Economic Geology
Vol. 97, 2002, pp. 897–911

SCIENTIFIC COMMUNICATIONS

LEAD ISOTOPE EVOLUTION OF MINERAL DEPOSITS IN THE PROTEROZOIC THROSSELL GROUP, WESTERN AUSTRALIA

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Abstract

The Meso-Neoproterozoic Throssell Group of the Paterson orogen in Western Australia hosts the Nifty and Maroochydore sediment-hosted, replacement Cu deposits, as well as subeconomic Pb-Cu-Au veins at Goosewacker, carbonate-hosted Zn-Pb at Warrabarty, and pyritic massive sulfide at Grevillea. We report new Pb isotope data for the Nifty deposit and the Rainbow and Grevillea prospects. These data are combined with published and unpublished data to characterize the Pb isotope signatures of the deposits and prospects in the Throssell Group. In addition these data are integrated into a model for the sources of Pb in the mineralizing systems.

Lead isotope data from mineralized occurrences in the Throssell Group plot as a linear trend in $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ space. Deposits and prospects are arranged, from least to most radiogenic, as Rainbow, Warrabarty, Nifty, Goosewacker, and Maroochydore, along the trend. Secondary isochron or mixing isochron models were previously proposed to interpret the Pb isotope trend for mineral deposits and prospects in the Throssell Group. Our investigation shows that the linear trend does not represent an isochron due to the syngenetic (pre-D_4) timing for mineralization at Warrabarty and Rainbow compared to an epigenetic (syn-D_4) timing for Maroochydore, Nifty, and Goosewacker. We propose a source-mixing model, with no time dependency, to explain the deposit Pb isotope linear trend where Pb from a primitive, mantle source (Pilbara Craton, μ = 9.88) is mixed with crustal Pb (Throssell Group sedimentary rock derived from the Rudall Complex, μ = 10.55). The position of deposits and prospects along the trend suggests that the Warrabarty and Rainbow prospects have more primitive Pb and that the Maroochydore deposit contains Pb from primarily a crustal source. The Nifty deposit, and the Goosewacker and Grevillea prospects, contain a mixture of both primitive and crustal Pb.

Introduction

The Paterson orogen (Fig. 1) is a northwesterly trending belt of Paleoproterozoic to Neoproterozoic rocks that occupies a 1,200-km-long zone across the central part of Western Australia (Myers and Hickman, 1990; Williams and Myers, 1990; Bagas and Williams, 1995; Myers et al., 1996). To the west of the Paterson orogen is the Archaean Pilbara Craton and to the north and northeast is the late Carboniferous to Early Permian Canning basin (Fig. 1). To the southwest is the Neoproterozoic Bangermall basin and to the south is the Neoproterozoic Savory basin.

The Meso- to Neoproterozoic Throssell Group of the Paterson orogen hosts two important ore deposits (Fig. 2), epigenetic Cu deposits at Nifty (Anderson, 1999; Anderson et al., 2001) and Maroochydore (McKnight, 1992; Reed, 1996). There are subeconomic occurrences of Pb-Cu-Au veins at Goosewacker (Froud, 1997), carbonate-replacement Pb-Zn at Warrabarty (Smith, 1996), disseminated Cu at Rainbow (Haynes et al., 1993), and massive pyrite at Grevillea (A. Carmichael, writ. commun., 1992). The Telfer Au-Cu vein and stockwork deposits occur in the overlying Lamil Group (Goellnicht et al., 1989, 1991; Dimo, 1990; Goellnicht, 1992, Rowins, 1994; Rowins et al., 1997, 1998), and the Kintyre unconformity-related U deposit occurs at the contact of the underlying Archean basement and the Throssell Group (Jackson and Andrew, 1990; Root and Robinson, 1990).

Lead isotope studies of metallogenic provinces have aided in the fingerprinting of deposit styles, determining ages of deposits or prospects, and estimating the source(s) of Pb in mineralizing systems. Lead isotope data for mineralization and rocks of the Throssell Group have been reported by McKnight (1992) and Reed (1996) for Maroochydore, Smith (1996) for Warrabarty, and Froud (1997) for Goosewacker. Lead isotope evolution models for mineralization in the Throssell Group have been proposed by Smith (1996) and Reed (1996). These studies differ significantly in their interpretation of the data. Smith (1996) proposed a model in which the Pb isotope data formed a secondary isochron at 840 Ma and suggested that all the mineralized occurrences in the Throssell formed at one time from a Pilbara Craton Pb source, whereas Reed (1996) favored a mixing-trend isochron at 717 Ma between lead derived from the Rudall Complex and from older more depleted lead from the Pilbara Craton. Determining the correct interpretation of the Pb isotope data is significant in light of genetic and exploration models for mineralization in the Throssell Group.

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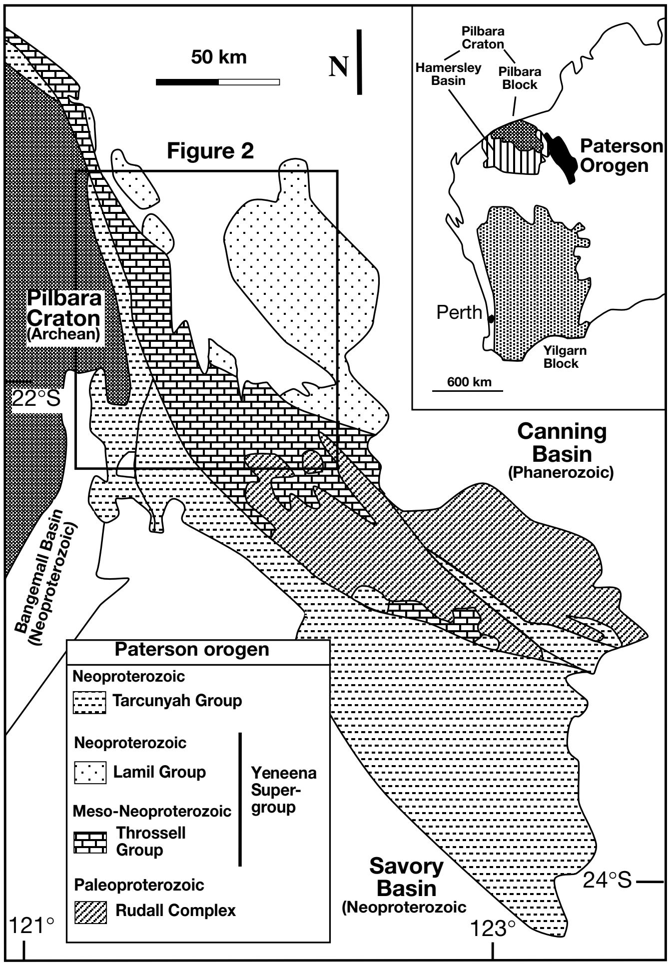

FIG. 1. Simplified map of the Paterson orogen, showing the distribution of the major stratigraphic units structures. Modified from Hickman and Clarke (1994), Smith (1996), Bagas and Lubieniecki (2000), and Anderson et al. (2001).

We report new Pb isotope data for the Nifty deposit and the Grevillea and Rainbow prospects. These new data, combined with a review of existing data and the Pb isotope models proposed by Reed (1996) and Smith (1996), have led to a greater understanding of the Pb isotope characteristics of the deposits and prospects in the Throssell Group. These data are used to propose a new source-mixing model for the sources of Pb in these mineralizing systems. The new Pb isotope data from Nifty, Grevillea, and Rainbow fill important gaps in the existing Throssell Group data set and are critical to, and support of, the source-mixing model.

Regional Geology

Stratigraphy

The Paterson orogen consists of the Paleoproterozoic Rudall Complex, the Meso- to Neoproterozoic Yeneena Supergroup and the Neoproterozoic Tarcunyah Group (Williams, 1990; Williams and Myers, 1990; Bagas et al., 1995, 1999; Williams et al., 1996; Williams and Bagas, 1999; Bagas, 2000). The Rudall Complex (Figs. 1 and 2) is the oldest unit and consists of three, tectonically juxtaposed packages of rocks, referred to as the Talbot, Connaughton, and Tabletop terranes (Bagas and Smithies, 1998; Bagas and Lubieniecki, 2000). The Talbot terrane, in the western part of the Rudall Complex, comprises banded orthogneiss and paragneiss metamorphosed to amphibolite facies (Smithes and Bagas, 1997). In the central part of the Rudall Complex the Connaughton terrane contains mafic gneiss and schist, orthogneiss, and paragneiss that have been metamorphosed to amphibolite-granulite facies. The Tabletop terrane, in the eastern part of the Rudall Complex, consists of a sequence of mafic schist, amphibolite, and metasedimentary rocks metamorphosed to upper greenschist facies (Bagas and Smithies, 1998).

Unconformably overlying the Rudall Complex are rocks of the Yeneena Supergroup, which contains the Throssell and Lamil Groups (Figs. 1 and 2). These rocks were deposited in the Yeneena basin, a strike-slip basin developed sometime between 1760 and 1200 Ma (Bagas and Smithes, 1998). The basal unit of the Throssell Group is the Coolbro Sandstone (Fig. 2) and this is conformably overlain by the shale-dominated Broadhurst Formation. The Coolbro Sandstone is interpreted as representing a fluvial-deltaic succession deposited in a dominantly transtensional basin, elongate northwest, southeast, and deepening toward the northeast (Hickman et al., 1994). The Broadhurst Formation is interpreted to represent rapid basin subsidence and pelagic deposition (Hickman and Clarke, 1994), and the depositional environment of the upper Broadhurst Formation was characterized as being a low-energy, low gradient shelf under subtidal conditions (Norris, 1987). The age of the Throssell Group has not been precisely determined.

Unconformably overlying, or in tectonic contact with, the Throssell Group is the Lamil Group, which consists of interbedded carbonate, mudstone, siltstone, and sandstone (Figs. 1 and 2). Neoproterozoic granitoids, and dolorite sills and dikes intrude the Lamil Group (Williams and Bagas, 1999). In fault contact with, or unconformably overlying, both the Rudall Complex and the Throssell Group is the Tarcunyah Group (Bagas and Smithies, 1998), which contains alternating sandstone and dolomite formations.

Structure and metamorphism

Three orogenic events (Yapungku, Miles, and Paterson orogenies) have deformed and metamorphosed Paterson orogen rocks (Hickman and Clarke, 1994; Hickman et al., 1994; Smithies and Bagas, 1997; Bagas and Smithies, 1998; Tyler et al., 1998). The Yapungku orogeny includes D_1 and D_2 and occurred between approximately 2000 and 1760 Ma, prior to the deposition of the Yeneena Supergroup and the Tarcunyah Group (Bagas and Smithies, 1995; Tyler et al., 1998). The Yapungku orogeny deformation includes an early penetrative schistosity followed by tight to isoclinal folding. The Miles orogeny consists of D_3 and D_4 and is a regional folding and cleavage event developed between 1200 and 700 Ma (Bagas and Smithies, 1995). Tyler et al (1998) suggested that the Miles orogeny occurred at approximately 1200 Ma, however Reed (1996) dated a syn-D_4 phlogopite at 717 Ma. A D_5 event, called the Blake Movement, is considered to be a local folding and faulting event with variable orientations and styles

FIG. 2. Geologic map of a northwestern portion of the Paterson orogen, showing the location of mineral deposits and prospects. Modified from Smith (1996) and Anderson et al. (2001).

(Williams and Bagas, 1999). The Paterson orogeny (D_6) is characterized by brittle deformation in response to north-northeast to south-southwest compression and is interpreted by Bagas and Smithies (1995) to be after 610 Ma and by Tyler et al. (1998) to be between 560 and 530 Ma.

Two main metamorphic events are recognized in Paterson orogen rocks, one associated with the Yapungku orogeny and a later event associated with the Miles orogeny. Amphibolite-granulite facies metamorphism associated with the Yapungku orogeny only affected the Rudall Complex (Clarke, 1991; Smithies and Bagas, 1997). The Yeneena Supergroup rocks were subjected to a second major metamorphic event during the Miles orogeny. This event, synchronous with D_4, is recognized as a retrogressive greenschist facies metamorphism in the Rudall Complex rocks and as greenschist facies metamorphism in the Yeneena Supergroup rocks (Hickman and Clarke, 1994; Bagas and Smithies, 1998).

Metallogeny

Figures 2 and 3 show the location and the relative stratigraphic position of the mineral deposits and prospects within the Paterson orogen. Table 1 lists the geologic characteristics of the deposits and prospects in the Throssell Group that are relevant to this study. Further details of these deposits and

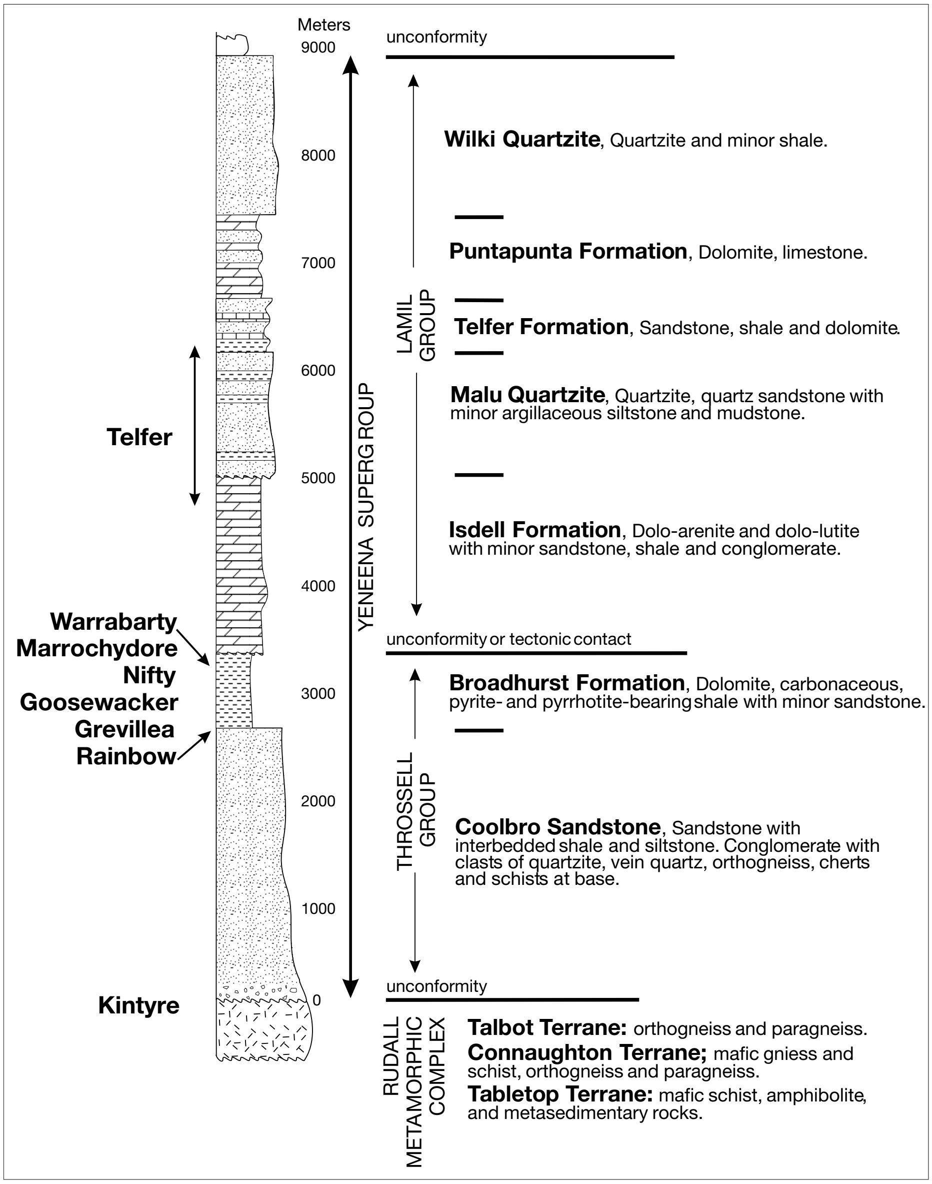

FIG. 3. Regional stratigraphic column for the Paterson orogen. Relevant startigraphic position of mineral deposits and prospects illustrated. Modified from Anderson et al. (2001).

prospects can be found in Anderson et al. (2001) and the references listed in Table 1.

Analytical Methods

Galenas from Nifty, Grevillea, Rainbow, Goosewacker, and Marrochydore were analyzed at Curtin University, Western Australia, using the methods described by McNaughton et al. (1988). Galenas fromWarrabarty were analyzed at the Commonwealth Scientific Industry Research Organization (CSIRO), New South Wales, according to the method outlined by Carr et al. (1995). Galena Pb isotope data are given in Table 2.

A whole-rock sample from the Rudell Complex was analyzed by sequential leaching (Table 3). Sample W1 is the leachate of the whole-rock powder aliquot leached in 6*N* HCl at 60°C for 3 h, W2 is the leachate of W1, treated with 5 percent HF at room temperature for 30 min. AWW is the residue of W3 (N. McNaughton, pers. commun., 1999). Table 3 lists Pb isotope analyses from the Rudell Complex and the Throssell Group. Details of the various analytical methods for the whole-rock samples can be found in the appropriate references given in Table 3.

Results

Lead isotope results for galena in mineral deposits and prospects in the Throssell Group are listed in Table 2 and plotted in Figure 4. At Nifty ten galena samples were collected and analyzed as part of this study. All samples come from quartz-pyrite-chalcopyrite-sphalerite-galena mineralization within a carbonaceous shale horizon, the pyrite marker bed (Anderson et al., 2001). These data are combined with galena analyzed by the Geological Survey of Western Australia and one galena analysis from Smith (1996). Nifty galena Pb isotope

TABLE 1. Comparison of Base and Precious Metal Occurrences in the Throssell Group

	Nifty (Cu)	Maroochydore (Cu)	Warrabarty (Zn, Pb)	Rainbow (Cu)	Grevilliea	Goosewacker (Pb, Cu, Au)
Host rock	Carbonaceous shale and dolomitic mudstone	Carbonaceous and dolomitic shale	Dolostone	Quartz arenites, chert, and chloritic siltstone	Carbonaceous siltstone and carbonate	Carbonaceous shale, siltstone, sandstone, and conglomerate
Geologic unit	Upper Broadhurst Fm.	Upper Broadhurst Fm.	Upper Broadhurst Fm.	Contact of Coolbro sandstone and basal Broadhurst Fm.	Lower to middle Broadhurst Fm.	Upper Broadhurst Fm
Metamorphic grade	Greenschist	Greenschist	Greenschist	Greenschist	Greenschist	Greenschist
Mineralization style	Strata-bound replacement and veins	Strata-bound disseminations and veins	Replacement breccia, veins, and zones of disseminated to massive sulfide	Sheetlike body (<1 m thick) of disseminated and massive sulfide	Massive sulfide	Veins
Ore mineralogy	Primary ore: chalcopyrite, pyrite, minor sphalerite, galena Secondary ore: malachite, azurite, cuprite, tenorite, native Cu, chalcocite	Primary ore: chalcopyrite, pyrite, minor sphalerite, galena Secondary ore: chalcocite, malachite, azurite, cuprite, native Cu	Sphalerite, pyrite, and galena, with minor chalcopyrite and rare arsenopyrite and bornite	Chalcopyrite, minor bornite	Pyrite with minor sphalerite and galena	Pyrite, galena, chalcopyrite, sphalerite, pyrrhotite, rare bornite and covellite, trace marcasite, bismuthinite, wittichenite
Gangue mineralogy	Quartz, dolomite, minor chlorite, fluorapatite, carbonaceous material, hematite, sericite, stilpnomelane	Dolomite, quartz, chlorite, fluorapatite, and potassium feldspar	Dolomite, minor quartz, pyrobitumen, and rare phlogopite	Quartz, chlorite, pyrrhotite, pyrite	No information	Quartz, siderite, rare hematite
Paragenesis	Syn-D_4 mineralization veins consist of IIA chalcopyrite-dolomite veins; IIB alteration margin quartz-dolomite veins; and IIC cleavage-parallel dolomite-quartz veins[1]	Pyrite, pyrrhotite, and chalcopyrite overgrowing, and in pressure shadows, of host carbonates and silicates and in D_4 stylolitic cleavage planes	Early gray-stage (pre-D_4): dolomite, sphalerite, galena, and pyrite; later white stage (syn-D_4): dolomite, quartz, minor chalcopyrite, sphalerite, and pyrite	No information	No information	Stage 1 quartz, pyrite, siderite veins; stage 2 quartz, siderite, pyrite, galena, chalcopyrite; stage 3 pyrite, galena, chalcopyrite, sphalerite-quartz ± siderite veins; stage 4 pyrite, galena, chalcopyrite, sphalerite, Bi minerals-siderite ± quartz veins; stage 5 pyrite veins
Alteration	Premineralization E1 Fe-Mg carbonate and E2 green quartz; synmineralization S1 chloritic shale, S2 silicified pyritic shale, S3 hydrothermal quartz-dolomite, S4 silicified dolomitic shale, S5 black quartz[1]	Mineralization accompanied by variable amounts of pyrite, quartz, dolomite and phlogopite Veins in pyritic shales surrounded by halos of chalcopyrite after framboidal pyrite	Mineralization associated with a medium- to coarse-grained massive dolomite that crosscuts bedding and pressure solution in earlier dolostones	No information	No information	Sericite-pyrite alteration restricted to stage 4 veins
Age of mineralization	Syn-D_4	Syn-D_4	Pre-D_4	Pre-D_4	Syn-D_4	Syn-D_4
Genetic model	Epigenetic structurally controlled strata-bound replacement and veining	Epigenetic structurally controlled strata-bound replacement and veining	Diagenetic infill, replacement, and veining	Diagenetic stratiform deposit	Epigenetic structurally controlled replacement	Epigenetic veins
Deposit size	Oxide ore: 12.2 Mt @ 2.52% Cu Sulphide ore: 26.3 Mt @ 4.6% Cu Overall: 101.8 Mt @ 1.6% Cu with 0.5% cutoff	Oxide ore: 14 Mt @ 1.6% Cu, 0.07% Co Overall: 51.3 Mt @ 1% Cu with 0.5% cutoff and 0.04% Co with 0.04 % cutoff	Subeconomic, 3 to 6 wt % Zn + Pb	Subeconomic, 54 m @ 0.3% Cu	Subeconomic	Subeconomic
Source	Anderson et al. (1997), Anderson (1999), Anderson et al. (2001), Straits Resources (2001)	Reed et al. (1995), Reed (1996), Straits Resources (2001)	Smith and Gemmell (1994), Smith (1996)	Haynes et al. (1993)	A. Carmichael (writ. commun., 1992) WMC Resources Ltd. (pers. commun., 1998)	Froud (1997)

[1] Detailed descriptions of Nifty vein and alteration stages are contained in Anderson et al. (2001)

TABLE 2. Galena Pb Isotope Results for Deposits and Prospects in the Throssell Group of the Paterson Orogen

Description	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Laboratory	Source
Nifty Cu deposit					
Gn bleb with qtz+py+cpy+gn+sph altn	17.370	15.663	37.823	GSWA/Curtin	Anderson (1999)
Gn+sph bleb in qtz+py+cpy+gn+sph altn	17.318	15.676	38.241	GSWA/Curtin	Anderson (1999)
Gn in qtz+py+cpy+gn+sph altn	17.354	15.642	37.763	GSWA/Curtin	Anderson (1999)
Gn in qtz+py+cpy+gn+sph altn	17.356	15.655	37.798	GSWA/Curtin	Anderson (1999)
Gn in qtz+py+cpy+gn+sph altn	17.337	15.625	37.705	GSWA/Curtin	Anderson (1999)
Gn in qtz+py+cpy+gn+sph altn	17.352	15.647	37.759	GSWA/Curtin	Anderson (1999)
Gn in qtz+py+cpy+gn+sph altn	17.362	15.649	37.775	GSWA/Curtin	Anderson (1999)
Gn in qtz+py+cpy+gn+sph altn	17.366	15.651	37.789	GSWA/Curtin	Anderson (1999)
Gn selvage on py grain	17.327	15.621	37.695	GSWA/Curtin	Anderson (1999)
Gn in qtz+py+cpy+gn+sph altn	17.390	15.627	37.734	GSWA/Curtin	GSWA (unpub. data)
Gn in qtz+py+cpy+gn+sph altn	17.343	15.623	37.685	GSWA/Curtin	GSWA (unpub. data)
Gn in qtz+py+cpy+gn+sph altn	17.356	15.631	37.711	CSIRO	Smith (1996)
Maroochydore Cu deposit					
Pb-Zn-Cu vn in pyritic shale	17.986	15.728	38.228	UWA/Curtin	McKnight (1992)
Footwall Pb-Zn vn	17.864	15.717	37.994	UWA/Curtin	McKnight (1992)
Gn vn in footwall siltstone	17.616	15.720	37.924	UWA/Curtin	McKnight (1992)
Gn in coarsely crystalline dol vn	17.643	15.708	37.853	UWA/Curtin	McKnight (1992)
Gn in antithetic reidel shears and assoc vn	18.606	15.769	38.879	UWA/Curtin	McKnight (1992)
Gn in coarsely crystalline dol vn	17.671	15.772	37.831	UWA/Curtin	McKnight (1992)
Gn+qtz+cpy+sph vn	18.572	15.779	38.878	GSWA/Curtin	GSWA (unpub. data)
Gn+qtz+cpy+sph vn	17.982	15.731	38.195	GSWA/Curtin	GSWA (unpub. data)
Gn	18.503	15.777	38.660	GSWA/Curtin	GSWA (unpub. data)
Gn+qtz+cpy+sph vn	17.621	15.706	37.849	GSWA/Curtin	GSWA (unpub. data)
Gn in qtz-phlog-dol sulfide vein	17.664	15.720	37.857	UWA/Curtin	Reed (1996)
Gn in qtz-phlog-dol sulfide vein	17.648	15.718	37.900	UWA/Curtin	Reed (1996)
Gn in qtz-phlog-dol sulfide vein	17.646	15.711	37.870	UWA/Curtin	Reed (1996)
Gn in qtz-phlog-dol sulfide vein	17.665	15.711	37.836	UWA/Curtin	Reed (1996)
Warrabarty Zn-Pb prospect					
Massive sp-gn-hem in gray stage	17.269	15.591	37.597	CSIRO	Smith (1996)
Sph-py-dol in gray-stage bx/vn	17.188	15.563	37.523	CSIRO	Smith (1996)
Massive sph-py-gn in gray stage	17.190	15.564	37.542	CSIRO	Smith (1996)
Gn in gray-stage vn	17.261	15.577	37.561	CSIRO	Smith (1996)
Gn in gray-stage vn	17.281	15.597	37.625	GSWA/Curtin	GSWA (unpub. data)
Gn in gray-stage vn	17.214	15.585	37.589	GSWA/Curtin	GSWA (unpub. data)
Gn in gray-stage vn	17.192	15.567	37.527	GSWA/Curtin	GSWA (unpub. data)
Rainbow Cu prospect					
"Gn, crosscutting cb-gn-cpy"	17.741	15.618	38.642	GSWA/Curtin	Anderson (1999)
Gn in bedding parallel qtz-chl sulfide vn	17.031	15.507	37.369	CSIRO	Smith (1996)
Goosewacker Pb-Cu-Au prospect					
Gn in stage 2 vn	17.598	15.708	38.278	GSWA/Curtin	Froud (1997)
Gn in stage 4 vn	17.483	15.670	38.248	GSWA/Curtin	Froud (1997)
Gn in stage 3 vn	17.488	15.685	38.233	GSWA/Curtin	Froud (1997)
Grevillea massive sulfide					
Gn in cb-vn	17.609	15.643	38.048	GSWA/Curtin	Anderson (1999)
Gn in cb-vn	17.592	15.630	37.982	GSWA/Curtin	Anderson (1999)

Abbreviations: altn = alteration, assoc = associated, bx = breccia, cb = carbonate, chl = chlorite, cpy = chalcopyrite, DDH = diamond drill hole, gn = galena, hem = hematite, py = pyrite, sph = sphalerite, vn = vein; CSIRO = Commonwealth Scientific and Industrial Research Organisation, Curtin = Curtin University of Technology, GSWA = Geological Survey of Western Australia; specific location details can be found in relevant references

data plot as a group in Figure 4. Galena analyzed in this study overlaps with the two existing galena results (Table 2).

Fourteen galena samples from quartz-phlogopite sulfide veins of the Maroochydore mineralization were analyzed by Reed (1996). Eight of the samples plot as a tight group with lower $^{206}Pb/^{204}Pb$ ratios compared to six samples which form a trend to more radiogenic ratios (Fig. 4). Reed (1996) concluded that the difference between the two groups was due to variable compositions of the source rocks at the time of mineralization because there appears to be no geologic difference between the samples.

Seven galena samples were analyzed from Warrabarty early (gray-stage) synmineralization veins or from massive sulfide that is paragenetically related to the gray-stage veins (Smith, 1996). Warrabarty galena data plot as a cluster and are the least radiogenic data for all the mineral deposits and prospects of the Throssell Group, with the exception of a single result from the Rainbow prospect.

TABLE 3. Whole-Rock and Mineral Separate Pb Isotope Data for Rudell Complex and Throssell Group

Sample	Unit	Sample type	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Source
Rudell Complex						
Rudell Complex 1	Syenogranite gneiss-Talbot terrane	K feldspar separate (104932)	16.758	15.591	36.510	Goelnicht (1992)
Rudell Complex 2	Metasyenograntic pegmatoid dike-Talbot terrane	K feldspar separate 104983)	18.272	15.663	38.628	Goelnicht (1992)
Rudell Complex 3	Seriate biotite meta-monzogranite- Talbot terrane	K feldspar separate (112102)	16.984	15.525	37.883	This study[1]
Rudell Complex 4	Porphyritic biotite monzogranitegneiss-Talbot terrane	K feldspar separate (112397)	16.728	15.566	37.443	This study[1]
Runton Adamellite 1	Biotite monzogranite-Tabletop terrane	WR = whole rock	18.261	15.749	39.259	N. McNaughton (writ. commun., 1990)
Runton Adamellite 2	Biotite monzogranite-Tabletop terrane	AWW = residue of W3	17.829	15.729	37.833	N. McNaughton (writ. commun., 1990)
Runton Adamellite 3	Biotite monzogranite-Tabletop terrane	W1 = leachate of WR	17.323	15.671	37.412	N. McNaughton (writ. commun., 1990)
Runton Adamellite 4	Biotite monzogranite-Tabletop terrane	W2 = leachate of W1	21.060	15.972	45.337	N. McNaughton (writ. commun., 1990)
Runton Adamellite 5	Biotite monzogranite-Tabletop terrane	W3 = leachate of W2	20.408	15.892	14.818	N. McNaughton (writ. commun., 1990)
Throssell Group						
Marrochydore	Broadhurst Fm.	Whole rock	19.086	15.789	38.681	Reed (1996)
Marrochydore	Broadhurst Fm.	Whole rock	18.617	15.848	38.877	Reed (1996)
Marrochydore	Broadhurst Fm.	Whole rock	17.728	15.715	37.891	Reed (1996)
Marrochydore	Broadhurst Fm.	Whole rock	17.738	15.725	37.945	Reed (1996)
Marrochydore	Broadhurst Fm.	Whole rock	18.287	15.750	38.140	Reed (1996)
Marrochydore	Broadhurst Fm.	Whole rock	22.171	15.991	44.587	Reed (1996)
Warrabarty	Broadhurst Fm.	Whole rock	17.388	15.674	37.868	Smith (1996)
Nifty	Broadhurst Fm.	Diagenetic pyrite nodule	17.467	15.672	37.834	Smith (1996)
Nifty	Broadhurst Fm.	Whole rock	17.925	15.664	38.350	Smith (1996)
Finch	Broadhurst Fm.	Whole rock	18.346	15.687	38.194	Smith (1996)
Moloch	Broadhurst Fm.	Whole rock	18.549	15.761	39.210	Smith (1996)
Rainbow	Coolbro Sandstone	Whole rock	22.883	16.069	42.877	Smith (1996)
Rainbow	Coolbro Sandstone	Whole rock	27.510	16.717	41.781	Smith (1996)
Eva Well intrusion	Mafic intrusion	Whole rock	18.702	15.786	38.896	Reed (1996)
Eva Well intrusion	Mafic intrusion	Whole rock	22.323	15.965	43.975	Reed (1996)
Eva Well intrusion	Mafic intrusion	Whole rock	19.768	15.817	40.178	Reed (1996)

For specific loacation details refer to relevant references; Finch is 20 km southwest of Nifty, Moloch is 15 km west of Goosewacker
[1] For sample details see Nelson (1994, 1995)

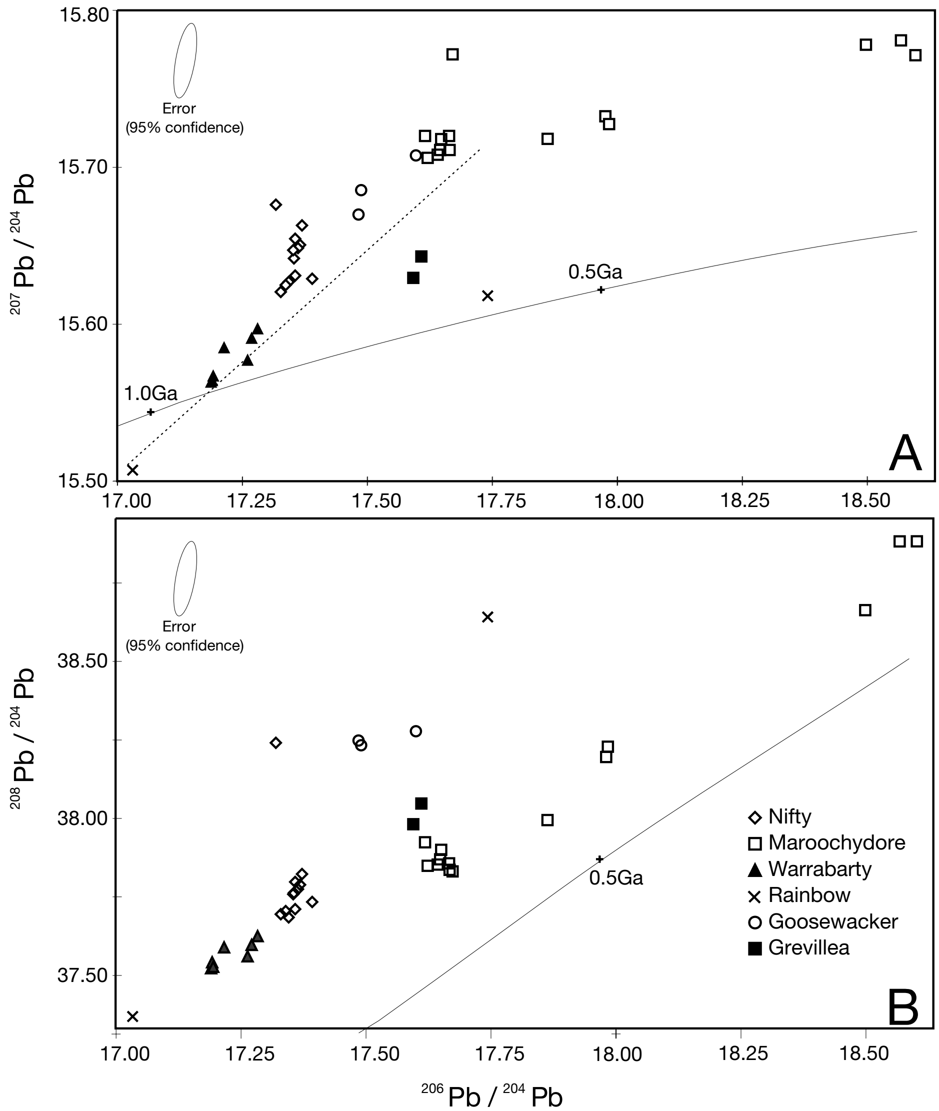

FIG. 4. Lead isotope data of sulfides from mineralized occurrences in the Throssell Group. Location of the deposits and prospects are shown in Figure 2. A. Diagram illustrating that the Throssell Group mineral deposits and prospects plot as clusters on a linear trend (dashed line). Warrabarty is located at the least radiogenic end and Maroochydore at the most radiogenic end of the trend. The growth curve of Cumming and Richards (1975) is included for reference. Data as listed in Table 2.

Two galenas from quartz-carbonate-chlorite sulfide veins from Rainbow were analyzed. One sample, from a bedding-parallel quartz-chlorite sulfide vein, has the least radiogenic ratios of all the galena from the Throssell Group mineralization. The other sample, from a crosscutting carbonate-sulfide vein collected as part of this study, has a more radiogenic signature.

Froud (1997) collected galena from the three main mineralized vein stages at Goosewacker (Tables 1 and 2). Two of the three Pb isotope results from Goosewacker plot as a group with $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios less than Maroochydore and greater than Nifty data (Fig. 4). The other sample is more radiogenic and plots with the Maroochydore data. In the thorogenic diagram (Fig. 4B) the Goosewacker data are more radiogenic than other Throssell Group mineral deposits and prospects.

Two galenas from dolomite veins at Grevillea were analyzed. Both samples have similar Pb isotope ratios and plot as a tight group that is somewhat separate (Fig. 4A) from the other deposits and prospects.

Throssell Group mineralization linear trend

Lead isotope data from mineralized occurrences in the Throssell Group form distinct clusters that plot along a linear trend in $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ space (Fig. 4A). Deposits and prospects are arranged, from least to most radiogenic, as Rainbow (least radiogenic sample), Warrabarty, Nifty, Goosewacker to Marrochydore, along the trend. Lead isotope data for Grevillea, the most radiogenic Rainbow sample and several of the Marrochydore samples plot off and below the trend. It could be argued that the linear trend is a feature of systematic error due to laboratory methods; however, this suggestion is not supported as the data from different deposits and prospects analyzed at different laboratories are consistent (Table 2).

Linear Pb isotope trends for ore deposits in mineral districts have been reported by Godwin and Sinclair (1982) for the northern Canadian cordillera, Andrew et al. (1984) and Beaudoin (1997) for the southeastern Canadian cordillera, Franklin et al. (1988) for the Superior and Southern provinces of the Canadain shield, LeHuray et al. (1987) for the carbonate-hosted Zn-Pb deposits in central Ireland, and Billström (1989) for the Svecofennian sulfide ores in Sweden and Finland. The general consensus of these studies is that Pb isotope trends represent mixing of Pb sources, either as secondary isochrons or source-mixing trends.

In order to properly interpret the deposit clusters and the apparent linear trend of Pb isotope data for the Throssell Group deposits and prospects, sources of Pb and the ages of mineralization need to be evaluated.

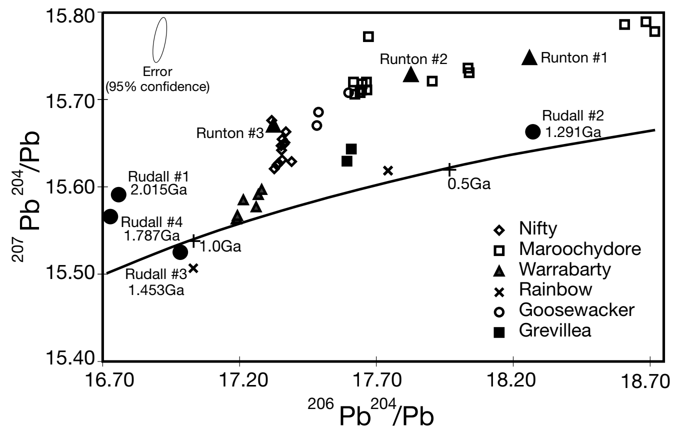

FIG. 5. Lead isotope data for the Rudall Complex (Table 3). Rudall 1 and 2 are metasyenogranites (Goellnicht, 1992), Rudall 3 and 4 are monzogranites (this study). Runton 1 to 3 are from the Runton Adamillite (N. McNaughton, writ. commun., 1990). Lead isotope data for the mineral deposits and prospects of the Throssell Group plotted for comparison. Growth curve of Cumming and Richards (1975) included for reference.

Potential Pb Sources

Potential sources for Pb in the deposits and prospects of the Throssell Group are the (1) Rudall Complex, (2) Pilbara Craton, (3) Pb internally sourced from the Broadhurst Formation or Coolbro Sandstone (Pb leached from sediment dominated by the Pilbara Craton or Rudall Complex detritus will have an isotopic signature consistent with the source), or (4) coeval igneous activity. Throughout most of the exposed Throssell Group the underlying basement rocks are unknown, however, there are two possibilities: the Lower Proterozoic Rudall Complex and the Archean Pilbara Craton (Fig. 2). In the Maroochydore area, an unconformable contact between the Throssell Group and the Rudall Complex is exposed (Hickman and Clarke, 1994; Bagas and Smithies, 1998). Here paleocurrent data within the lowermost conglomerate units of the Coolbro Sandstone close to the Maroochydore deposit (Fig. 2) indicate a northeasterly and northerly directed flow, suggesting that the dominant detritus in this area was from the Rudall Complex (Hickman and Clarke, 1994). Warrabarty is located on the western margin of the Paterson orogen and is in closer proximity to the Pilbara Craton than the Rudall Complex. Therefore it is likely that Throssell Group sediment in the Warrabarty area was dominated by material derived from the Pilbara Craton with minor amounts of Rudall Complex detritus. There is no information on the rocks below the Throssell Group at Nifty, Goosewacker, or Grevillea.

Rudall Complex

Limited Pb isotope data are available for the Rudall Complex. Two samples of potassium feldspar separates (samples Rudall 3 and 4; Table 3) from pre-D_2 gneisses of the Talbot terrane used for U-Pb zircon dating (Nelson, 1995, 1996) were provided by the Geological Survey of Western Australia and analyzed as part of this study. These samples are the least radiogenic of the data and are considered to be the best estimate of the Rudall Complex Pb initial ratio (Fig. 5). These samples also plot relatively close to the least radiogenic end of the Throssell mineralization trend (Fig. 5).

Goellnicht (1992) reports Pb isotope analyses for two potassium feldspar separates from metasyenogranites of the Talbot terrane that were used for age dating (samples Rudall 1 and 2; Table 3). These analyses are considered problematic due to conflicting ages (Nelson, 1995) and a reinterpretation of the geology of the outcrops from which the samples were collected (Bagas, pers. commun., 1998). Data from the Runton Adamellite, a post-D_2 nonfoliated biotite monzogranite (Chin and de Laeter, 1981) of the Tabletop terrane plots parallel to the Cumming and Richards (1975) growth curve, however these data are more radiogenic than the other Rudall Complex data.

As the interpreted Pb isotope initial ratio data from the Rudall Complex plot over a wide range in Figure 5 it is suggested that these rocks had a heterogeneous Pb signature that is not readily characterized.

Pilbara Craton

The second option for a Pb source is the Pilbara Craton. Figure 6 presents whole-rock Pb isotope data for the Pilbara (3.6–3.0 Ga) and Mount Bruce (2.8–2.6 Ga) Supergroups from Richards et al. (1981), Richards and Blockley (1984), and Thorpe et al. (1992). Figure 6 has Pb isotope data plotted in stratigraphic order with the Talga Talga Subgroup of the Pilbara Supergroup being the oldest unit and the Kylena Basalt of the Fortescue being the youngest of the Mount Bruce Supergroup. Duffer Formation samples from the volcanic-hosted massive sulphide (VHMS) deposits of Big Stubby and Lennons Find plot with the least radiogenic Pilbara values, although the Talga Talga Subgroup and the Mount Ada Basalt are stratigraphically below the Duffer Formation. Model Pb data from the North Pole VHMS deposit, hosted by the Towers Formation, plot as a group above the Duffer Formation data along the Cumming and Richards (1975) Pb growth curve. The Fortescue Group data, and specifically the Kylena Basalt, plot along the growth curve as a cluster (see inset in Fig. 6A).

Lead from the Pilbara Craton is considered to have a primitive mantle origin because the Pb isotope data from rocks and VHMS mineralization of the Pilbara Craton plot along

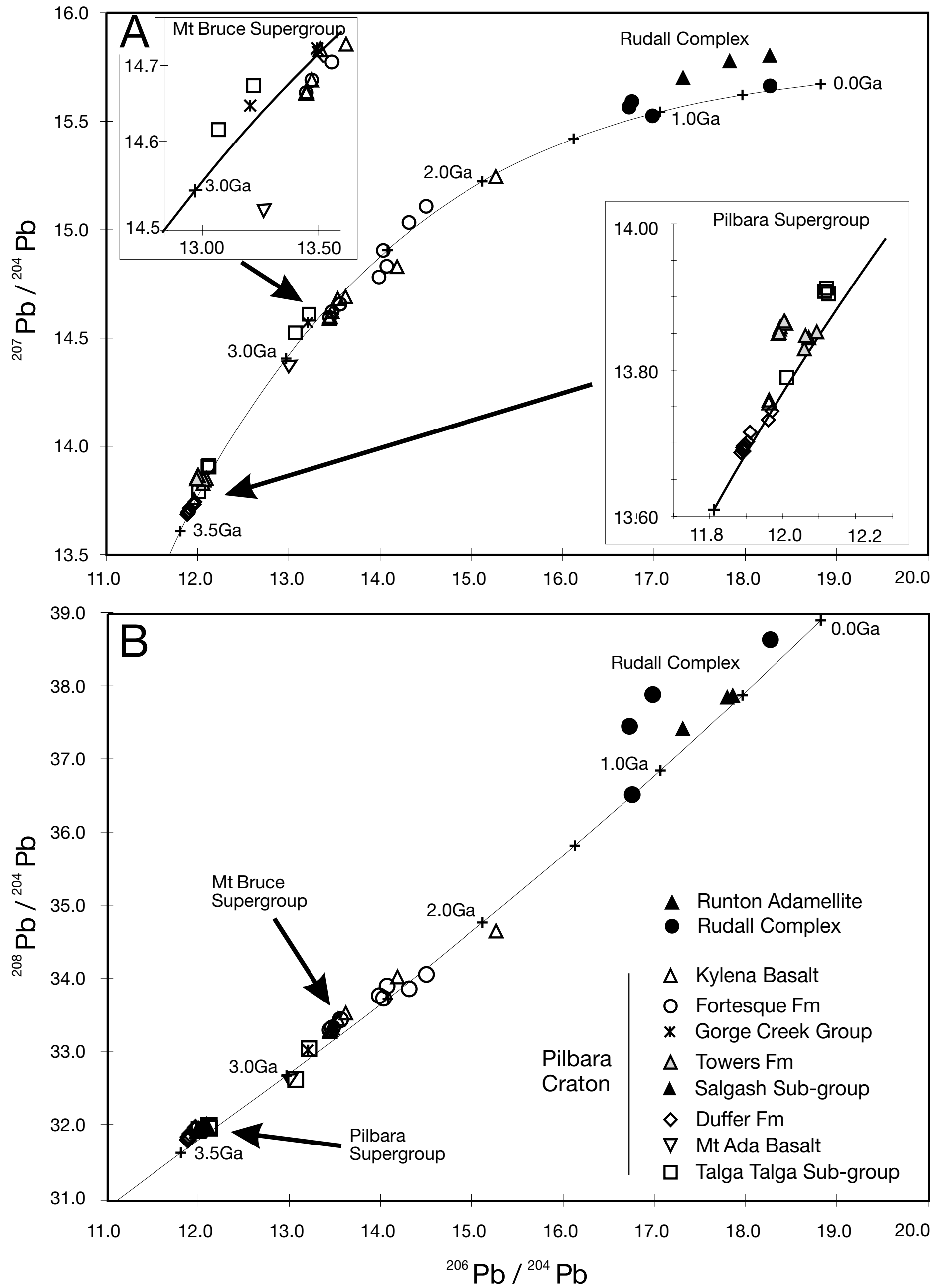

FIG. 6. Lead isotope data from the Pilbara and Mount Bruce Supergroups of the Pilbara Craton. Lead isotope data from the Rudall Complex is less radiogenic than the Pilbara Craton data. Data as given in Richards et al. (1981), Richards and Blockley (1984), and Thorpe et al. (1992). Growth curve of Cumming and Richards (1975) included for reference.

the two-stage Pb growth curve of Cummings and Richards (1975). Lead-lead ages calculated from the massive sulfide mineralization are equivalent to zircon U-Pb ages for the host rocks (Richards and Blockey, 1984), indicating that the galena isotope ratios are the initial Pb isotope ratios for the Pilbara Craton.

Throssell Group

Whole-rock Pb isotope data from the Throssell Group sedimentary rocks are shown in Figure 7. Reed (1996) analyzed nine whole-rock samples and Smith (1996) analyzed six whole-rock samples and one diagenetic pyrite from the Throssell Group (Table 3). These data form a broad radiogenic field above the Cumming and Richards (1975) growth curve. The radiogenic nature of this data is due to very low initial Pb values in the rocks.

Figure 6 illustrates that the Pb from the Rudall Complex is more radiogenic than the Pb from the Pilbara Craton. A comparison of data in Figures 6 and 7 illustrates that the least radiogenic Pb in the Throssell Group sedimentary rocks is similar to the Pb isotope values of the Rudall Complex.

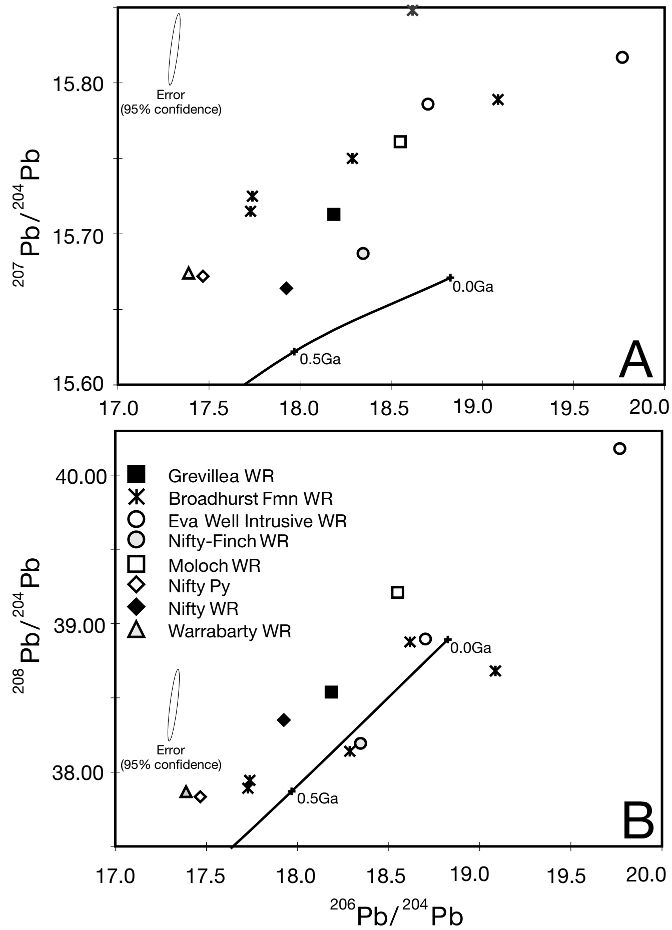

FIG. 7. Whole-rock Pb isotope data for the Throssell Group and the Eva Well intrusion. These data form a field that is generally more radiogenic than the growth curve of Cumming and Richard (1975). Data as listed Table 3.

Coeval igneous activity

Ground magnetics, gravity surveys, and diamond drilling in the Maroochydore area have defined a mafic igneous body, with traces of chalcopyrite, pyrrhotite, pyrite, and pentlandite, which is subconcordant to bedding, called the Eva Well intrusion (Reed, 1996). The age of crystallization of the Eva Well intrusion is considered to be 816 ± 6 Ma based on U-Pb SHRIMP dating of zircons (Reed, 1996). The Eva Well intrusion is the only syn-D_4 igneous activity recognized to date in the Paterson orogen. Two whole-rock Pb isotope analyses from the Eva Well intrusion plot within the Throssell Group sedimentary whole-rock field (Fig. 7).

Previous Pb Isotope Models

Previously, two models were proposed for the Pb isotope evolution of the Throssell Group mineral deposits and prospects by Smith (1996) and Reed (1996). The interpretations presented in these models are reviewed and, in light of new Pb isotope data reported in this paper and recent knowledge on the relative timing of mineralizing events, a new Pb isotope model for the Throssell Group mineralization is proposed. A preliminary assessment of this model was discussed in Anderson et al. (1998).

Secondary isochron model (Smith, 1996)

Smith (1996) characterized the Pb signature of the Warrabarty Pb-Zn prospect and modeled potential Pb sources of the Pilbara Craton, Rudall Complex, and Yeneena Supergroup sediments (Fig. 8A). Smith (1996) was the first to note that Pb isotope ratios of galena from Rainbow, Warrabarty, Nifty, and

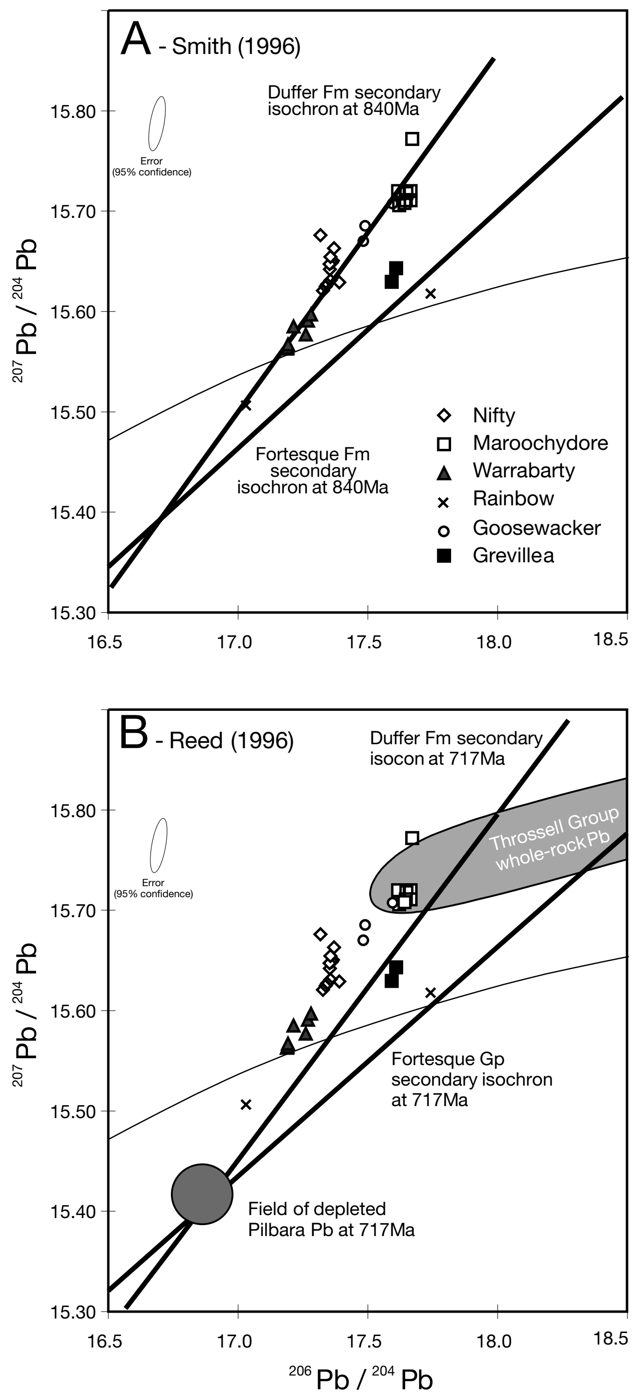

FIG. 8. Previous Pb isotope models for mineral deposits and prospects in the Throssell Group. A. Secondary isochron model proposed by Smith (1996) with a calculated age of 840 Ma. B. Mixing isochron model of Reed (1996) with a calculated age of 717 Ma. Shaded region for Throssell Group rocks represent data as listed in Table 3. See text for discussion.

Maroochydore defined a linear trend. He also suggested that the continuation of that trend intersected data from the Big Stubby VHMS deposit in the Duffer Formation of the Pilbara Supergroup. Smith (1996) interpreted the Pb isotope linear trend to represent a secondary isochron calculated at 840 Ma and concluded that this age was consistent with a diagenetic timing for the Warrabarty mineralization and by implication all other mineralized occurrences in the Throssell Group. He suggested a basin-wide, syngenetic mineralizing event with Pb in all the deposits and prospects being derived from leaching of Throssell Group sediments that had a Pilbara Craton provenance. At the time of Smith's (1996) interpretation little was known about the structural and paragenetic timing of the Nifty and Maroochydore deposits.

Mixing isochron model (Reed, 1996)

Reed (1996) modeled the origin of lead at the Maroochydore copper deposit using pyrite, chalcopyrite, galena, and whole-rock Pb isotope analyses, an Ar/Ar age of 717 ± 5 Ma on synmineralization phlogopite, and the 816 ± 6 Ma age of the Eva Well intrusion (Fig. 8B). Reed (1996) defined a field of Maroochydore galena and Broadhurst Formation whole-rock Pb isotope data and interpreted this Pb to have been leached from the Rudall Complex. Reed (1996) also constructed paleoisochrons for the Warrawoona and Fortescue Groups at 717 Ma and defined a second field of depleted lead from the Pilbara Craton at the intersection of those isochrons (Fig. 8B). He interpreted the Throssell mineral deposit linear trend to be a mixing isochron at 717 Ma between Pb derived from the Rudall Complex and the field of older, more depleted lead from the Pilbara Craton. Reed (1996) concluded that, because the Pb isotope analyses of the Maroochydore deposit plot within the Throssell Group whole-rock Pb field, the host rocks are the most likely source of the Pb in the deposit.

Discussions of previous models

The main difference between the two previous Throssell Group models (Reed, 1996; and Smith, 1996) is whether the Throssell mineralization Pb isotope trend is a secondary isochron at 840 Ma or a mixing trend isochrcon at 717 Ma. Smith (1996) interpreted Warrabarty mineralization as occurring after late diagenetic dolomitization and bedding-parallel pressure solution but before regional D_2 deformation. He suggested that all the mineralization occurred simultaneously throughout the basin at 840 Ma.

Reed (1996) directly dated Maroochydore mineralization at 717 ± 5 Ma (syn-D_4) using Ar/Ar on synmineralization phlogopite in chalcopyrite veins. This age, and the knowledge at that time of the mineral deposits, also led Reed (1996) to suggest that all mineralization occurred synchronously throughout the Throssell Group of the Paterson orogen but at 717 Ma. It could be argued that if the interpretation that all mineralization in the Throssell Group occurred predeformation (Smith, 1996), the (syn-D_4 717 ± 5 Ma Ar/Ar age reflects reequilibration or Ar loss during subsequent metamorphism, with chalcopyrite having been remobilized into phlogopite-bearing veins. No evidence of reequilibration or Ar loss is observed in the twelve-step incremental heating plateau of the Ar/Ar results (Reed, 1996). Furthermore, no textural evidence of remobilized sygenetic chalcopyrite has been observed at Maroochydore (Reed, 1996) or Nifty (Anderson et al., 2001).

As the geologic evidence overwhelmingly indicates mineralization formed at different times during the evolution of the Paterson orogen, the use of isochron models to explain the Pb isotope data is incorrect, and a new model is needed to explain the character and distribution of the Pb isotope data. Clarification is also required as to the source(s) of Pb because Smith (1996) favored a source from Throssell Group sediments with a Pilbara Craton source and Reed (1996) suggested mixing between sedimentary Pb, originally derived from the Rudell Complex with Pb derived from the older, more depleted Pilbara Craton.

New Throssell Group Pb Isotope Model

A new model is proposed to explain the Pb isotope trend of prospects or deposits in the Throssell Group and the sources of Pb (Fig. 9). We suggest that the Pb isotope trend represents a mixing line, but not an isochron as previously interpreted, between a crustal Pb reservoir defined by least radiogenic Throssel Group sedimentary whole-rock Pb and a primitive reservoir defined by the Pb evolution trend of Pilbara data, The position of prospects and deposits along the Throssell mineralization trend is a function of the relative proportion of crustal and primitive Pb. Unlike previous models, our model makes no assumptions concerning the relative timing of mineralization and focuses on the types and relative proportions of source Pb.

In order to reinterpret the Throssell Group Pb isotope minerlization trend, two Pb evolution curves (Fig. 9) were calculated with a T_1 of 3.7 Ga and initial values of $^{206}Pb/^{204}Pb$

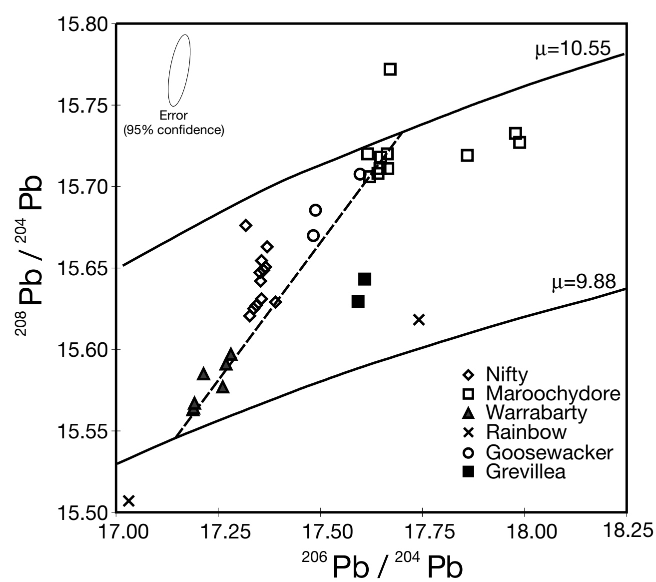

FIG. 9. New Pb isotope evolution model for mineralization in the Proterozoic Throssell Group, Western Australia. The linear Pb isotope trend for deposits and prospects (dashed line) is interpreted to be a source-mixing model where Pb from a primitive source (μ = 9.88) is mixed with crustal Pb (μ = 10.55). The position of deposits and prospects along the linear Pb isotope trend suggests that Pb in Warrabarty is dominated by primitive Pb (Pilbara source) and that Pb in Maroochydore has a crustal source (Pb leached from sediment with a Rudall Complex provenance). Lead in Nifty, Goosewacker, and Grevillea is interpreted to have a mixed source.

and $^{207}Pb/^{204}Pb$ of 11.152 and 12.998, respectively (Stacy and Kramer, 1975). The μ values (present $^{238}U/^{204}Pb$) were varied until a curve (μ = 10.55) fitted the upper end of the Throssell Group (crustal source) and a less radiogenic curve (μ = 9.88) fitted the extension of the Pilbara Craton trend. The lower μ value curve plots close to the Cumming and Richards (1975) growth curve indicating a mantle source. Calculating isotope evolution trends of Pb from two source reservoirs with differing μ values (10.55 and 9.88) allows a source-mixing model to be assessed.

The position of deposits and prospects along the linear Pb isotope trend indicates that Pb in the Warrabarty Pb-Zn prospect is dominated by primitive Pb (Pilbara source) but Pb at the Maroochydore Cu deposit has a crustal source (Pb leached from Thossell Group sediment with a Rudall Complex provenance). Lead in the Nifty Cu deposit, Goosewacker Pb-Cu-Au vein prospect, and Grevillea massive sulfide prospect all appear to have a mixed source. The Rainbow Cu prospect is interpreted to contain more primitive, mantle-derived Pb.

In light of this new Pb isotope model and current knowledge of deposit geology, the following scenario is proposed for the mineralizing events of the Throssell Group of the Paterson orogen (Fig. 10). After deposition of the sedimentary rocks (pre-D_4) of the Throssell Group (Fig. 10A), fluids circulating through the Coolbro Sandstone and the Broadhurst Formation, possibly in response to the initiation of the Miles orogeny, formed mineralization at Warrabarty and Rainbow (Fig. 10B). Zinc-lead mineralization at Warrabarty formed during late diagenesis of the Broadhurst Formation (Smith, 1996). Copper mineralization at Rainbow is hosted in the upper Coolbro Sandstone and basal Broadhurst Formation and has been described as a miniature analogue of the stratiform Cu deposits of the Zambian copperbelt (Haynes et al., 1993). As both the Warrabarty and Rainbow mineralizations contain the least radiogenic Pb in all of the Thorssell Group deposits and prospects it is interpreted that the Pb in the hydrothermal fluids either circulated through the basement Pilbara Craton or the basal units of the Yennena basin in areas containing detritus originating from the Pilbara Craton.

Compression associated with the Miles orogeny (syn-D_4) caused the expulsion of hydrothermal fluids from deep in the basin (Fig. 10C). Fluid expulsion was driven by lithostatic loading due to overriding thrust sheets with hydrothermal fluids flowing toward the foreland (Anderson et al., 2001). These fluids interacted with receptive lithologies in the Broadhurst Formation and precipitated the copper mineralization at Nifty and Marrochydore, as well as the Goosewacker Pb-Cu-Au veins. Lack of information on the Grevillea prospect makes conclusions as to its genesis tenuous, but it most likely formed at the same time as Nifty and the other prospects.

The source of Pb in the syn-D_4 phases of mineralization is mixed. These fluids have most likely interacted with rocks that have both the Pilbara and Rudall Pb signatures. It is most likely that the Throssell Group units in the south contain more Rudall Complex detritus and therefore fluid interacting with these rocks, and the underlying Rudall Complex, will have a less radiogenic signature, as is the case for the Maroochydore deposit. The six maroochydore galenas that plot well off the linear trend (Fig. 4A) have very radiogenic signatures, indicating

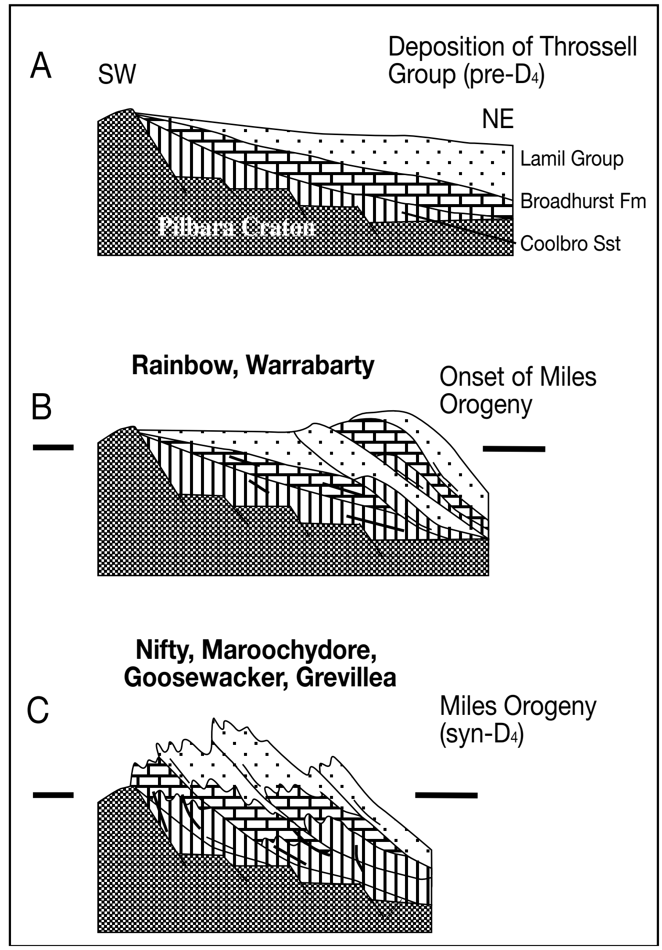

FIG. 10. Schematic model of the mineralization events of the Throssell Group of the Paterson orogen. A. Deposition of the sedimentary rocks of the Throssell Group above rifted Pilbara Craton crust in pre-D_4. B. Fluid flow through the Coolbroo Sandstone and the Broadhurst Formation, possibly related to the onset of the Miles orogeny, resulted in the deposition of stratiform Cu at Rainbow and strata-bound Pb-Zn at Warrabarty. C. During the Miles orogeny (syn-D_4) fluids sourced from deep in the basin flowed along thrust faults to receptive sites in the Broadhurst Formation, forming the epigenetic Cu deposits at Nifty and Marrochydore, the Goosewacker Cu-Pb-Au veins, and the Grevillea massive sulfide prospects. Modified from Smith (1996).

that parts of the Rudall Complex had heterogeneous, and high, U/Pb values. Nifty, Goosewacker, and Grevillea have a mixed Pb source signature and the fluids responsible for these mineralized occurrences likely interacted with Thossell Group sediments that contained both Pilbara Craton and Rudall Complex detritus.

Conclusions

New galena Pb isotope data from the Nifty copper deposit and other regional prospects in the Throssell Group have been combined with existing galena and whole-rock data to interpret the characteristics and sources of Pb in mineralization within the Paterson orogen. Lead isotope ratios from the Throssell Group deposits and prospects plot as a linear trend, which is interpreted to indicate mixing between two Pb sources where lead from a primitive source (μ = 9.88) is mixed with crustal Pb (μ = 10.55). The position of deposits and prospects along the linear Pb isotope trend indicates that the Pb in the Warrabarty Pb-Zn and Rainbow Cu prospects is dominated by primitive Pb (Pilbara source) and Pb at the Maroochydore Cu deposit has a crustal source (Pb leached from sediment with a Rudall Complex provenance). Lead in the Nifty Cu deposit, Goosewacker Pb-Cu-Au vein prospect, and Grevillea massive sulfide prospect all appear to have a mixed source.

Previous lead isotope models proposed the Throssell Group linear Pb isotope trend to be secondary or mixing isochrons. Isochron models require all deposits to have formed at the same time, however textural evidence indicates that Warrabarty (Smith, 1996) and Rainbow (Haynes et al., 1993) formed pre-D_4 while Nifty (Anderson et al., 2001), Maroochydore (Reed, 1996), and Goosewacker (Froud, 1997) formed syn-D_4. The differences in the timing of mineralization suggests that the Throssell Group Pb isotope linear trend is not an isochron as previously interpreted but represents a mixing trend between crustal and primitive (mantle-derived) sources of Pb.

Determining the correct interpretation of the Pb isotope data in the Throssell Group mineralization is important for use in genetic and exploration models. In the Throssell Group syndeformational mineralizing systems are larger and contain more metal than syngenetic systems. Mineralizing systems with mixed or crustal sources of Pb appear to have a greater chance of containing economic mineralization compared to systems with a mantle source of Pb. These conclusions suggest that the most prospective portions of the Throssell Group of the Paterson orogen are areas affected by D_4 deformation that are underlain by Rudall Complex orogen or units containing a significant proportion of Rudall Complex detritus. Areas of the Paterson orogen underlain by predominately Pilbara Craton or units with predominately Pilbara Craton detritus appear less likely to contain major deposits.

Acknowledgments

This study formed part of a Ph.D. project by B.R.A. who acknowledges the receipt of an Australian Research Council, Australian Postgraduate Award (Industry) scholarship. The industry partner was WMC Resources Ltd. and we greatly appreciate the financial and logistic support given during the course of this study. Geologists at the Nifty mine are thanked for their assistance in the field and for discussions on Nifty and the Paterson orogen. Pat Dare, Terry Burns, David Sharp, Alistair Reed, and Tim Craske are gratefully acknowledged for their continuous support throughout all stages of the research. The new owners of Nifty, Straits Resources Ltd., are also thanked.

Geologists from the Geological Survey of Western Australia (GSWA) have also provided significant insights into the region, in particular we thank Leon Bagas, Ian Williams, and Kath Grey. Unpublished Pb isotope data from the GSWA are included with their permission. We thank Ron Berry and Ross Large of the Centre for Ore Deposit Research, University of Tasmania, for their support during the project and the preparation of this manuscript. Neil NcNaughton of the University of Western Australia is thanked for providing unpublished Pb isotope data. This paper has greatly benefited from critical reviews by Wayne Goodfellow, an anonymous reviewer, and an editorial board member of *Economic Geology*.

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