The precious-metals potential of the Rockley Volcanics in the Lachlan Fold Belt

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Earlier reports (Wyborn 1988: BMR Research Newsletter 8, 13–14; Wyborn 1990: BMR Research Newsletter 13, 8) highlighted the precious-metal potential of Ordovician shoshonitic magmas in the central Lachlan Fold Belt (Fig. 15). Intrusive complexes and volcanics derived from these magmas host important Cu–Au deposits in the Parkes–Narromine and Orange–Wellington belts, and the Fifield–Nyngan belt contains Alaskan-type mafic–ultramafic intrusions enriched in platinum. These areas are currently the main focus of exploration activity. Following joint AGSO–Geological Survey of New South Wales geological mapping of the Bathurst 1:250 000 Sheet area as part of the National Geoscience Mapping Accord (NGMA; Stuart-Smith & Wallace 1994: Oberon 1:100 000 Sheet, 8830, preliminary-edition geological map, AGSO), a geochemical study of the Rockley Volcanics in the Oberon Sheet area was undertaken. Platinum-group-element (PGE) and Au data from this study form part of this report.

Stratigraphy

The Rockley Volcanics are a series of shoshonitic mafic and ultramafic (peridotite and pyroxenite) extrusive rocks and derived volcanogenic sedimentary rocks emplaced in the Middle to Late Ordovician. They are transitional to and overlie the widespread quartz-rich turbidites of the Adaminaby Group, which was deposited in the Early Ordovician. In the Bathurst 1:250 000 Sheet area south of the Bathurst Granite, they form part of a belt of mafic–ultramafic Ordovician volcanics which correlate with the Sofala Volcanics north of the Bathurst Granite. Elsewhere in the eastern part of the Lachlan Fold Belt, they also correlate with volcanics in the Fifield–Nyngan, Parkes–Narromine, and Orange–Wellington belts, and with the Kiandra Volcanics (Fig. 15).

Geochemistry

The whole-rock chemistry of the Rockley Volcanics is similar to that described by Wyborn (1992: Tectonophysics, 214, 177–192) for Ordovician shoshonites of the eastern Lachlan Fold Belt. Nd-isotope systematics on a basalt sample yielded a εNd value of 5.8, typical of Ordovician shoshonite derived from a long-term light-rare-earth-element- (LREE-) depleted mantle (Wyborn & Sun 1993: AGSO Research Newsletter 19, 13–14). The basalts have high MgO (7–11wt%), high K_2O (1.45–2.52%), and $K_2O:Na_2O$ ratios of 0.4–1.03. The basaltic rocks are also characterised by high large-ion-lithophile-element (LILE) concentrations (Ba up to 5000 ppm) and P_2O_5 (up to 0.31%), and low high-field-strength elements (TiO_2 <0.6%, Nb <10 ppm, Zr <50 ppm, Y <15 ppm) and LREEs (La 3–8 ppm; Ce 6–19 ppm).

Aliquots of selected samples of ultramafic and mafic rocks from the Rockley Volcanics were analysed by fire assay, followed by inductively coupled plasma–mass spectrometry (ICP–MS) for Pt, Pd, and Au, at Analabs in Perth. These samples are a good representation of the variety of Ordovician volcanics throughout the Oberon Sheet area. Three Tertiary basalt samples from the Oberon area were also analysed for PGEs for comparison with the Ordovician volcanics.

The Rockley Volcanics, ranging in composition from peridotite to basalt, have Pt, Pd, and Au abundances similar to Ordovician mafic volcanic suites that Wyborn (1990: op. cit.) described from elsewhere in the Lachlan Fold Belt. [Pt + Pd] abundances range from 5 to 36 ppb, while Au averages 1.5 ppb and has maximum abundances of 3 ppb in mafic volcanics and volcanic-derived sedimentary rocks. These concentrations contrast with the low PGE concentrations in the Tertiary volcanics, in which [Pt + Pd] is <1 ppb. The use of MgO as an index of fractionation (Fig. 16) demonstrates that Pd and Au systematically increase with fractionation, and that Pt abundances increase slightly from peridotite to pyroxenite, then fall appreciably with decreasing MgO; thus, Pt and Pd are inversely related during the pyroxenite–basalt stage of fractionation. Figure 16 suggests additionally that [Pt + Pd] increases with fractionation to a possible maximum ≅20 ppb at MgO ~20 per cent, then levels out as compositions become more basaltic.

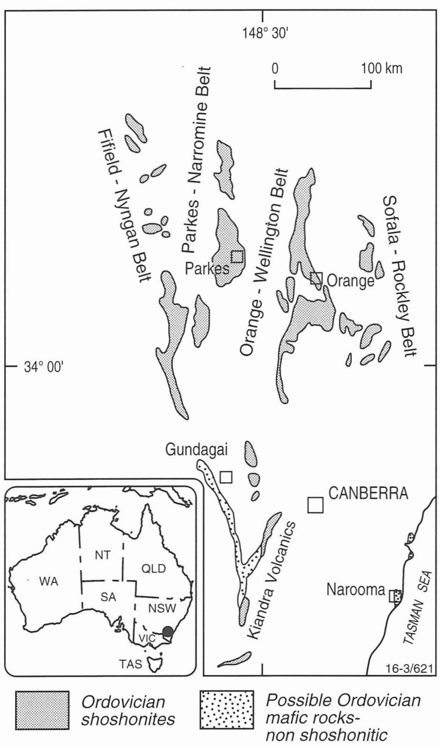

Fig. 15. Locations of Ordovician and possible Ordovician magmatic rocks in the eastern Lachlan Fold Belt.

Pt:Pd:Au ratios derived from interpolated trends in Figure 16 for various rock compositions in the peridotite-to-basalt assemblage are: peridotite (MgO ~35%) 14:5:1; pyroxenite (MgO ~23%) 7:6:1; and basalt (MgO ~8%) 2:5:1. These trends show that the Pd:Au ratio is constant throughout the evolution of the suite, and that there is an overall sevenfold decrease in Pt in the system as it becomes less magnesian. PGE levels and ratios in the volcanolithic samples are consistent with those in the primary magmatic rocks with the same MgO, except for two samples with low Pd (<5 ppb) and Au (<1 ppb) and one sample with high Pt (17.5 ppb) and Pd (19 ppb; Fig. 16). This suggests that the sedimentary and depositional processes which occurred during the history of these rocks had minor significance in mobilising PGE or changing their inherited PGE.

Discussion

The elevated PGE abundances in the Ordovician volcanics in the Oberon Sheet area, and their pattern of variation with fractionation, are consistent with evidence presented by Wyborn (1990: op. cit.) that Ordovician magmas in the eastern Lachlan Fold Belt were sulphur-undersaturated during their early history, and thus retained PGEs in their melts. Pt:Pd:Au ratios of these rocks are also consistent with expected magmatic ratios pertaining to S-undersaturated conditions for Ordovician shoshonites elsewhere in the Lachlan Fold Belt (Wyborn & Sun 1994: AGSO Research Newsletter 21, 7–8). The fractionation history of the mafic–ultramafic rocks suggests that sulphur depletion continued to be a factor in determining PGE concentration throughout the later stages of the evolution of the magmas. In contrast, the consistently low PGE abundances of the

Tertiary basalts provide evidence that these rocks were sulphur-saturated, and that PGEs were removed from their melts at an early stage in the evolution of these magmas.

Although there are analogues for Pt enrichment and high Pt:Pd ratios in the magnesium-rich rocks of Alaskan-type zoned complexes — such as in the Fifield–Nyngan belt, in the Urals, and at Tulameen, Canada (Johan 1994: International Mineralogical Association, 16th General Meeting, Pisa) — there is no clear explanation for the variation in Pt and Pd abundances and lower Pt:Pd ratios in non-cumulate volcanic rocks. Wyborn (1990: op. cit.) reviewed the available experimental evidence to explain the causes of decoupling between Pt and Pd (Amosse et al. 1990: Chemical Geology, 81, 45–53; Johan et al. 1989: Mineralogy & Petrology, 40, 289–309), and concluded that the high partition coefficient of Pt and low coefficent of Pd in the Fe–Pt–Pd alloy system under sustained conditions of high $f(O_2)$ — hence low sulphur fugacity — could be a plausible explanation for the moderately rapid depletion of Pt.

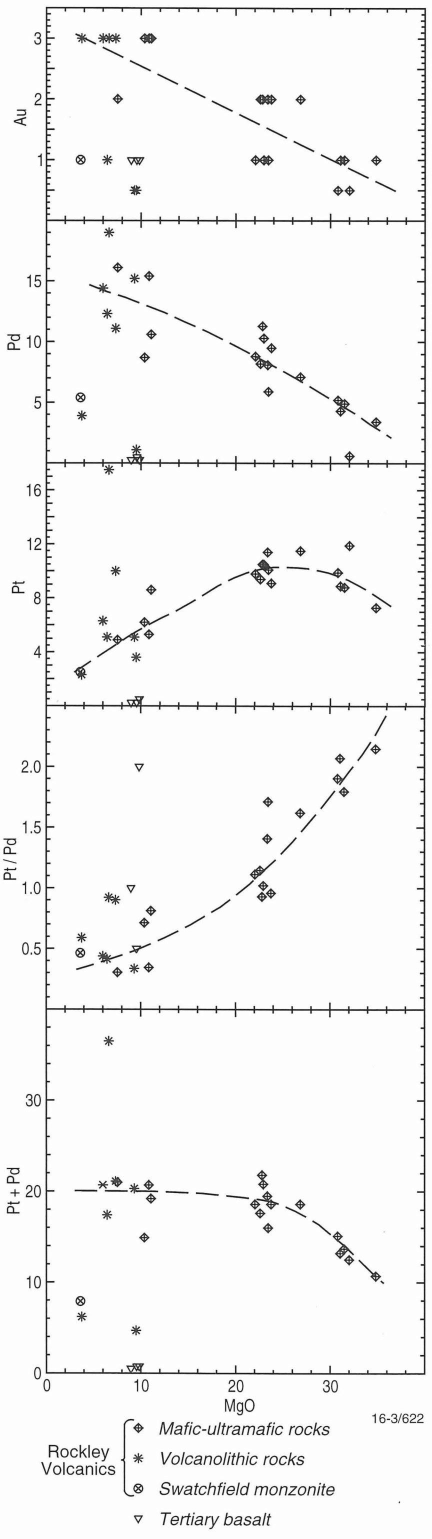

Fig. 16. Relationships between Pt, Pd, and Au (in parts per billion) and fractionation represented by MgO (weight per cent) for suites of samples from the Rockley Volcanics and Tertiary basalts from the Oberon 1:100 000 Sheet area.

Chrome-spinel is an important accessory mineral in the ultramafic rocks (Cr contents 2000–3400 ppm), but is absent from or only a minor constituent of the more basaltic non-cumulus rocks. A correlation between Pt and Cr in ultramafic cumulates and less magnesian rocks suggests that chrome-spinel could be a factor controlling the concentration of Pt (Fig. 17). A close relationship between Pt and chrome-spinel is also suggested by experiments carried out by Capobianco & Drake (1990: Geochemica et Cosmochimica Acta, 54, 869–874), which — although they excluded data on Pt — highlighted the incompatibility of Pd in spinel and the high compatibility of Rh and Ru in this mineral.

PGEs in the Rockley Volcanics can amount to about 20 times their concentrations in 'normal' basaltic assemblages, as exemplified by the Tertiary volcanics, and reflect the typically high concentrations of these elements in Ordovician shoshonites elsewhere in the central Lachlan Fold Belt. Pt is more highly concentrated in the ultramafic rocks, and Pd and Au increase as the rocks become more felsic. Favourable localities for Pt enrichment in the Oberon area therefore should be peridotite–pyroxenite rock assemblages, particularly those near Rockley — such as Dunns Plains and Dog Rocks. Depending on the timing of the entry of sulphur into the system, Pd and Au — on the other hand — would have been concentrated in felsic differentiates, such as the monzonite (MgO ~3.6%) identified during the NGMA mapping in the Swatchfield area south of Black Springs (Wallace & Stuart-Smith 1994: AGSO Record 1994/12). The Swatchfield monzonite (part of the Rockley Volcanics) appears to have undergone an estimated anomalous threefold depletion in Pd and Au (Fig. 16), suggesting that these elements had been extracted from the system at an earlier stage — possibly by fluid separation in a mineralising event. Pd and Au also appear to have been lost from two of the volcanolithic samples. In contrast, the anomalously high Pt and Pd volcanolithic

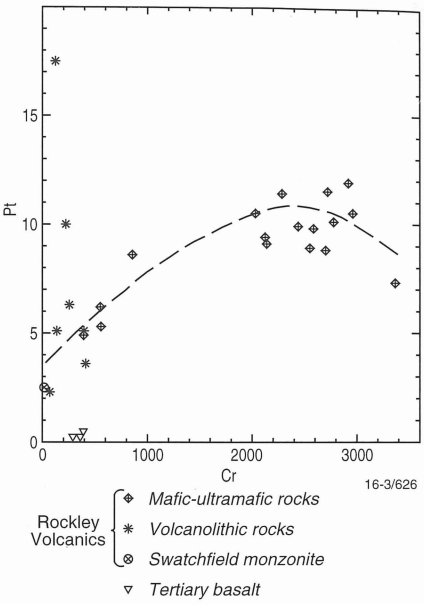

Fig. 17. Relationships between Pt (in parts per billion) and Cr (in parts per million) for suites of samples from the Rockley Volcanics and Tertiary basalts from the Oberon 1:100 000 Sheet area (symbols as for Fig. 16). The similarity of trends in this diagram and the Pt v. MgO diagram (Fig. 16) distinguishes Cr as an effective fractionation index for Pt.

rocks from the Shooters Hill area south of Oberon might reflect derivation from a locally enriched PGE source.

No compelling evidence is suggested from the samples analysed that any significant widespread selective Au depletion occurred in the Oberon area by processes associated with burial metamorphism, as suggested by Wyborn (1988: op. cit.) for other areas. The recently completed NGMA mapping shows that a considerable proportion of Au mineralisation in the Oberon area coincided with faults. This association suggests that localised mobilisation of Au, rather than a general mobilisation of Au brought about by burial metamorphism, may be a more likely explanation for Au enrichment in Oberon. Such mobilisation of Au and PGEs from the Rockley Volcanics would have been assisted by fracturing and entry of hot S-rich fluids associated with later intrusions, as — for example — in the Lucky Draw gold deposit at Burraga (Brewer & Arundell 1994: Geological Survey of New South Wales, Report GS 1994/139). South of Black Springs, therefore, the contact aureoles of the Carboniferous Greenslopes and Isabella Granites in the outcrop of the Rockley Volcanics (particularly the Swatchfield monzonite) could be attractive for Au and Pd exploration.

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Lead-isotope model ages

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Alternative approaches, and the age of the Broken Hill Pb–Zn ore

Applications of other approaches to obtain Pb-isotope model ages for the Proterozoic Pb–Zn ores have been less successful. For example, the plumbotectonics model of Zartman & Doe (1981: Tectonophysics, 75, 135–162) and Zartman & Haines (1988: Geochimica et Cosmochimica Acta, 52, 1327–1339) — involving mixing of four components (upper crust, lower crust, depleted mantle, and orogene) through crustal differentiation and recycling by subduction processes — tends to yield Pb model ages that are younger than the geological ages, especially for samples with low μ values. It is interesting to note that the new version (V4) of the plumbotectonics model of Zartman & Haines (1988) increases the age discrepancy. Thus, to improve the accuracy of model ages derived from a plumbotectonics model for Proterozoic Pb–Zn ores, the use of geological age control points, as we have done, is essential.

What does this imply for model ages calculated from a two-stage Pb-evolution model without geological age control?

Such model ages must accommodate large uncertainties, including estimates of the age of the Earth (4.57 to 4.47 Ga?), time of the second-stage Pb evolution, and variable μ values. Inevitably, this approach creates a broad spectrum of model ages with large uncertainties for Proterozoic Pb–Zn ores. Consequently, in order to optimise model-age calculation, input of other geological constraints is necessary.

Ehlers et al. (1996: Geological Society of Australia, Abstracts, 41, 127) adopted a different two-stage-model approach for the Broken Hill Pb–Zn ore. To establish their two-stage model, they used as their control a Pb–Pb isochron (1565 ± 22 Ma) that Gulson (1984: Economic Geology, 79, 476–490) had published for apatites from the ore lode and mine sequence. They concluded that 'this age is indistinguishable from two-stage Pb model ages of Broken Hill lode sulphides, which yield a mean age of 1574 Ma (μ = 9.7, indicative of a crustal Pb source).' On this basis they suggested that the Broken Hill orebody was concentrated during high-grade metamorphism at about 1600–1590 Ma, which was established by study of U–Pb ages of metamorphic zircon, sphene, and monazite (Gulson 1984: Economic Geology, 79, 476–490; Page & Laing 1992: Economic Geology, 87, 2138–2168). When Pb-isotope data from the Broken Hill ore (very homogeneous) and from apatites in the ore lode (CSIRO database) are plotted together, the apatite Pb–Pb isochron passes through the ore leads. This is expected for an ore lode and apatite system with extremely low $^{238}U/^{204}Pb$ (i.e., μ practically zero), and thus there was virtually no radiogenic Pb growth from the time of ore formation to the time when regional granulite-facies metamorphism at Broken Hill cooled down to the blocking temperature for the U–Pb system of apatite in the ore lode (Gulson 1984: op. cit.). Consequently, this approach will not be able to estimate the time gap between ore formation and the apatite Pb–Pb isochron age. It will not give a unique formation age for the Broken Hill Pb–Zn ore.

In contrast to the above view that the Broken Hill lode formed during high-grade metamorphism, the galena Pb and zircon U–Pb data concur with the hypothesis that the Broken Hill Pb–Zn ore is of synsedimentary, exhalative, or syndiagenetic origin, and its formation age is best represented by a zircon U–Pb age of 1690 ± 5 Ma for the Potosi Gneiss in the mine sequence (Page & Laing 1992: op. cit.). Furthermore, very low $\delta^{13}C_{PDB}$ values of about –22 per mil observed in calcite of the Broken Hill ore (e.g., Dong et al. 1987: Transactions of the Institution of Mining and Metallurgy, Section B: Applied Earth Science, 96, B15–29) imply that ore formation was associated with hydrocarbon activity in the sedimentary basin.

Table 1. Comparison of Pb model ages with geological ages (zircon U–Pb) of host sequences of Early Proterozoic VMS, an Early Proterozoic granite, and mid-Proterozoic sediment-hosted Pb–Zn ores

Deposit	*U–Pb age Ma*	*Model age Ma*	*Reference for zircon U–Pb age*
Flin Flon VMS	1886	1880	Gordon et al. 1990: Geological Association of Canada, Special Paper, 37, 177–199
Wisconsin VMS	1860	1875–1820	Afifa et al. 1984: Economic Geology, 79, 338-353
Koongie Park VMS	1840	1820	Page et al. 1994: AGSO Research Newsletter, 20, 5–7
Cullen Batholith	1825	1830	Stuart-Smith et al. 1993: AGSO Bulletin 229
Broken Hill	1690	1675	Page & Laing 1992: Economic Geology, 87, 2138–2168
Mount Isa	1652	1653	Page & Sweet in press: Australian Journal of Earth Sciences
HYC	1640	1640	Page & Sweet in press: op. cit.
Century	1595	1575	Page & Sweet in press: op. cit.

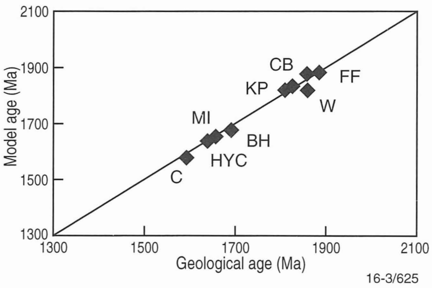

Fig. 18. Comparison of Pb-isotope model ages with zircon U–Pb ages of the host sequences for some Early Proterozoic VMS and sediment-hosted Pb–Zn deposits. Letter symbols are the same as in Figure 19.

Anomalous Pb model ages, and implications for the source rocks

Lead model ages and respective geological ages are sometimes grossly discrepant. Such discordances in model-age estimation, when evaluated together with information from the regional geology, can offer useful insights into source-rock characteristics. For example, as shown in Figure 18 and Table 1, the Pb model age for the Koongie Park VMS mineralisation — about 20 km southwest of Halls Creek, in the East Kimberley (WA) — agrees well with the zircon age of the host Koongie Park Formation, dated at 1843 ± 2 Ma (Page et al. 1994: AGSO Research Newsletter, 20, 5–7). In contrast, Pb model ages for Cu–Pb–Zn mineralisation at Little Mount Isa and Ilmars, about 30 km northeast of Halls Creek, hosted in ~1880-Ma Biscay Formation (Hoatson et al. 1995: AGSO Research Newsletter, 22, 1–2), are anomalous (2200–2300 Ma). A viable explanation for these anomalous Pb model ages is that their source region has an Archaean age, and has experienced retarded Pb-isotope evolution in a long-term low-μ environment caused by U loss during Archaean high-grade metamorphism. This possibility can be further evaluated by data on the $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot (Fig. 19b). As Th is less mobile than U during high-grade metamorphism it will produce a 'normal' amount of decay product ^{208}Pb. Data in Figure 19b show that $^{208}Pb/^{204}Pb$ values for Little Mount Isa and Ilmars ores lie far above the growth curve, but are similar to that for the Koongie Park VMS. Thus, Pb-isotope data for these anomalous samples provide further strong, albeit circumstantial, evidence for the existence of Archaean basement in the Halls Creek region of the East Kimberley.

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