1996) suggested that the Willyama block, which

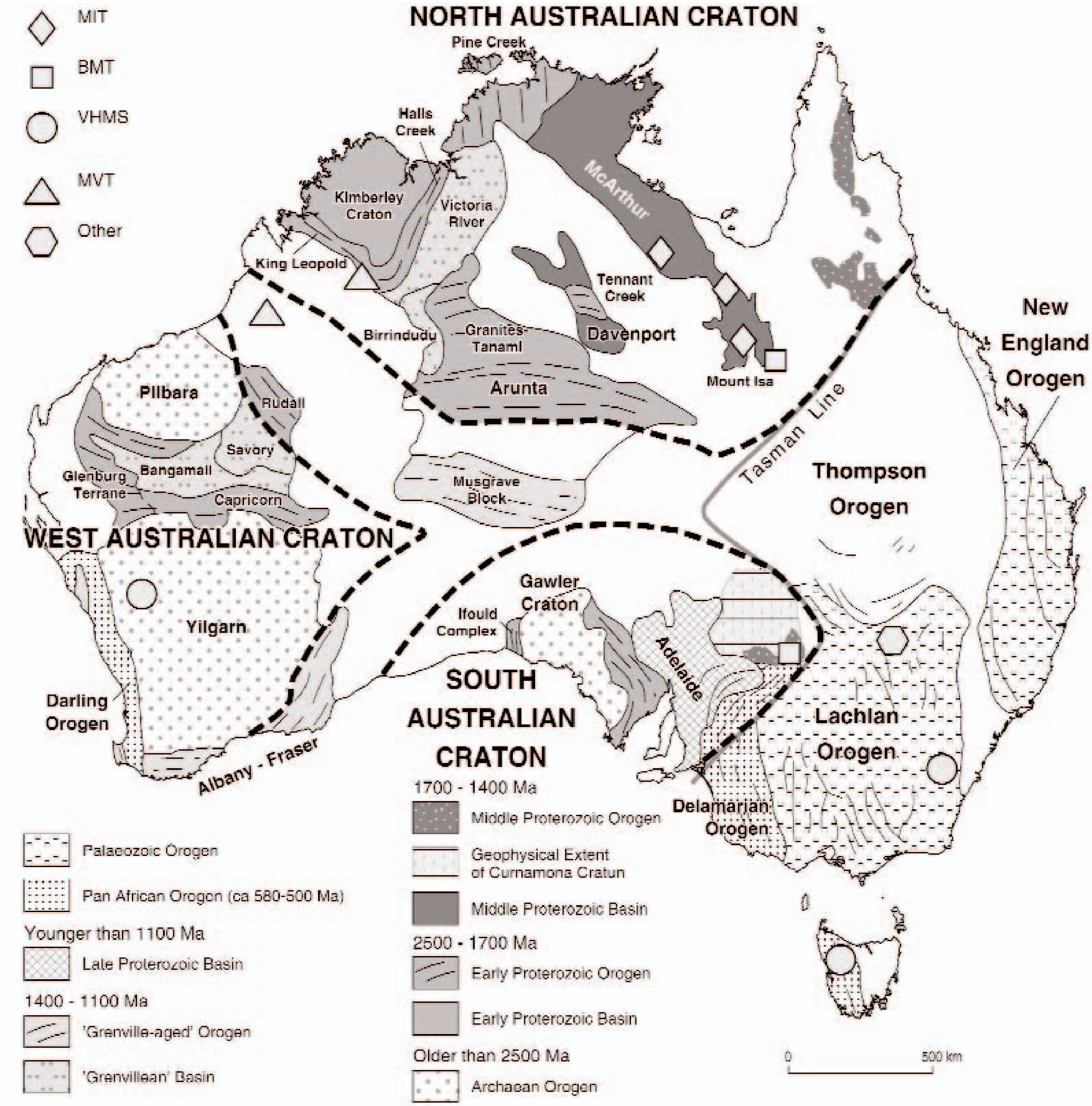

FIG. 21. Generalized tectonic map of Australia, showing the location of important Zn-Pb-Ag deposits (modified after Betts et al., 2002).

hosts the Broken Hill deposit, is the southern extension of the "Diamantina rift", a narrow, dismembered, north-trending rift that extended through the Mount Isa Eastern succession to the Einasleigh province in the north. This hypothesized rift, which may be a failed aulocogen, contains all of the known Broken Hill-type deposits in Australia.

The intensity of Australian Zn-Pb-Ag mineralization in the period between 1.70 and 1.57 Ga is unique in the world. Although mineralization of similar age is known, for instance, in southern Africa, the intensity is much less than in Australia. The correspondence between these mineralizing events and far-field tectonic events in the North and South Australian cratons and, possibly, the southwestern United States implies a close link with accretion along the southern margin of Rodinia. Another factor that might have enhanced mineralizing processes in the Australia Proterozoic is the high heat flow through much of Proterozoic Australia at the time of mineralization (McLaren et al., 2003). High heat flow would have enhanced mineralizing processes, even in the relatively low temperature Mount Isa-type ore-forming system.

Paleozoic evolution

Paleozoic rocks host important deposits in the Tasman fold belt of eastern Australia and the Canning basin of Western

Australia. The Tasman fold belt, which is separated from the Noth and South Australian cratons by the Tasman line (Fig. 21), consists of a series of "suspect" terranes that generally young from west to east. Coney et al. (1990) identified four epochs in the evolution of the Tasman fold belt, of which only the older two have significant known Zn-Pb-Ag deposits. VHMS deposits formed during the first epoch at two discrete time intervals: 500 to 480 and 420 Ma. During the first interval, the felsic-dominated Mount Read Volcanic belt, which hosts the 500 Ma Rosebery and Hellyer deposits, formed as a postcollisional "relaxation rift" developed on Proterozoic continental basement (Crawford and Berry, 1992). Deposits of the Thalanga province formed at 480 Ma, also in felsic-dominated volcanic rocks, although within a rifted-arc environment (Stolz, 1995). Cambro-Ordovician felsic volcanism is very restricted in the Tasman fold belt, which is mostly dominated by turbidites and mafic volcanic rocks (Coney, 1992). The second mineralized interval, which is also dominated by VHMS deposits (e.g., Woodlawn) in felsic volcanic belts, occurred in Silurian ensialic rifts (e.g., Bain et al., 1987). During the second epoch in the evolution of the Tasman fold belt, which involved extensive deformation (Coney et al., 1990), the Elura deposit formed epigenetically during the inversion of the Cobar basin (Glen et al., 1992).

In the Canning basin, Mississippi Valley-type mineralization appears to have been triggered by the local Pryces Creek and Meda events at 410 and 360 Ma, respectively. Although the Pryces Creek event does not correspond to a regional event in northern Australia, the associated Meda transpression corresponds to the beginning of the Alice Springs orogeny, suggesting that far-field events caused local deformation and mineralization here, as in the Mount Isa-type system.

Conclusions

The vast majority of Australian Zn-Pb-Ag resources formed in three periods: ~2.95, 1.69 to 1.58, and 0.50 to 0.35 Ga. Tectonic events along the southern margin of Rodinia triggered the 1.69 to 1.58 Ga event, which was by far the economically most important. The 0.50 to 0.35 Ga event is mostly related to crustal growth along the eastern seaboard, and the ~2.95 Ga event is related to rifting of the Murchison province. With the exception of the 0.50 to 0.35 Ga event, these do not correspond to major mineralizing events elsewhere in the world.

Ore fluids that form Zn-Pb-Ag deposits can be split into two groups: high-temperature, reduced fluids-related VHMS and Broken Hill-type ore-forming systems, and lower temperature, H_2S-poor fluids-related to Mount Isa- and Mississippi Valley-type systems. The fluid characteristics are determined by the tectonic setting and composition of the basin in which they formed. Higher temperature fluids formed by seawater convection in rift basins dominated by Fe^{2+}-rich volcanic and immature siliciclastic rock produce reduced, high-temperature VHMS and Broken Hill-type deposits. Evidence of such fluids is found in semiconformable, base metal-depleted albite ± hematite ± epidote alteration zones that occur 1 to 4 km stratigraphically below the ore position.

Lower temperature basinal brines that form Mount Isa- and Mississippi Valley-type deposits are expelled from depocenters in the lower parts of intracratonic extensional basins dominated by carbonates and mature siliciclastic rocks. Low heat flow and lack of Fe^{2+} in these basins produces H_2S-poor, oxidized, low-temperature brines, which form base metal depleted, regional orthoclase-hematite assemblages several kilometers below ore positions in Mount Isa-type–bearing basins. The overall characteristics of a basin can be used to predict the types of deposits it may contain, and the presence, location, and style of regional alteration zones can be used to determine if ore fluids formed in a basin and provide vectors or guides to possible locations of metal accumulation within the basin stratigraphy (Table 9).

In VHMS and Broken Hill-type systems, synvolcanic or synsedimentary faults, which focus fluids into traps at or below the sea floor, can be recognized through facies or thickness changes of units. In Mount Isa- and Mississippi Valley-type systems, (sub)basin bounding faults appear to be fluid conduits. In some systems the intersection of bounding faults and transfer zones focused fluid flow. Basins that host the deposits also may have formed in dilational jogs within local wrench fault systems.

Metals precipitate from reduced VHMS and Broken Hill-type fluids by mixing with seawater. Metals retention at the trap site is enhanced if mixing takes place either in a brine pool or below the sea floor in a porous (volcani)clastic medium. Metals precipitate from oxidized Mount Isa- and Mississippi Valley-type ore fluids by mixing with H_2S produced by TSR, facilitated by the presence of hydrocarbons and/or organic matter. This occurs at depths ranging from a few kilometers to just below the sea floor. Failed petroleum traps may be effective traps in Mississippi Valley- and Mount Isa-type systems.

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REFERENCES

Allen, R.L., 1994, Syn-volcanic, subseafloor replacement model for Rosebery and other massive sulfide ores [abs.]: Contentious Issues in Tasmanian Geology Symposium, Geological Society of Australia Tasmanian Division, Extended Abstracts Volume, p. 89–91.

Anderson, G.M., 1975, Precipitation of Mississippi Valley-type ores: Economic Geology, v. 70, p. 937–942.

——1991, Organic maturation and ore precipitation in southeast Missouri: Economic Geology, v. 86, p. 909–926.

Anderson, G.M., and Macqueen, R.W., 1987, Mississippi Valley-type lead-zinc deposits: Geoscience Canada Reprint Series 3, p. 79–90.

Anderson, H.E., and Goodfellow, W.D., 2000, Geochemistry and isotope chemistry of the Moyie sills: Implications for the early tectonic setting of the Mesoproterozoic Purcell basin: Geological Association of Canada Mineral Deposits Division Special Publication 1, p. 302–321.

Arne, D., 1996, Thermal setting of the Cadjebut Pb-Zn deposit, Western Australia: Journal of Geochemical Exploration, v. 57, p. 45–56

Bailes, A.H., and Galley, A.G., 1991, Geological setting of base metal mineralization in the Anderson area: Manitoba Energy and Mines, Minerals Division Report of Activities 1991, p. 8–13.

——1996, Setting of Paleoproterozoic volcanic-hosted massive base metal sulfide deposits, Snow Lake: Geological Survey of Canada Bulletin, v. 426, p. 105–138.

Bain, J.H.C., Wyborn, D., Henderson, G.A.M., Stuart-Smith, P.G., Abell, R.S., and Solomon, M., 1987, Regional geological setting of the Woodlawn and Captains Flat massive sulphide deposits, NSW, Australia, *in* Brennan, E., ed., Proceedings of the Pacific Rim Congress '87: Parkville, Australasian Institute of Mining and Metallurgy, p. 25–28.

Barnicoat, A.C., Sheldon, H.A., and Ord, A., 2005, Faulting in porous rocks: Resolving a paradox and exploration implications [abs.]: James Cook University of Northern Australia Economic Geology Research Unit Contribution 64, p. 7.

Bauer, P.W., and Williams, M.L., 1994, The age of Proterozoic orogenesis in New Mexico, U.S.A.: Precambrian Research, v. 67, p. 349–356.

Beales, F.W., 1975, Precipitation mechanisms for Mississippi Valley-type deposits: ECONOMIC GEOLOGY, v. 70, p. 943–948.

Beales, F.W., and Jackson, S.A., 1968, Pine Point: A stratigraphical approach: Canadian Mining and Metallurgy Bulletin, v. 61, p. 868–878.

Beardsmore, T.J., Newberry, S.P., and Laing, W.P., 1988, The Maronan Supergroup: An inferred early volcano-sedimentary rift sequence in the Mount Isa inlier, and its implications for ensialic rifting in the Middle Proterozoic of northwest Queensland: Precambrian Research, v. 40/41, p. 487–507.

Betts, P.G., Giles, D., Lister, G.S., and Frick, L.R., 2002, Evolution of the Australian lithosphere: Australian Journal of Earth Sciences, v. 49, p. 661–698.

Bleeker, W., 1999, Structure, stratigraphy, and primary setting of the Kidd Creek volcanogenic massive sulfide deposit: A semi-quantitative reconstruction: ECONOMIC GEOLOGY MONOGRAPH 10, p. 71–122.

Bodon, S.B., 1998, Paragenetic relationships and their implications for ore genesis at the Cannington Ag-Pb-Zn deposit, Mount Isa inlier, Queensland, Australia: ECONOMIC GEOLOGY, v. 93, p. 1463–1488.

Bradley, A.J., 1994, The origin of Mississippi Valley-type sulfide mineralization at Twelve Mile Bore, Lennard shelf, Western Australia: Unpublished B.Sc. Honours thesis, Nedlands, University of Western Australia, 76 p.

Brauhart, C.W., Groves, D.I., and Morant, P., 1998, Regional alteration systems associated with VHMS mineralization at Panorama, Pilbara, Western Australia: ECONOMIC GEOLOGY, v. 93, p. 292–302.

Brauhart, C.W., Huston, D.L., and Andrew, A., 2000, Definition of regional alteration in the Panorama VMS district using oxygen isotope mapping: Implications for the origin of the hydrothermal system and applications to exploration: Mineralium Deposita, v. 35, p. 727–740.

Brauhart, C.W., Huston, D.L., Groves, D.I., Mikucki, E.J., and Gardoll, S.J., 2001, Geochemical mass transfer patterns as indicators of the architecture of a complete VHMS hydrothermal alteration system in the Panorama district, Pilbara, Western Australia: ECONOMIC GEOLOGY, v. 96, p. 1263–1278.

Broadbent, G.C., Myers, R.E., and Wright, J.V., 1998, Geology and origin of shale-hosted Zn-Pb-Ag mineralization at the Century deposit, northwest Queensland, Australia: ECONOMIC GEOLOGY, v. 93, p. 1264–1294.

Bull, S.W., 1998, Sedimentology of the Palaeoproterozoic Barney Creek Formation in DDH BMR McArthur 2, southern McArthur basin, Northern Territory: Australian Journal of Earth Sciences, v. 45, p. 21–32.

Burrett, C., and Berry, R., 2000, Proterozoic Australia-western United States (AUSWUS) fit between Laurentia and Australia: Geology, v. 28, p. 103–106.

Butterfield, D.A., Massoth, G.J., McDuff, R.E., Lupton, J.E., and Lilley, M.D., 1990, Geochemistry of hydrothermal fluids from Axial Seamount hydrothermal emissions study vent field, Juan de Fuca Ridge: Subseafloor boiling and subsequent fluid-rock interaction: Journal of Geophysical Research, v. 95, p. 12895–12931.

Cartwright, I., 1999, Regional oxygen isotope zonation at Broken Hill, New South Wales, Australia: Large-scale fluid flow and implications for Pb-Zn-Ag mineralization: ECONOMIC GEOLOGY, v. 94, p. 357–374.

Cas, R.A.F., 1992, Submarine volcanism: Eruption styles, products, and relevance to understanding the host-rock successions to VHMS deposits: ECONOMIC GEOLOGY, v. 87, p. 511–541.

Cassidy, K.F., Champion, D.C., and Huston, D.L., 2005, Crustal evolution constraints on the metallogeny of the Yilgarn craton [abs.], *in* Mao, J., and Bierlein, F.P., eds., Mineral deposit research: Meeting the global challenge: Heidelberg, Springer, p. 901–904.

Chapman, L.H., 2004, Geology and mineralization styles of the George Fisher Zn-Pb-Ag deposit, Mount Isa: ECONOMIC GEOLOGY, v. 99, p. 233–255.

Chapman, L.H., and Williams, P.J., 1998, Evolution of pyroxene-pyroxenoid-garnet alteration at the Cannington Ag-Pb-Zn deposit, Cloncurry district, Queensland Australia: ECONOMIC GEOLOGY, v. 93, p. 1390–1405.

Chen, J., Walter, M.R., Logan, G.A., Hinman, M.C., and Summons, R.E., 2003, The Paleoproterozoic McArthur River (HYC) Pb/Zn/Ag deposit of northern Australia: Organic geochemistry and ore genesis: Earth and Planetary Science Letters, v. 210, p. 467–479.

Christensen, J.N., Halliday, A.N., Vearncombe, J.R., and Kesler, S.E., 1995, Testing models of large-scale crustal fluid flow using direct dating of sulfides: Rb-Sr evidence of early dewatering and formation of Mississippi Valley-type deposits, Canning basin, Australia: ECONOMIC GEOLOGY, v. 90, p. 887–884.

Coney, P.J., 1992, The Lachlan belt of eastern Australia and Circum-Pacific tectonic evolution: Tectonophysics, v. 214, p. 1–25.

Coney, P.J., Edwards, A., Hine, R., Morrison, R., and Windrim, D., 1990, The regional tectonics of the Tasman orogenic system, eastern Australia: Journal of Structural Geology, v. 12, p. 519–543.

Converse, D.R., Holland, H.D., and Edmond, J.M., 1984, Flow rates in the axial hot springs of the East Pacific Rise (21°N): Implications for the heat budgets and the formation of massive sulfide deposits: Earth and Planetary Science Letters, v. 69, p. 159–175.

Cook, N.D.J., and Ashley, P.M., 1992, Meta-evaporite sequence, exhalative chemical sediments and associated rocks in the Proterozoic Willyama Supergroup, South Australia: Implications for metallogenesis: Precambrian Research, v. 56, p. 211–226.

Cooke, D.R., Bull, S.W., Donovan, S., and Rogers, J.R., 1998, K-metasomatism and base metal depletion in volcanic rocks from the McArthur basin, Northern Territory–implications for base metal mineralization: ECONOMIC GEOLOGY, v. 93, p. 1237–1263.

Cooke, D.R., Bull, S.R., Large, R.R., and McGoldrick, P.J., 2000, The importance of oxidized brines for the formation of Australian Proterozoic stratiform sediment-hosted Pb-Zn (SEDEX) deposits: ECONOMIC GEOLOGY, v. 95, p. 1–19.

Crawford, A.J., and Berry, R.F., 1992, Tectonic implications of Late Proterozoic-early Palaeozoic igneous rock associations in Western Tasmania: Tectonophysics, v. 214, p. 37–56.

Croxford, N.J.W., and Jephcott, S., 1972, The McArthur lead-zinc-silver deposit, N.T.: Proceedings of the Australasian Institute of Mining and Metallurgy, v. 243, p. 1–26.

Daly, S.J., Fanning, G.M., and Fairclough, M.C., 1998, Tectonic evolution and exploration potential of the Gawler craton, South Australia: AGSO Journal of Australian Geology and Geophysics, v. 17, p. 145–168.

de Jong, G., and Williams, P.J., 1995, Giant metasomatic system formed during exhumation of mid-crustal Proterozoic rocks in the vicinity of the Cloncurry fault, northwest Queensland: Australian Journal of Earth Sciences, v. 42, p. 281–290.

de Ronde, C.E.J., 1995, Fluid chemistry and isotopic characteristics of seafloor hydrothermal systems and associated VHMS deposits: Potential for magmatic contributions: Mineralogical Association of Canada Short Course Series, v. 23, p. 479–510.

Donaghy, T., Hall, M., and Gibson, G., 1998, The Palaeoproterozoic Thackeringa Group: Deposition, deformation and stratigraphy [abs.]: AGSO Record 1998/25, p. 17–20.

Dörling, S.L., Dentith, M.C., Groves, D.I., and Vearncombe, J.R., 1996, Mississippi Valley-type deposits of the southeast Lennard shelf: An example of the interplay of extensional deformation, sedimentation and mineralization: Society of Economic Geologists Special Publication 4, p. 96–111.

Dörling, S.L., Groves, D.I., and Muhling, P., 1998, Lennard shelf Mississippi Valley-type (MVT) Pb-Zn deposits, Western Australia: AGSO Journal of Australian Geology and Geophysics, v. 17, p. 115–120.

Doyle, M.G., and Allen, R.L., 2003, Subsea-floor replacement in VHMS deposits: Ore Geology Reviews, v. 23, p. 183–222.

Doyle, M.G., and Huston, D.L., 1999, The subsea-floor replacement origin of the Ordovician Highway-Reward volcanic-associated massive sulfide deposit, Mount Windsor subprovince, Australia: ECONOMIC GEOLOGY, v. 94, p. 825–844.

Drummond, B.J., Sexton, M.J., Barton, T.J., and Shaw, R.D., 1991, The nature of faulting along the margins of the Fitzroy trough, Canning basin, and implications for the tectonic development of the trough: Exploration Geophysics, v. 22, p. 111–116.

Eastoe, C.J., Gustin, M.S., Hurlburt, D.F., and Orr, R.R., 1990, Sulfur isotopes in Early Proterozoic volcanogenic massive sulfide deposits: New data from Arizona and implications for ocean chemistry: Precambrian Research, v. 46, p. 353–364.

Ehlers, K., Foster, J., and Nutman, A.P., 1996, The Broken Hill ore body: Concentration of the lead during high grade metamorphism [abs.]: Geological Society of Australia Abstracts, v. 41, p. 127.

Eisele, J., and Isachsen, C.E., 2001, Crustal growth in southern Arizona: U-Pb geochronologic and Sm-Nd isotopic evidence for addition of the Paleoproterozoic Cochise block to the Mazatzal province: American Journal of Science, v. 301, p. 773–797.

Eisenlohr, B.N., Tompkins, L.A., Cathles, L.M., Barley, M.E., and Groves, D.I., 1994, Mississippi Valley-type deposits: Products of brine expulsion by eustatically induced hydrocarbon generation? An example from northwestern Australia: Geology, v. 22, p. 315–318.

Eldridge, C.S., Barton, P.B., Jr., and Ohmoto, H., 1983, Mineral textures and their bearing on formation of the kuroko orebodies: Economic Geology Monograph 5, p. 241–281.

Eldridge, C.S., William, N., and Walshe, J.L., 1993, Sulfur isotope variability in sediment-hosted massive sulfide deposits as determined using the ion microprobe SHRIMP II: A study of the HYC deposit at McArthur River, Northern Territory, Australia: Economic Geology, v. 88, p. 1–26.

Etminan, H., and Hoffman, C.F., 1989, Biomarkers in fluid inclusions: A new tool in constraining source regimes and its implications for the genesis of Mississippi Valley-type deposits: Geology, v. 17, p. 19–22.

Ewers, G.R., and Ryburn, R.J., 1997, OZMIN documentation: AGSO's national mineral deposits database: AGSO Record 1994/43, 2nd ed., 91 p.

Fisher, Q.J., Casey, M., Harris, S.D., and Knipe, R.J., 2003, Fluid-flow properties of faults in sandstone: The importance of temperature history: Geology, v. 31, p. 965–968.

Fleming, M.J., Ormsby, W.R., and Nicholson, P.M., 1994, The geology of the Woodcutters lead-zinc-silver mine: Australasian Institute of Mining and Metallurgy Annual Conference, Darwin, August 5–9, 1994, Proceedings, p. 21–28.

Franklin, J.M., Lydon, J.W., and Sangster, D.M., 1981, Volcanic-associated massive sulfide deposits: Economic Geology 75th Anniversary Volume, p. 485–627.

Franklin, J.M., Gibson, H.L., Jonasson, I.R., and Galley, A.G., 2005, Volcanogenic massive sulfide deposits: Economic Geology 100th Anniversary Volume, p. 523–560.

Galley, A.G., 1993, Characteristics of semi-conformable alteration zones associated with volcanogenic massive sulphide districts: Journal of Geochemical Exploration, v. 48, p. 175–200.

——2003, Composite synvolcanic intrusions associated with Precambrian VMS-related hydrothermal systems: Mineralium Deposita, v. 38, p. 443–473.

Garven, G., 1995, Continental-scale groundwater flow and geologic processes: Annual Review of Earth and Planetary Sciences, v. 24, p. 89–117.

Garven, G., and Freeze, R.A., 1984, Theoretical analysis of the role of groundwater flow in the genesis of stratabound ore deposits. 2. Quantitative results: American Journal of Science, v. 284, p. 1125–1174.

Garven, G., Ge, S., Person, M.A. and Sverjensky, D.A., 1993, Genesis of stratabound ore deposits in the Midcontinent basins of North America. 1. The role of regional groundwater flow: American Journal of Science, v. 293, p. 497–568.

Garven, G., Bull, S.W., and Large, R.R., 2001, Hydrothermal fluid flow models of stratiform ore genesis in the McArthur basin, Northern Territory, Australia: Geofluids, v. 1, p. 289–311.

Gemmell, J.B., and Large, R.R., 1992, Stringer system and alteration zones underlying the Hellyer VHMS deposit, Tasmania, Australia: Economic Geology, v. 87, p. 620–649.

Gibson, G.M., and Nutman, A.P., 2004, Detachment faulting and bimodal magmatism in the Palaeoproterozoic Willyama Supergroup, south-central Australia: Keys to recognition of a multiply deformed Precambrian metamorphic core complex: Journal of the Geological Society of London, v. 161, p. 55–66.

Gibson, H.L., 1989, The Mine Sequence of the central Noranda volcanic complex: Geology, alteration, massive sulfide deposits and volcanological reconstruction: Unpublished Ph.D. thesis, Northfield, MN, Carleton University, 715 p.

Glen, R.A., Dallmeyer, R.D., and Black, L.P., 1992, Isotopic dating of basin inversion—the Palaeozoic Cobar basin, Lachlan orogen, Australia: Tectonophysics, v. 214, p. 249–268.

Goldhaber, M.B., and Orr, W.L., 1994, Kinetic controls on thermochemical sulfate reduction as a source of sedimentary H_2S, *in* Vairavmurthy, M.A., Schoonen, M.A.A., Eglinton, T.I., Luther, G.W., III, and Manowitz, B., eds., Geochemical transformations of sedimentary sulfur: American Chemical Society Symposium Series, v. 612, p. 412–425.

Goodfellow, W.D., Jonasson, I.R., and Morin, J.A., 1986, Environment of formation of the Howards Pass (XY) Zn-Pb deposit, Selwyn basin, Yukon: Canadian Institute of Mining and Metallurgy Special Volume 37, p. 19–50.

Goodfellow, W.D., Lydon, J.W., and Turner, R.W., 1993, Geology and genesis of stratiform sediment-hosted (SEDEX) Zn-Pb-Ag sulphide deposits: Geological Association of Canada Special Paper 40, p. 201–251.

Grondjis, M.F., and Schouten, C., 1937, A study of the Mount Isa ores: Economic Geology, v. 32, p. 407–450.

Gunn, P.J., and Ly, K.C., 1989 The petroleum prospectivity of the Joseph Bonaparte Gulf area, northwestern Australia: Australian Petroleum Exploration Association Journal, v. 29, p. 509–526.

Haines, P.W., Pietsch, Rawlings, D.J., and Madigan, T.L., 1993, Mount Young SD53–15. 1:250 000 geological map series, explanatory notes: Government Printer of the Northern Territory, 81 p.

Hannington, M.D., Jonasson, I.R., Herzig, P.M., and Petersen, S., 1995, Physical and chemical processes of seafloor mineralization at mid-ocean ridges: American Geophysical Monograph 91, p. 115–157.

Hannington, M.D., Galley, A.G., Herzig, P.M., and Peterson, S., 1998, Comparison of the TAG mound and stockwork complex with Cyprus-type massive sulfide deposits: Proceedings of the Ocean Drilling Program, Scientific Results, v. 158, p. 389–415.

Hannington, M.D., Barrie, C.T., and Bleeker, W., 1999, The giant Kidd Creek volcanogenic massive sulfide deposit, western Abitibi subprovince, Canada: Summary and synthesis: Economic Geology Monograph 10, p. 661–672.

Hannington, M.D., de Ronde, C.E.J., and Sven Petersen, A., 2005, Sea-floor tectonics and submarine hydrothermal systems: Economic Geology 100th Anniversary Volume, p. 111–143.

Hanor, J. S., 1994, Origins of saline fluids in sedimentary basins: Geological Society Special Publication 78, p. 151–174

——1996, Controls on the solubilization of lead and zinc in basinal brines: Society of Economic Geologists Special Publication 4, p. 483–500.

Haydon, R.C., and McConachy, G.W., 1987, The stratigraphic setting of Pb-Zn-Ag mineralization at Broken Hill: Economic Geology, v. 82, p. 826–856.

Hayes, T., and Palmer, J., 1989, Late Cambrian lithofacies and their control on the Mississippi Valley-type mineralization in the Ozark region: U.S. Geological Survey Circular 1035, p. 51–54.

Hiatt, E.E., Kyser, K., and Dalrymple, R.W., 2003, Relationships among sedimentology, stratigraphy, and diagenesis in the Proterozoic Thelon basin, Nunavut, Canada: Implications for palaeoaquiferes and sedimentary-hosted mineral deposits: Journal of Geochemical Exploration, v. 80, p. 221–240.

Hill, R.G.M., 1997, Stratigraphy, structure and alteration of hanging wall sedimentary rocks at the Sulphur Springs volcanogenic massive sulfide (VMS) prospect, east Pilbara craton, Western Australia: Unpublished B.Sc. Honours thesis, Nedlands, University of Western Australia, 66 p.

Hinman, M.C., 1995, Base-metal mineralisation at McArthur River: Structure and kinematics of the HYC-Cooley zone at McArthur River: Australian Geological Survey Organisation Record 1995/5, 29 p.

——1996, Constraints, timing and processes of stratiform base metal mineralization at the HYC Ag-Pb-Zn deposit, McArthur River [abs.]: James Cook University of Northern Australia Economic Research Unit Contribution 55, p. 56–59.

——2001, Inhalation, thermochemical sulphate reduction, and realistic processes of ore formation at McArthur River, Northern Territory [abs.]: James Cook University of Northern Australia Economic Research Unit Contribution 59, p. 82–83.

Hobbs, B.E., Walshe, J.L., Ord, A., Zhang, Y., and Carr, G.R., 1998, The Broken Hill ore body: A high temperature, high pressure scenario [abs.]: AGSO Record 1998/2, p. 98–103.

Huston, D.L., 1999, Stable isotopes and their significance for understanding the genesis of VHMS deposits: A review: Reviews in Economic Geology, v. 10, p. 151–180.

Huston, D.L., and Cas, R.A.F., 2000, Shallow water VHMS deposits: How common are they? [abs.]: University of Tasmania, Centre for Ore Deposit and Exploration Studies Special Publication 3, p. 93–95.

Huston, D.L., and Large, R.R., 1987, Genetic and exploration significance of the zinc ratio (100Zn/[Zn + Pb]) in massive sulfide systems: ECONOMIC GEOLOGY, v. 82, p. 1521–1539.
Huston, D.L., Wyborn, L.A.I., and Steven, B.J.P., 1998, Pb-Zn-Ag mineral systems: An example from Broken Hill: Australian Geological Survey Organisation Record 1998/25, p. 59–63.
Huston, D.L., Brauhart, C.W., Folkert, S., Davidson, G.J., and Groves, D.I., 2001, Metal leaching and inorganic sulfate reduction in VHMS mineral systems: Evidence from the paleo-Archean Panorama district, Western Australia: Geology, v. 29, p. 687–690.
Huston, D.L., Champion, D.C., and Cassidy, K.F., 2005, Tectonic controls on the endowment of Archean cratons in VHMS deposits: Evidence from Pb and Nd isotopes [abs.], *in* Mao, J., and Bierlein, F.P., eds., Mineral deposit research: Meeting the global challenge: Heidelberg, Springer, p. 15–18.
Hutton, L.J., and Wilson, I.H., 1984, Mount Oxide region 1:250 000 geological map commentary, explanatory notes: Australian Government Publishing Service, 27 p.
Idnurm, M, 2000, Toward a high resolution Late Palaeoproterozoic-earliest Mesoproterozoic apparent polar wander path for northern Australia: Australian Journal of Earth Sciences, v. 47, p. 405–430.
Ireland, T., Bull, S.W., and Large, R.R., 2004a, Mass flow sedimentology within the HYC Zn-Pb-Ag deposit, Northern Territory, Australia: Evidence for syn-sedimentary ore genesis: Mineralium Deposita, v. 39, p. 143–158.
Ireland, T., Large, R.R., McGoldrick, P., and Blake, M., 2004b, Spatial distribution patterns of sulfur isotopes, nodular carbonate, and ore textures in the McArthur (HYC) Zn-Pb-Ag deposit, Northern Territory, Australia: ECONOMIC GEOLOGY, v. 99, p. 1687–1710.
Jackson, M.J., Muir, M.D., and Plumb, K.A., 1987, Geology of the southern McArthur basin, Northern Territory: Bureau of Mineral Resources Bulletin 220, 173 p.
Jackson, M.J., Scott, D.L., and Rawlings, D.J., 2000, Stratigraphic framework for the Leichardt and Calvert superbasins: Review and correlations of the pre-1700 Ma successions between Mt. Isa and McArthur River: Australian Journal of Earth Sciences, v. 47, p. 381–404.
James, S.D., Pearce, J.A., and Oliver, R.A., 1987, The geochemistry of the lower Proterozoic Willyama Complex volcanics, Broken Hill block, New South Wales: Geological Society Special Publication 33, p. 395–408.
Johnson, I.R., and Klingner, G.D., 1975, Broken Hill ore deposit and its environment: Australasian Institute of Mining and Metallurgy Monograph 5, p. 476–491.
Karlstrom, K.E., Ahall, K.-I., Harlan, S.S., Williams, M.L., McLelland, J., and Geissman, J.W., 2001, Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia: Precambrian Research, v. 111, p. 5–30.
Kelley, K.D., Leach, D.L., Johnson, C.A., Clark, J.L., Fayek, M., Slack, J.F., Anderson, V.M., Ayuso, R.A., and Ridley, W.I., 2004, Textural, composition, and sulfur isotope variations of sulfide minerals in the Red Dog Zn-Pb-Ag deposits, Brooks Range, Alaska: Implications for ore formation: ECONOMIC GEOLOGY, v. 99, p. 1509–1532.
Kennard, J.M., Jackson, M.J., Romine, K.K., Shaw, R.D., and Southgate, P.N., 1994, Depositional sequences and associated petroleum systems of the Canning basin, W.A., *in* Purcell, P.G., and Purcell, R.R., eds., The sedimentary basins of Western Australia: West Australia basins Symposium, Perth, August, Proceedings, p. 657–676.
Kesler, S.E., Jones, H.D., Furman, F.C., Sassen, R., Anderson, W.H., and Kyle, J.R., 1994, Role of crude oil in the genesis of Mississippi Valley-type deposits: Evidence from the Cincinnati arch: Geology, v. 22, p. 609–612.
Kharaka, Y.K., Maest, A.S., Carothers, W.W., Law, L.M., Lamothe, P.J., and Fries, T.L., 1987, Geochemistry of metal-rich brines from central Mississippi Salt Dome basin, U.S.A.: Applied Geochemistry, v. 2, p. 543–562.
King, H.F., and Thomson, B.P., 1953, The geology of the Broken Hill district, *in* Edwards, A.B., ed., Geology of Australian ore deposits: Empire Mining and Metallurgical Congress, 5th, Australia and New Zealand: Australasian Institute of Mining and Metallurgy Publication, v. 1, p. 533–577.
Korsch, R.J., Rawlings, D.J., Goleby, B.R., Gibson, G.M., and Johnstone, D.W., 2004, Deep seismic profiling in the southern McArthur basin: Implications for mineralisation [abs.]: Centre for Global Metallogeny, University of Western Australia Publication 33, p. 289–291.
Kullerud, G., and Yoder, H.S., 1959, Pyrite stability relations in the Fe-S system: ECONOMIC GEOLOGY, v. 54, p. 533–572.
Lagerblad, B., and Gorbatschev, R., 1985, Hydrothermal alteration as a control of regional geochemistry and ore formation in the central Baltic Shield: Geologisch Rundschau, v. 74, p. 33–49.
Laing, W.P., 1996, The Diamantina orogen linking the Willyama and Cloncurry terranes, eastern Australia: University of Tasmania, Centre for Ore Deposit and Exploration Studies Special Publication 1, p. 67–70.
Laing, W.P., Marjoribanks, R.W., and Rutland, R.W., 1978, Structure of the Broken Hill mine area and its significance for the genesis of the orebodies: ECONOMIC GEOLOGY, v. 73, p. 1112–1136.
Lambert, I.B., and Scott, K.M., 1973, Implications of geochemical investigations of sedimentary rocks within and around the McArthur River zinc-lead-silver deposit, Northern Territory, Australia: Journal of Exploration Geochemistry, v. 2, p. 307–330.
Lapwood, E.R., 1948, Convection of a fluid in a porous medium: Cambridge Philosophical Society Proceedings, v. 44, p. 508–521.
Large, R.R., McGoldrick, P.J., Berry, R.F., and Young, C.H., 1988, A tightly folded, gold-rich, massive sulfide deposit: Que River mine, Tasmania: ECONOMIC GEOLOGY, v. 83, p. 681–693.
Large, R.R., Doyle, M., Raymond, O., Cooke, D., Jones, A., and Heasman, L., 1996a, Evaluation of the role of Cambrian granites in the genesis of world class VHMS deposits in Tasmania: Ore Geology Reviews, v. 10, p. 215–230.
Large, R.R., Bodon, S., Davidson, G., and Cooke, D., 1996b, The chemistry of BHT ore formation—one of the keys to understanding differences between SEDEX and BHT deposits: Centre for Ore Deposit and Exploration Studies Special Publication 1, p. 105–112.
Large, R.R., Bull, S.W., Cooke, D.R., and McGoldrick, P.J., 1998, A genetic model for the HYC deposit, Australia: Based on regional sedimentology, geochemistry, and sulfide-sediment relationships: ECONOMIC GEOLOGY, v. 93, p. 1345–1368.
Large, R.R., Bull, P.J., and McGoldrick, P.J., 2000, Lithogeochemical halos and geochemical vectors to stratiform sediment hosted Zn-Pb-Ag deposits. Part 2. HYC deposit, McArthur River, Northern Territory: Journal of Geochemical Exploration, v. 68, p. 105–126.
Large, R.R., Allen, R.L., Blake, M.D., and Herrmann, W., 2001, Hydrothermal alteration and volatile element halos for the Rosebery K lens VHMS deposit, western Tasmania: ECONOMIC GEOLOGY, v. 96, p. 1055–1072.
Lawrence, L.J., 1967, Sulphide neomagmas and highly metamorphosed sulphide deposits: Mineralium Deposita, v. 2, p. 5–10.
——1973, Polymetamorphism of the sulphide ores of Broken Hill, N.S.W., Australia: Mineralium Deposita, v. 8, p. 211–236.
Lawrie, K.C., and Hinman, M.C., 1998, Cobar-style polymetallic Au-Cu-Zn-Pb-Zn deposits: AGSO Journal of Australian Geology and Geophysics, v. 17, p. 169–188.
Leach, D.L., Marsh, E., Emsbo, P., Rombach, C.S, Kelley, K.D., and Anthony, M., 2004, Nature of hydrothermal fluids at the shale-hosted Red Dog Zn-Pb-Ag deposits, Brooks Range, Alaska: ECONOMIC GEOLOGY, v. 99, p. 1449–1480.
Leach, D.L., Sangster, D.F., Kelley, K.D., Large, R.R., Garven, G., Allen, C.R., Gutzmer, J., and Walters, S., 2005, Sediment-hosted zinc deposits: A global perspective: ECONOMIC GEOLOGY 100TH ANNIVERSARY VOLUME, p. 561–608.
Lee, R.J., and Rowley, M., 1990, Sorby Hills (W.A.) lead-zinc-silver: Australasian Institute of Mining and Metallurgy Monograph 17, p. 197–202.
Logan, G.A., Hinman, M.C., Walter, M.R., and Summons, R.E., 2001, Biogeochemistry of the 1640 Ma McArthur (HYC) lead-zinc ore and host sediments, Northern Territory, Australia: Geochimica et Cosmochimica Acta, v. 65, p. 2317–2336.
Lydon, J.W., 1977, The significance of metal ratios in hydrothermal ore deposits: Unpublished Ph.D. thesis, Kingston, ON, Queen's University, 601 p.
MacGeehan, P.J., 1978, The geochemistry of altered volcanic rocks at Matagami, Quebec: A geothermal model for massive sulfide genesis: Canadian Journal of Earth Sciences, v. 15, p. 551–570.
Machel, H.G., 2001, Bacterial and thermochemical sulfate reduction in diagenetic settings—old and new insights: Sedimentary Geology, v. 140, p. 143–175.
Mavrogenes, J.A., MacIntosh, I.W., and Ellis, D.J., 2001, Partial melting of the Broken Hill galena-sphalerite ore—experimental studies in the system PbS-Fe-S-Zn-S-(Ag_2S): ECONOMIC GEOLOGY, v. 96, p. 205–210.
McCracken, S.R., Etminan, H., Connor, A.G., and Williams, V.A., 1996, Geology of the Admiral Bay carbonate-hosted zinc-lead deposit, Canning basin, Western Australia: Society of Economic Geologists Special Publication 4, p. 330–349.
McGoldrick, P.J., and Keays, R.R., 1990, Mount Isa copper and lead-zinc-silver ores: coincidence or cogenesis?: ECONOMIC GEOLOGY, v. 85, p. 641–650.

McLaren, S., Sandiford, M., Hand, M., Neumann, N., Wyborn, L., and Bastrakova, I., 2003, The hot southern continent: Heat flow and heat production in Australian Proterozoic terranes: Geological Society of Australia Special Publication 22, p. 151–161.

McManus, A., and Wallace, M.W., 1992, Age of Mississippi Valley-type sulfides determined using cathodoluminescence cement stratigraphy, Lennard shelf, Canning basin, Western Australia: ECONOMIC GEOLOGY, v. 87, p. 189–193.

Middleton, H., and Wallace, M.W., 2003, The evolution of fluid flow systems prior to, during and post MVT mineralization in the Givetian-Frasnian carbonates of the Emanuel Range-Western Australia: Journal of Geochemical Exploration, v. 78–79, p. 91–97.

Moldovanyi, E.P., and Walter, L.M., 1992, Regional trends in water chemistry, Smackover Formation, southwest Arkansas: Geochemical and physical controls: American Association of Petroleum Geologists Bulletin, v. 76, p. 864–894.

Morton, R.L., and Franklin, J.M., 1987, Two-fold classification of Archean volcanic-associated massive sulfide deposits: ECONOMIC GEOLOGY, v. 82, p. 1057–1063.

Mory, A.J., and Beere, G.M., 1988 Geology of the onshore Bonaparte and Ord basins in Western Australia: Geological Survey of Western Australia Bulletin 134, 184 p.

Muhling, P.C. 1994 Lennard shelf Pb-Zn mineralization [abs.]: Geological Society of Australia Abstracts, v. 37, p. 307–308

Muir, M.D., Donnely, T.H., Wilkins, R.W.T., and Armstrong, K.J., 1985, Stable isotope, petrological and fluid inclusion studies of minor mineral deposits from the McArthur basin: Implications for the genesis of some sediment-hosted base metal mineralisation from the Northern Territory: Australian Journal of Earth Sciences, v. 32, p. 239–260.

Munha, J., and Kerrich, R., 1980, Sea water basalt interaction in spilites from the Iberian Pyrite Belt: Contributions to Mineralogy and Petrology, v. 73, p. 191–200.

Murphy, G.C., 1990, Lennard shelf lead-zinc deposits: Australasian Institute of Mining and Metallurgy Monograph 14, p. 1103–1109.

Myers, J.S., Shaw, R.D., and Tyler, I.M., 1996, Tectonic evolution of Proterozoic Australia: Tectonics, v. 15, p. 1431–1446.

Neudert, M.K., and Russell, R.E., 1982, Shallow water and hypersaline features from the middle Proterozoic Mt. Isa Sequence: Nature, v. 293, p. 284–286.

Nutman, A.P., and Ehlers, P.D., 1998, Evidence for multiple Palaeoproterozoic thermal events and magmatism adjacent to the Broken Hill Pb-Zn-Ag orebody, Australia: Precambrian Research, v. 90, p. 203–238.

O'Brien, G.W., Higgins, R., Symonds, P., Quaife, P., Colwell, J., and Blevin, J., 1996, Basement control on the development of extension systems in Australia's Timor Sea: An example of hybrid hard linked/soft linked faulting?: Australian Petroleum Exploration Association Journal, v. 76, p. 161–200.

Ohmoto, H., Mizukami, M., Drummond, S.E., Eldridge, C.S., Pisutha-Arnond, V., and Lenaugh, T.C., 1983, Chemical processes in kuroko formation: ECONOMIC GEOLOGY MONOGRAPH 5, p. 570–604.

Oliver, J., 1986, Fluids expelled tectonically from orogenic belts: Their role in hydrocarbon migration and other geologic phenomena: Geology, v. 14, p. 99–102.

Page, R.W., and Laing, W.P., 1992, Felsic metavolcanic rocks related to the Broken Hill Pb-Zn-Ag orebody, Australia: Geology, depositional age, and timing of high-grade metamorphism: ECONOMIC GEOLOGY, v. 87, p. 2138–2168.

Page, R.W., and Sun, S.-S., 1998, Aspects of geochronology and crustal evolution in the Eastern fold belt, Mt. Isa inlier: Australian Journal of Earth Sciences, v. 45, p. 343–362.

Page, R.W., Stevens B.P.J., Gibson G.M., and Conor C.H.H., 2000a, Geochronology of Willyama Supergroup rocks between Olary and Broken Hill and comparison to northern Australia: Australian Geologic Survey Organisation Record 2000/10, p. 72–75.

Page, R.W., Jackson, M.J., and Krassay, A.A., 2000b, Constraining sequence stratigraphy in north Australia basins: SHRIMP U-Pb zircon geochronology between Mt. Isa and McArthur River: Australian Journal of Earth Sciences, v. 47, p. 431–460.

Painter, M.G.M., Golding, S.G., Hanan, K.W., and Neudert, M.K., 1999, Sedimentologic, petrographic, and sulfur isotope constraints on fine-grained pyrite formation at Mount Isa mine and environments, northwest Queensland, Australia: ECONOMIC GEOLOGY, v. 94, p. 883–912.

Parr, J.M., and Plimer, I.R., 1993, Models for Broken Hill-type lead-zinc-silver deposits: Geological Association of Canada Special Paper 40, p. 253–288.

Parr, J.M., Stevens, B.P.J., Carr, G.R., and Page, R.W., 2004, Subseafloor origin for Broken Hill Pb-Zn-Ag mineralization, New South Wales, Australia: Geology, v. 32, p. 589–592.

Perkins, W.G., 1998, Timing of formation of Proterozoic stratiform fine-grained pyrite: Postdiagenetic cleavage replacement at Mt. Isa: ECONOMIC GEOLOGY, v. 93, p. 1153–1164.

Pietsch, B.A., Rawlings, D.J., Creaser, P.M., Kruse, P.D., Ahmad. M., Ferenzi, P.A., and Findhammer, T.L.R., 1991, Bauhinia Downs SD53–3. 1:250 000 geological map series, explanatory notes: Government Printer of the Northern Territory, 76 p.

Pisutha-Arnond, V., and Ohmoto, H., 1983, Thermal history, and chemical and isotopic compositions of the ore-forming fluids responsible for the kuroko massive sulfide deposits in the Hokuroku district of Japan: ECONOMIC GEOLOGY MONOGRAPH 5, 523–558.

Plimer, I.R., 1977, The origin of albite-rich rocks enclosing the cobaltian pyrite deposit at Thackaringa, N.S.W., Australia: Mineralium Deposita, v. 12, p. 175–187.

——1979, Sulphide rock zonation and hydrothermal alteration at Broken Hill, Australia: Institute of Mining and Metallurgy Transactions, v. 88, sec. B, p. B161–B176.

——1984, The role of fluorine in submarine exhalative systems with special reference to Broken Hill, Australia: Mineralium Deposita, v. 19, p. 19–25.

——1987, Remobilization in high-grade metamorphic environments: Ore Geology Reviews, v. 2, p. 231–245.

Polito, P.A., Kyser, T.K., Golding, S.D., and Southgate, P.N., 2006a, Zinc deposits and related mineralization of the Burketown mineral field, including the world-class Century deposit, northern Australia: Fluid inclusion and stable isotope evidence for basin fluid sources: ECONOMIC GEOLOGY, v. 101, p. 1251–1273.

Polito, P.A., Kyser, T.K., and Jackson, M.J., 2006b, The role of sandstone diagenesis and aquifer evolution in the formation of uranium and zinc-lead deposits, southern McArthur basin, Northern Territory, Australia: ECONOMIC GEOLOGY, v. 101, p. 1189–1209.

Polito, P.A., Kyser, T.K., Southgate, P.N., and Jackson, M.J., 2006c, Sandstone diagenesis in the Mount Isa basin: An isotopic and fluid inclusion perspective in relationship to district-wide Zn, Pb, and Cu mineralization: ECONOMIC GEOLOGY, v. 101, p. 1159–1188.

Pottorf, F.J., and Barnes, H.L., 1983, Mineralogy, geochemistry, and ore genesis of hydrothermal sediments from the Atlantis II Deep, Red Sea: ECONOMIC GEOLOGY MONOGRAPH 5, p. 198–223.

Rasmussen, B., Krapez, B., and Groves, D.I., 1997, Assessment of base metal prospectivity in sedimentary basins based on the association between hydrocarbon and metalliferous brines migration: A feasibility study based on the Fitzroy trough/Lennard shelf, Western Australia: Minerals and Energy Research Institute of Western Australia Report 181, 202 p.

Ringrose, C. R., 1989, Studies of selected carbonate-hosted lead-zinc deposits in the Kimberley region: Geological Survey of Western Australia Report 24, 103 p.

Roedder, E., 1968, The noncolloidal origin of "colloform" textures in sphalerite: ECONOMIC GEOLOGY, v. 63, p. 451–471.

Rohrlach, B., Fu, M., and Clarke, J., 1996, The geology and paragenesis of the Walford Creek Zn-Pb-Cu-Ag prospect [abs.]: James Cook University of North Queensland, Economic Geology Research Unit Contribution 55, p. 99–103.

Romine, K.K., Southgate, P.N., Kennard, J.M., and Jackson, M.J., 1994, The Ordovician to Silurian phase of the Canning basin, W.A.: Structure and sequence evolution, *in* Purcell, P.G., and Purcell, R.R., eds., The sedimentary basins of Western Australia: West Australia basins Symposium, Perth, August, Proceedings, p. 677–696.

Rowley, M., and Lee, R.J., 1986, The Sorby Hills, W.A., lead-silver-zinc province, *in* Berkman, D.A., ed., Congress of Mining and Metallurgical Institutions Congress Geology and Exploration: Publications of the Congress of Mining and Metallurgical Institutions Congress, 13th, v. 2, p. 173–180.

Rubenach, M.J., and Barker, A.J., 1998, Metamorphic and metasomatic evolution of the Snake Creek anticline, Eastern succession, Mt. Isa inlier: Australian Journal of Earth Sciences, v. 45, p. 363–372.

Sami, T.T., James, N.P., Kyser, T.K., Southgate, P.N., Jackson, M.J., and Page, R.W., 2000, Evolution of Late Palaeoproterozoic ramp systems, Lower McNamara Group, northeastern Australia: Society for Sedimentary Geology Special Publication 67, p. 243–274.

Sangster, D.F., 1990, Mississippi Valley-type and sedex lead-zinc deposits: A comparative examination: Institute of Mining and Metallurgy Transactions, v. 99, sec. B, p. B21–B42.

Sawkins, F.J., 1968, The significance of Na/K and Cl/SO_4 ratios in fluid inclusions and subsurface waters, with respect to the genesis of Mississippi Valley-type ore deposits: ECONOMIC GEOLOGY, v. 63, p. 935–942.
——1982, The formation of Kuroko-type deposits viewed within the broader context of ore genesis theory: Mining Geology, v. 32, p. 25–33.
Schiffman, P., and Smith, B.M., 1988, Petrology and oxygen isotope geochemistry of a fossil seawater hydrothermal system within the Solea graben, northern Troodos Ophiolite, Cyprus: Journal of Geophysical Research, v. 93B, p. 4612–4624.
Schwartz, M.O., and Melcher, F., 2003, The Perkoa zinc deposit, Burkina Faso: ECONOMIC GEOLOGY, v. 98, p. 1463–1486.
Scott, D.L., Rawlings, D.J., Page, R.W., Tarlowski, C.Z., Idnurm, M., Jackson, M.J., and Southgate, P.N., 2000, Basement framework and geodynamic evolution of the Palaeoproterozoic superbasins of north-central Australia: An integrated review of geochemical, geochronological and geophysical data: Australian Journal of Earth Sciences, v. 47, p. 341–380.
Scrimgeouer, I., 2003, Developing a revised framework for the Arunta region [ext. abs.]: Northern Territory Geological Survey Record 2003–001, p. 107–121.
Sharp, J.M., 1978, Energy and momentum transport model of the Ouachita basin and its possible impact on formation of economic mineral deposits: ECONOMIC GEOLOGY, v. 73, p. 1057–1068.
Shvarov, Y., and Bastrakov, E., 1999, HCh: A software package for geochemical equilibrium modelling—user's guide: Australian Geological Survey Organisation Record 1999/25, 61 p.
Sillitoe, R.H., Hannington, M.D., and Thompson, J.F.H., 1996, High-sulfidation deposits in the volcanogenic massive sulfide environment: ECONOMIC GEOLOGY, v. 91, p. 204–212.
Skirrow, R.G., and Franklin, J.M., 1994, Silicification and metal leaching in semiconformable alteration beneath the Chisel Lake massive sulfide deposit, Snow Lake, Manitoba: ECONOMIC GEOLOGY, v. 89, p. 31–50.
Smith, J.W., and Croxford, N.J.W., 1973, Sulfur isotope ratios in the McArthur zinc-lead-silver deposit: Nature, v. 245, p. 10–12.
Smith, R.N., 1973, Trace element dispersion within some major stratiform orebodies: Unpublished B.Sc. Honours thesis, Parkville, Victoria, University of Melbourne, 132 p.
Smith, R.N., and Huston, D.L., 1992, Distribution and association of selected trace elements at the Rosebery deposit, Tasmania: ECONOMIC GEOLOGY, v. 87, p. 706–719.
Solomon, M., 1976, "Volcanic" massive sulphide deposits and their host rocks—a review and an explanation, *in* Wolf, K.H., ed., Handbook of strataform ore deposits. II. Regional studies and specific deposits: New York, Elsevier, p. 21–50.
Solomon, M., and Khin Zaw, 1997, Formation on the sea floor of the Hellyer volcanogenic massive sulfide deposit: ECONOMIC GEOLOGY, v. 92, p. 686–695.
Solomon, M., Eastoe, C.J., Walshe, J.L., and Green, G.R., 1988, Mineral deposits and sulfur isotope abundances in the Mount Read Volcanics between Que River and Mount Darwin, Tasmania, ECONOMIC GEOLOGY, v. 83, p. 1307–1328.
Solomon, P.J., 1965, Investigations into sulfide mineralization at Mount Isa, Queensland: ECONOMIC GEOLOGY, v. 60, p. 737–765.
Southgate, P.N., Bradshaw, B.E., Domalga, J., Jackson, M.J., Idnurm, M., Krassay, A.A., Page, R.W., Sami, T.T., Scott, D.L., Lindsay, J.F., McConachie, B.A., and Tarlowski, C., 2000a, Chronostratigraphic basin framework for Palaeoproterozoic rocks (1730–1575 Ma) in northern Australian and implications for base-metal mineralisation: Australian Journal of Earth Sciences, v. 47, p. 461–484.
Southgate, P.N., Scott, D.L., Sami, T.T., Domalga, J., Jackson, M.J., James, N.P., and Kyser, T.K., 2000b, Basin shape and sediment architecture in the Gun Supersequence: A strike-slip model for Pb-Zn-Ag ore genesis at Mt. Isa: Australian Journal of Earth Sciences, v. 47, p. 509–531.
Spry, P.G., Peter, J.M., and Slack, J.F., 2001, Meta-exhalites as exploration guides to ore: Reviews in Economic Geology, v. 11, p. 163–202.
Stanton, R.L., 1962, Elemental constitution of the Black Star orebodies, Mount Isa, Queensland, and its interpretation: Transactions of the Institution of Mining and Metallurgy, v. 72, p. 69–124.
——1976, Petrochemical studies of the ore environment at Broken Hill, New South Wales: 1. Constituents of "banded iron formations:" Institute of Mining and Metallurgy Transactions, v. 85, sec. B, p. B33–B46.
——1990, Magmatic evolution and ore type-lava type affiliations of volcanic exhalative ores: Australasian Institute of Mining and Metallurgy Monograph 16, p. 101–108.
Stevens, B.J.P., 2003, Understanding the Broken Hill Pb-Zn fluid system [abs.]: Geoscience Australia Record 2003/13, p. 166–169.
Stevens, B.P.J., and Barron, L.M., 2002, Volcanic textures in the Palaeoproterozoic Hores Gneiss, Broken Hill, Australia: Geological Survey of New South Wales, Quarterly Notes, v. 113, p. 1–22.
Stevens, B.P.J., Barnes, R.G., Brown, R.E., Stroud, W.J., and Willis, I.L., 1988, The Willyama Supergroup in the Broken Hill and Euriowie blocks, New South Wales: Precambrian Research, v. 40/41, p. 297–327.
Stevens, B., Parr, J., and Carr, G., 2004, New insights into the Broken Hill Pb-Zn fluid system [abs.]: Geological Society of Australia Abstracts, v. 73, p. 125.
Stolz, A.J., 1995, Geochemistry of the Mount Windsor Volcanics: Implications for the tectonic setting of Cambro-Ordovician VHMS mineralization in northeastern Australia: ECONOMIC GEOLOGY, v. 90, p. 1080–1097.
Sun-S.-S., Carr, G.R., and Page, R.W., 1996, A continued effort to improve lead-isotope model ages: AGSO Research Newsletter 24, p. 19–20.
Sverjensky, D.A., 1984, Oil field brines as ore-forming solutions: ECONOMIC GEOLOGY, v. 79, p. 23–37.
Taylor, B.E., 1986, Magmatic volatiles: Isotopic variation of C, H and S: Reviews in Mineralogy, v. 16, p. 185–226.
Tompkins, L.A., Rayner, M.J., Groves, D.I., and Roche, M.T., 1994, Evaporites: in situ sulfur sources for rhythmically banded ore in the Cadjebut Mississippi Valley-type Zn-Pb deposit, Western Australia: ECONOMIC GEOLOGY, v. 89, p. 467–492.
Tompkins, L.A., Eisenlohr, B., Groves, D.I., and Raetz, M., 1997, Temporal changes in mineralization style at the Cadjebut Mississippi Valley-type Zn-Pb deposit, Lennard shelf, W.A.: ECONOMIC GEOLOGY, v. 92, p. 843–862.
Tornos, F., 2006, Environment of formation and styles of volcanogenic massive sulfides: The Iberian Pyrite Belt: Ore Geology Reviews, v. 28, p. 259–307.
Turner, J.S., and Gustafson, L.B., 1978, The flow of hot saline solutions from vents in the sea floor: Some implications for exhalative massive sulfides and other ore deposits: ECONOMIC GEOLOGY, v. 73, p. 1082–1100.
Turner, R.J.W., Leitch, C.H.B., Ross, K., Hoy, T., Delaney, G.D., and Hagen, A., 1996, Sullivan stratiform lead-zinc deposit, British Columbia: Rift setting, associated district-scale hydrothermal field, and comparison to BHT deposits: University of Tasmania, Centre for Ore Deposit and Exploration Studies Special Publication 1, p. 153–163.
Vaasjoki, M., and Gulson, B.L., 1986, Carbonate-hosted base metal deposits: Lead isotope data bearing on their genesis and exploration: ECONOMIC GEOLOGY, v. 81, p. 156–172.
van Staal, C.R., Wilson, R.A., Rogers, N., Fyfee, L.R., Langton, J.P., McCutcheon, S.R., McNicoll, V., and Ravenhurst, C.E., 2003, Geology and tectonic history of the Bathurst Supergroup, Bathurst mining camp, and its relationships to coeval rocks in southwestern New Brunswick and adjacent mines: A synthesis: ECONOMIC GEOLOGY MONOGRAPH 11, p 37–60.
Vaughan, J.P., and Stanton, R.L., 1986, Sedimentary and metamorphic factors in the development of the Pegmont stratiform Pb-Zn deposit, Queensland, Australia: Transactions of the Institution of Mining and Metallurgy, v. 95, sec. B, p. B94–B121.
Vearncombe, J.R., Dentith, M., Dörling, S., Reed, A., Cooper, R., Hart, J., Muhling, P., Windrim, D., and Woad, G., 1995, Regional and prospect-scale fault controls on Mississippi Valley-type Zn-Pb mineralization at Blendevale, Canning basin, Western Australia: ECONOMIC GEOLOGY, v. 90, p. 181–186.
Vearncombe, J.R., Chisnall, A.W., Dentith, M., Dörling, S., Rayner, M.J., and Holyland, P.W., 1996, Structural controls on Mississippi Valley-type mineralization, the southeast Lennard shelf, Western Australia: Society of Economic Geologists Special Publication 4, p. 74–95.
Vearncombe, S.E., Vearncombe, J.R., and Barley, M.E., 1998, Fault and stratigraphic controls on volcanogenic massive sulfide deposits in the Strelley belt, Pilbara craton, Western Australia: Precambrian Research, v. 88, p. 67–82.
Vernon, R.H., 1969, The Willyama Complex, Broken Hill area: Journal of Geological Society of Australia, v. 16, p. 20–55.
Von Damm, K. L., 1990, Seafloor hydrothermal activity: Black smoker chemistry and chimneys: Annual Reviews in Earth and Planetary Sciences, v. 18, p. 173–204.
Wade, W.J., Hanor, J.S., and Sassen, R., 1989, Controls on H_2S concentration and hydrocarbon destruction in the eastern Smackover trend: Gulf Coast Association Geological Societies Transactions, v. 39, p. 309–320.
Wallace, M.W., Kerans, C., Playford, M.E., and McManus, A., 1991, Burial diagenesis in the Upper Devonian reef complexes of the Geikie Gorge

region, Canning basin, Western Australia: American Association of Petroleum Geologists Bulletin, v. 75, p. 1018–1038.
Wallace, M.W., Middleton, H.A., Johns, B. and Marshallsea, S., 2002, Hydrocarbons and Mississippi Valley-type sulfides in the Devonian reef complexes of the eastern Lennard shelf, Canning basin, Western Australia, *in* Keep, M., and Moss, S., eds., The sedimentary basins of Western Australia 3. Proceedings of the West Australian basins Symposium: Perth, Petroleum Exploration Society of Australia, p. 795–815.
Walters, S.G., 1996, An overview of Broken Hill-type deposits: University of Tasmania, Centre for Ore Deposit and Exploration Studies Special Publication 1, p. 1–10.
Walters, S., and Bailey, A., 1998, Geology and mineralization of the Cannington Ag-Pb-Zn deposit: An example of Broken Hill-type mineralization in the Eastern succession, Mount Isa inlier, Australia: ECONOMIC GEOLOGY, v. 93, p. 1307–1329.
Warren, J.K., and Kempton, R.H., 1997, Evaporite sedimentology and the origin of evaporite-associated Mississippi Valley-type sulfides in the Cadjebut mine area, Lennard shelf, Canning basin, Western Australia: SEPM (Society for Sedimentary Geology) Special Publication 57, p. 183–205.
Wedepohl, K.H., 1972a, Zinc. 30–E. Abundances in common igneous rock types: Crustal abundance, *in* Wedepohl, K.H., ed., Handbook of geochemistry: Berlin, Springer-Verlag, p. 30–E-1 to 30–E-20.
——1972b, Zinc. 30–K. Abundances in common sediments and sedimentary rocks, *in* Wedepohl, K.H., ed., Handbook of geochemistry: Berlin, Springer-Verlag, p. 30–K-1 to 30–K-13.
——1974a, Lead. 82–E. Abundances in common igneous rock types; crustal abundance, *in* Wedepohl, K.H., ed., Handbook of geochemistry: Berlin, Springer-Verlag, p. 82–E-1 to 82–E-18.
——1974b, Lead. 82–K. Abundances in common sediments and sedimentary rocks, *in* Wedepohl, K.H., ed., Handbook of geochemistry: Berlin, Springer-Verlag, p. 82–K-1 to 82–K-9.
Werdon, M.B., Layer, P.W., and Newberry, R.J., 2004, $^{40}Ar/^{39}Ar$ dating of Zn-Pb-Ag mineralization in the northern Brooks Range, Alaska: ECONOMIC GEOLOGY, v. 99, p. 1323–1344.
Williams, N., 1978a, Studies of base metal sulfide deposits at McArthur River, Northern Territory, Australia: I. The Cooley and Ridge deposits: ECONOMIC GEOLOGY, v. 73, p. 1005–1035.
——1978b, Studies of base metal sulfide deposits at McArthur River, Northern Territory, Australia: II. The sulfide-S and organic-C relationships of the concordant deposits and their significance: ECONOMIC GEOLOGY, v. 73, p. 1036–1056.
Williams, N., and Logan, R.G., 1981, Depositional environments of the sediments hosting the McArthur River stratiform Pb-Zn deposit [abs.]: Geological Society of Australia Abstracts, v. 3, p. 8.
Willis, I.L., 1989, Broken Hill stratigraphy: Sydney, Geological Survey of New South Wales, 1 sheet.
Willis, I.L., Brown, R.E., Stroud, W.J., and Stevens, B.J.P., 1983, The early Proterozoic Willyama Supergroup: Stratigraphic subdivision and interpretation of high- to low-grade metamorphic rocks in the Broken Hill block, New South Wales: Journal of the Geological Society of Australia, v. 30, p. 195–224.
Woodall, R., 1990, Gold in Australia: Australasian Institute of Mining and Metallurgy Monograph 14, p. 45–68.
Wooden, J.L., and DeWitt, E., 1991, Pb isotopic evidence for the boundary between the Early Proterozoic Mojave and central Arizona crustal provinces in western Arizona: Arizona Geological Society Digest 19, p. 27–50.
Wyborn, L., 1998, Younger ca 1500 Ma granites of the Williams and Naraku batholiths, Cloncurry district, eastern Mt. Isa inlier: Geochemistry, origin, metallogenic significance and exploration indicators: Australian Journal of Earth Sciences, v. 45, p. 397–412.
Yang, J., Large, R.R., Bull, S., and Scott, D.L., 2006, Basin-scale numerical modeling to test the role of buoyancy-driven fluid flow and heat transport in the formation of stratiform Zn-Pb-Ag deposits in the northern Mt. Isa basin: ECONOMIC GEOLOGY, v. 101, p. 1275–1292.
Yang, K., and Scott, S.D., 1996, Possible contribution of a metal-rich magmatic fluid to a sea-floor hydrothermal system: Nature, v. 383, p. 420–423.
Zaleski, E., and Peterson, V. L., 1995, Depositional setting and deformation of massive sulfide deposits, iron-formation, and associated alteration in the Manitouwadge greenstone belt, Superior province, Ontario: ECONOMIC GEOLOGY, v. 90, p. 2244–2261.
Zhang, Y., Sorjonen-Ward, P., Ord, A., and Southgate, P.N., 2006, Fluid flow during deformation associated with structural closure of the Isa superbasin after 1575 Ma in the central and northern Lawn Hill platform, Northern Australia: ECONOMIC GEOLOGY, v. 101, p. 1293–1312.