

# A review of Pb-isotope constraints on the genesis of lode-gold deposits in the Yilgarn Craton, Western Australia

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## Abstract

Archaean lode-gold deposits within the Yilgarn Craton of Western Australia have made a major contribution to world gold production over the last century. However, models for the genesis of this class of deposits, particularly aspects of fluid and solute sources, remain controversial and require specific tests of their veracity. A systematic study of the initial Pb-isotopic compositions of Yilgarn lode-gold deposits and potential source rocks for ore components places constraints on possible source regions, and hence genetic models of ore formation.

The inferred initial isotopic composition of Pb in Yilgarn ore deposits correlates with that of the crustal Pb in the rocks of hosting greenstone belts, but is independent of the host rock to the deposit. Accordingly, the ore-deposit initial Pb-isotope compositions show regional variations with crustal rocks. These are inferred to vary with the age, composition and degree of metamorphic-magmatic depletion of the lower to middle crust, which is considered to be the source of Pb in the deposits. With the available geological constraints, the heterogeneous source can be modelled as follows; derivation from early Archaean ( $\geq 3.7$  Ga) crust which is metamorphically depleted and/or partially melted at ca. 3.3 Ga; further reworking from ca. 2.7 Ga; and then sampling of the Pb in this heterogeneous crust by auriferous fluids at ca. 2.63 Ga. The Pb isotope modelling of source regions is not unique, but requires that the ore deposit Pb has an older crustal component which varies systematically on a regional scale independent of the composition, metamorphic grade and age of crustal rocks. This constrains the source of Pb in lode-gold deposits to include a component from the high-grade mid- to lower-crust via either metamorphic or magmatic processes.

## Introduction

Lode-gold deposits in the Yilgarn Craton account for much of the annual gold production in Australia (*i.e.* 175 tonnes Au in 1995). Understanding the mode of formation of such deposits is pivotal to discovering new unexposed deposits, and hence much effort has been directed towards the establishment of robust deposit models which are predictive. The isotopic composition of Pb in ore deposits may be used as a tracer of Pb sources, and hence help constrain mineralisation processes. To use Pb isotopes as a source tracer, it is important to determine; (i) the initial Pb-isotopic composition and age of the ore system, and (ii) the coeval Pb in potential sources in, or below, the terrain hosting the gold deposit.

Over the last decade, colleagues and students of the authors at the Key Centre for Strategic Mineral Deposits have utilised the joint mass spectrometer facilities at Curtin University as part of multidisciplinary research into lode-gold deposits. This contribution describes the role of Pb-isotope tracer studies in developing the current understanding of Archaean lode-gold deposit source-regions within the Yilgarn Craton of Western Australia.

## Geological background

The Yilgarn Craton is composed of; (i) greenstone belts consisting of volcanic, sedimentary and intrusive

rocks, which are typically metamorphosed and variably deformed, and (ii) complex granitoid-gneiss terrains which separate the greenstone belts (Gee *et al.* 1981). Almost all of the Yilgarn lode-gold production comes from areas within greenstone belts.

Mineralisation may occur in various styles, from breccia lodes, vein sets, laminated veins or shear zones and as disseminated lodes. However, there are a number of common characteristics of lode-gold deposits (summarised by Groves 1993; Groves *et al.* 1995); an epigenetic timing of mineralisation, varying broadly from syn-metamorphic in deposits hosted by mid-amphibolite to granulite facies rocks, to post-metamorphic in deposits hosted by greenschist to low-amphibolite facies rocks, a ubiquitous structural control on mineralisation with deposits commonly forming adjacent to secondary or higher order splays off major faults or shear zones, a gold-only element association where base metal enrichments are generally negligible and K, LILE, CO<sub>2</sub>, Na or Ca are added to proximal wallrocks, an H<sub>2</sub>O ± CO<sub>2</sub> ± CH<sub>4</sub>, low-salinity ore fluid, and a range of crustal depths, from near surface (very low metamorphic grade) environments to granulite facies conditions, for gold mineralisation.

## Age of lode-gold mineralisation

For Pb isotope modelling purposes, it is important to constrain the age of lode-gold mineralisation. As predicted by the crustal continuum model, Archaean lode-gold deposits of the Yilgarn Craton are broadly coeval at

2.64-2.63 Ga (Groves 1993). Although the available reliable data are few, Pb-Pb and Sm-Nd isochrons, mineral U/Pb ages and Ar-Ar plateau ages for hydrothermal or alteration minerals associated with mineralisation are broadly synchronous (Clark *et al.* 1989; Barnicoat *et al.* 1991; Wang *et al.* 1993; Kent 1994; Kent & McDougall 1995), although at least one major deposit (Mt Charlotte) may be 30 m.y. younger than the nearby Golden Mile mineralisation (Kent & McDougall 1995). In addition, age constraints provided by the youngest granitoids cut by lode-gold deposits and dykes which cut mineralisation are in agreement with the direct dating of mineralisation (e.g. Kent 1994; Bloem *et al.* 1995; Kent & McDougall 1995). Hence, for the Pb isotope modelling presented below, an age of 2.63 Ga is taken for mineralisation. In addition to the dating of the lode-gold deposits, relative timing criteria and age estimates for metamorphic and deformational events (McNaughton *et al.* 1990a) are also compatible with this age. Magmatic activity broadly synchronous with mineralisation includes suites of late granitoids in the Murchison Province (Wiedenbeck & Watkins 1993; Yeats 1996), and a suite of late granites within the granitoid-gneiss terrains of the southwestern Southern Cross Province (Qiu *et al.* 1995).

### Lead reservoirs coeval with lode-gold mineralisation

Unlike ore systems where the initial Pb-isotope compositions can often be determined from ore sulphides, it is more difficult to determine the coeval Pb-isotope composition of the rocks which may represent the reservoirs for Pb contributing to the ore fluid. The only common mineral which may allow initial Pb-isotope ratios to be estimated is K-feldspar, which is generally restricted to granitoids. Other minerals and rocks have U/Pb > 0 and hence their Pb-isotope ratios have changed since formation. However, these materials may be analysed, and knowing the age of mineralisation, allow constraints to be placed on their Pb-isotope ratios at the time of mineralisation.

#### Granitoids

Granitoids of the Norseman-Wiluna belt of the Eastern Goldfields Province of Western Australia have been analysed and data are shown in Figure 1. The estimated composition of crustal rocks within the belt at 2.63 Ga is based on the Pb in a synvolcanic VHMS deposit at Teutonic Bore, and granitoids at Stennet Rocks, both compositions recalculated from their formation age to 2.63 Ga (McNaughton *et al.* 1990a,b).

The initial Pb-isotope compositions of the granitoids, based on K-feldspar data, are divided into three groups (Fig 1). The main group shows all data constrained to within two 2.63 Ga isochrons shown as parallel lines, and with K-feldspar data concentrated towards the intersection of the crosscutting crustal line. This group includes all available data on granitoids which are intrusive into the greenstone belts north of the Victory mine, Kambalda. Towards the west and south of Kambalda, the granitoids fall above these parallel lines, whereas, towards the northeast and east in the Eastern Goldfields Province they fall below these lines (both open circles; Fig 1). For comparison, granitoid K-feldspar data from

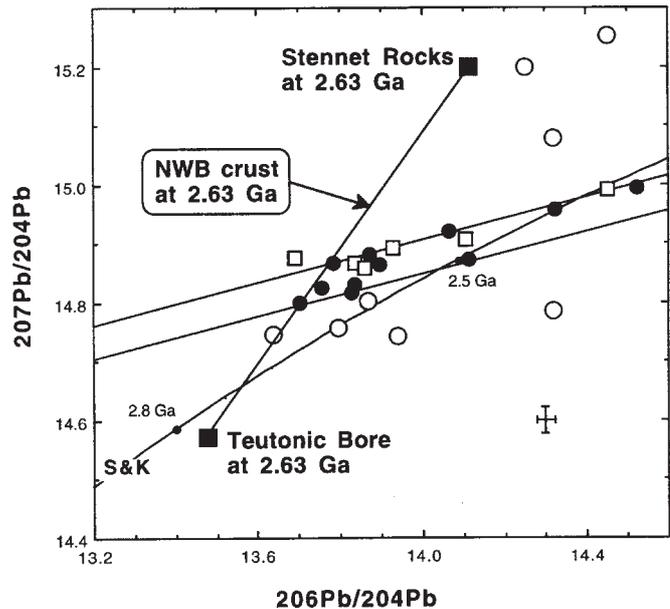


Figure 1. Common Pb-isotope plot showing K-feldspar data compared to the Stacey & Kramers (1975) lithospheric growth curve and the estimated composition of the crustal rocks of the Norseman-Wiluna belt (NWB) at the time of gold mineralisation (i.e. from Stennet Rocks to Teutonic Bore at 2.63 Ga; McNaughton *et al.* 1990b). Error bars are  $2\sigma$ . Symbols; closed circles = NWB granitoids intrusive into greenstones north of Kambalda with 2.63 Ga isochrons bracketing these data; open circles (below parallel lines) = intrusive granitoids of the North-eastern Goldfields; open circles (above parallel lines) and Stennet Rocks = intrusive granitoids of the Norseman area and south of Coolgardie; open squares = Murchison and Southern Cross data. References; Oversby (1975), McNaughton & Bickle (1987), Perring & McNaughton (1992), Knight (1994), Wang *et al.* (1993), Ojala (1995), and unpublished data.

the Murchison and Southern Cross Provinces are also shown (open squares; Fig 1), and broadly overlap the granitoid trend in the Norseman-Wiluna belt.

The granitoids of the northeastern Eastern Goldfields Province are interpreted to have a different source region to all other areas. The inferred boundary of this isotopically distinctive terrane approximately corresponds to the position of the Keith-Kilkinny lineament. Towards the south and west of Kambalda, older crustal rocks in the granitoid source regions have been inferred on the basis of isotopic data (Oversby 1975; Perring & McNaughton 1992).

#### Greenstones

The Pb-isotope data for lithologies within greenstone belts in the Norseman-Wiluna belt are shown in Figure 2. Relative to the estimated crust at 2.63 Ga and the main granitoid field (shown as parallel lines; from Fig 1), the rocks of the Norseman region plot largely above the granitoid data, whereas those of the Kambalda-Kalgoorlie-Mt Pleasant region plot below. These data are modern Pb-isotopic compositions. The Pb in each rock at the time of mineralisation is not known, but will plot along a 2.63 Ga isochron fitted to each data point but at a less radiogenic composition. Scatter in the data may be induced by open system behaviour of Pb-U between volcanism and modern times, but the general adherence of data to consistent fields suggests this effect is minor.

Therefore, the initial Pb-isotope ratios for the greenstones could lie on the 2.63 Ga crustal mixing line, slightly above and below the granitoid data.

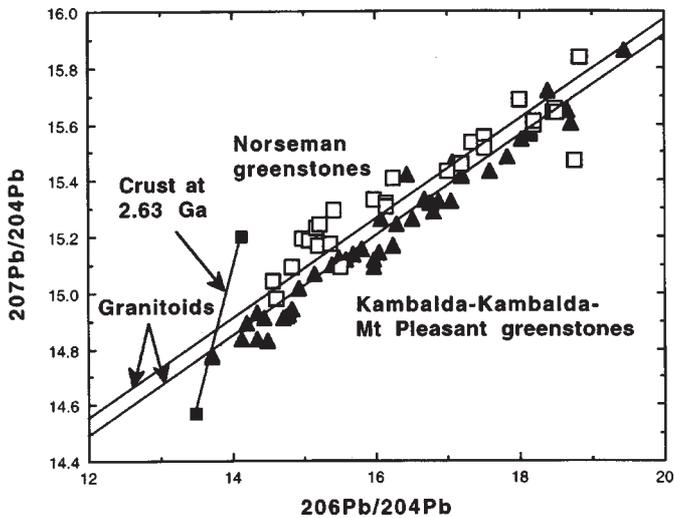


Figure 2. Common Pb-isotope plot showing the Norseman-Wiluna belt crustal mixing line and 2.63 Ga isochrons bracketing the granitoid Pb field (from Fig 1) compared to all greenstone data for the Kambalda-Kalgoorlie-Mt Pleasant region (triangles), and the Norseman region (squares). Data from: open squares (Perring & McNaughton 1992; McCuaig & McNaughton, unpublished data); closed triangles (Roddick 1983; Chauvel *et al.* 1985; McNaughton *et al.* 1988; Gebre-Mariam *et al.* 1993).

As with the granitoid data, the distinctly more radiogenic Pb in greenstones from the Norseman area, compared to the Kambalda-Kalgoorlie-Mt Pleasant area, represents a fundamental and provincial difference in the source of the Pb in both the greenstones and intrusive granitoids. The (gradational?) boundary between these different regions lies somewhere south of Kambalda and north of Norseman. Importantly, the southern part of the Norseman-Wiluna belt shows the most radiogenic Pb in both the granitoid and greenstone lithologies. To date, there are no published Pb-isotope data on greenstone lithologies from outside the Norseman-Wiluna belt.

#### Initial lead isotope composition of ore systems

The initial Pb of lode-gold ore systems is best determined from Pb-rich minerals genetically associated with the ore. Lead sulphide (galena) or tellurides are used, if they are present, but Fe-sulphides (pyrite, pyrrhotite) are more common and reliably preserve the initial Pb-isotope compositions in some cases (e.g. Ho *et al.* 1994). In a few cases, K-feldspar, sphalerite and scheelite associated with the ore have yielded reliable initial Pb-isotope ratios (Barnicoat *et al.* 1991; unpublished data).

Galena, with  $U/Pb = 0$ , is considered to be the best sampling medium to establish the initial Pb-isotope composition of lode-gold ore system. Galena occurs as a trace mineral in a proportion of lode-gold deposits. However, previous studies have shown that it does not always preserve the initial Pb of the ore system (e.g. Browning *et al.* 1983; Perring & McNaughton 1990; McNaughton *et al.* in

press). Similarly, Pb tellurides may be used (Browning *et al.* 1983), but are rarer than galena. Iron sulphides are common ore-related minerals in the majority of deposits, and, with proper sampling methodologies (e.g. Ho *et al.* 1994), can yield the initial Pb-isotope ratios. For most deposits, a number of ore sulphide samples have been analysed and an assessment of the data must be made to determine if the initial Pb ratios are preserved. In deposits where a range of Pb-isotope compositions occur, the least radiogenic composition is taken as the best estimate of the initial Pb (e.g. Ho *et al.* 1994). More radiogenic compositions are attributed to *in situ* U-decay, from U either within the sulphide or within inclusions in the sulphide, or from more radiogenic Pb mobilised into the sulphide from an external source after sulphide formation. In the following discussion, only initial Pb-isotope compositions, which are inferred using the criteria discussed above and by McNaughton *et al.* (1990b) and Ho *et al.* (1994), are considered.

Figure 3 presents the initial uraniumogenic Pb-isotope ratios of deposits within the Norseman-Wiluna belt. The data form a linear array, and show provinciality *i.e.* a systematic change in Pb-isotope composition between geographic regions (Groves *et al.* 1995). The least radiogenic end of the array is represented by deposits to the north of the belt, whereas the most radiogenic data are from around Norseman at the southern end of the belt. These differences correlate with both the granitoid (Fig 1) and greenstone data (Fig 2) from these regions. Further, within some areas along the regional strike of the greenstone belts, the initial Pb-isotope ratios from deposits are invariant at the scale of >100kms (e.g. Mt Pleasant area to Kalgoorlie to Victory mine, Kambalda; McNaughton *et al.* 1993), whereas other areas show systematic changes on this scale (e.g. from Victory mine, Kambalda to Norseman; Fig 3). There is a weak correlation

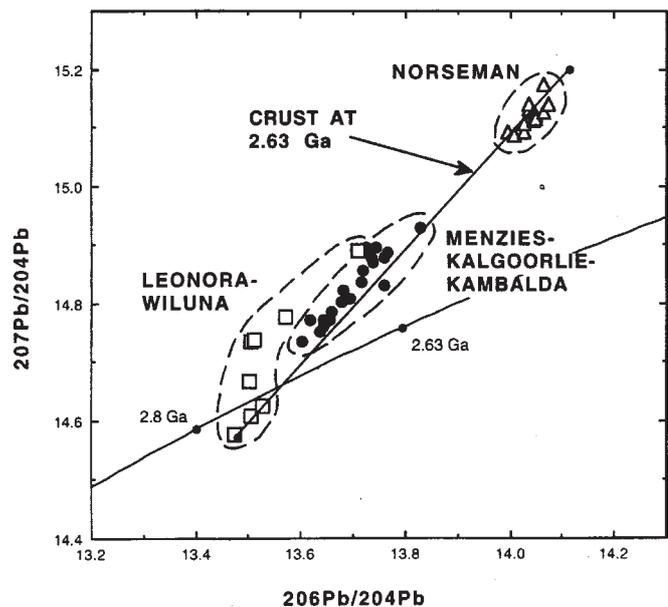


Figure 3. Common Pb-isotope plot showing the initial Pb for gold deposits from the Norseman-Wiluna belt, Stacey & Kramers (1975) growth curve and the crustal mixing line at 2.63 Ga from Fig 1. The gold deposit data fall into groups which correlate with geographical regions. Data from: McNaughton *et al.* (1990b, 1993) and Groves *et al.* (1995).





## Conclusions

Lead isotope data from Yilgarn lode-gold deposits and presently exposed rocks may place important constraints on the crustal evolution and metallogenesis of the craton. Modelling of Pb-isotope compositions of rocks and ores within the known and partly inferred temporal framework of the craton can yield an infinite number of solutions. The Pb-isotope modelling suggested in this review (Fig 6) suggests that the Yilgarn craton is underlain by crustal rocks which may be >3.7 Ga old. This old crust comprised both mafic and intermediate components which evolved to form heterogeneous crust by the time of a major depletion event (metamorphism-partial melting) at ca. 3.3 Ga or older. Thereafter, the depleted crust evolved to produce Pb-isotope compositions at 2.63 Ga, the time of broadly coeval gold mineralisation across the craton, which lie within a triangular field of Pb-isotope compositions on a  $^{207}\text{Pb}/^{204}\text{Pb}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$  diagram, defined by crustal components with different geochemical compositions and histories. The initial Pb-isotope compositions of the gold deposits closely adhere to this triangular field, and, together with geological constraints, are best interpreted to indicate that all deposits obtained their Pb mostly from the older depleted crust at mid to lower crustal levels. This conclusion is compatible with a crustal continuum of deposits (Groves 1993) from granulite to subgreenschist facies settings, a ubiquitous spatial association with major crustal-scale shear or fault zones, the occurrence of deposits in all rock types and a similarity of geochemical and ore fluid characteristics on a craton scale (Ho et al. 1992; McNaughton et al. 1992, 1993). The deep source of Pb constrains the fluid source to high metamorphic grade regions, and implies that mineralisation resulted from either high grade metamorphic or deep magmatic processes.

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