Structural Controls on Sulfur Isotope Variations in Archean Orogenic Gold Deposits, Eastern Goldfields Province, Yilgarn, Western Australia

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Abstract
The published mean $\delta^{34}S$ values of ore-related pyrites from orogenic gold deposits of the Eastern Goldfields Province, Yilgarn Craton lie between -4‰ and +4‰. As for orogenic gold deposits worldwide, most deposits have positive means and a restricted range of $\delta^{34}S$ values, but some have negative means and wider ranges of $\delta^{34}S$ values. Wall-rock carbonation and back-mixing of similar-source fluids with different fluid pathways can explain some of the more oxidised $\delta^{34}S$ signatures. However, structural setting appears to be the most important factor controlling ore-fluid oxidation state and hence the distribution of $\delta^{34}S$ values in gold-related pyrites. Shear-hosted deposits appear to have experienced fluid-dominated processes such as phase separation, whereas vein-hosted or rock-hosted deposits (e.g., disseminated, replacement or stockwork deposits) formed under conditions of greater rock buffering. At Victory-Defiance, in particular, negative $\delta^{34}S$ values are more common in gently-dipping dilational structures, compared to more compressional steeply-dipping structures. It appears most likely that fluid-pressure fluctuations during fault-valve cycles establish different fluid-flow regimes in structures with different orientations. Rapid fluid-pressure fluctuations in dilational structures during seismic activity can cause partitioning of reduced gas phases from the ore fluid during extreme phase separation, and hence are an effective method of orogenic ore-fluid oxidation, leading to large, local fluctuations in oxidation state of the ore fluid. It is thus not necessary to invoke mixing with oxidised magmatic fluids to explain $\delta^{34}S$ signatures indicative of oxidation. In any case, available, robust geochronology in the Eastern Goldfields Province prohibits the direct involvement of oxidised magmatic fluids from adjacent granitic intrusions in orogenic gold genesis.

Thus, negative mean $\delta^{34}S$ values and large variations in $\delta^{34}S$ values of ore-related pyrites in world-class orogenic gold deposits are interpreted to result from multiple mechanisms of gold precipitation within a single, ubiquitous ore fluid in specific structural settings, rather than the result of specific oxidised ore fluids with a different source. Such signatures are indicative, but not diagnostic, of anomalously large orogenic gold systems.

Key words: Archean, Yilgarn, orogenic lode gold, sulfur isotopes
Introduction

Sulfides in orogenic gold deposits typically have sulfur isotopic compositions ($\delta^{34}\text{S}$) ranging from 0 to +9‰ (McCuaig and Kerrich, 1998), which is typically interpreted to be the product of precipitation from a dominantly reduced ore fluid with a homogeneous isotopic composition. Several of the giant, and many world-class, orogenic gold deposits appear to have been deposited from reduced ore fluids and have restricted ranges of $\delta^{34}\text{S}$ values (e.g., Ashanti, Homestake, Ballarat, Bendigo: summarised by Groves et al. 2003). However, some giant orogenic gold deposits (e.g., Golden Mile, Timmins and Kirkland Lake) have much larger $\delta^{34}\text{S}$ ranges in gold-related pyrites, requiring either mixture of sulfur from several disparate sources under reduced conditions at the site of ore formation, or precipitation from a single sulfur source under more oxidising conditions (Ohmoto and Rye, 1979). Cameron and Hattori (1987) proposed that oxidised fluids were responsible for the anomalously large gold endowment in these deposits. Whether the ore fluids were originally oxidised (e.g., through magmatic volatiles) or whether they became oxidised through ore-depositional processes (i.e., fluid-rock reaction, phase separation and/or fluid mixing) is a highly controversial issue in genetic models of orogenic gold-deposit formation (Phillips et al. 1986; Cameron and Hattori, 1987; Hattori, 1987; Cameron, 1988; Kerrich, 1989; Phillips et al. 1996; Walshe et al. 1999; Ridley and Diamond, 2000; Hall et al. 2001; Groves et al. 2003; Neumayr et al. 2005; Evans et al. 2006). This paper focuses on orogenic gold deposits of variable size and style in the Eastern Goldfields Province of the Yilgarn Craton. Its aim is to determine whether the large ranges of $\delta^{34}\text{S}_{(\text{py})}$ values are an indication of anomalous fluid sources or of variations in gold depositional processes, and whether they can be directly related to the formation of world-class orogenic gold deposits. Our approach to this aim is to draw conclusions from the regional relationships between sulfur isotope variability and deposit characteristics (hydrothermal alteration assemblages, ore-fluid composition, and structural style of mineralisation) over a range of deposit sizes. One deposit, Victory-Defiance, is evaluated in more detail.

Gold in orogenic deposits occurs most commonly in close association with sulfide minerals, and most authors concur that it was transported in the ore fluid predominantly as a sulfide complex (Seward, 1973; Phillips and Groves, 1983; Mikucki, 1998; Loucks and Mavrogenes, 1999). Therefore, sulfide-sulfur isotope
ratios are useful for constraining ore depositional processes (Ohmoto and Rye, 1979). Sulfur isotopes in orogenic gold sulfides are potentially a sensitive indicator of ore-fluid oxidation state. Reduced sulfur complexes in neutral solutions are capable of transporting gold in high concentrations, and gold solubility increases with oxygen fugacity up to the boundary between reduced and oxidised sulfur species (Fig. 1). The solubility of gold decreases rapidly at higher oxygen fugacities, where sulfate is the dominant sulfur species in the ore fluid. Therefore, fluid oxidation is an efficient mechanism for gold precipitation (Roberts, 1987). It also produces large sulfur isotopic fractionations between oxidised and reduced sulfur species, which is manifested as light $\delta^{34}$S compositions in deposited sulfides (Fig. 1 and Ohmoto and Rye, 1979). The magnitude of the fractionation is greater at lower temperatures, and is also effectively greater at high sulfur activities because the pyrite stability field spans more of the fractionation range of dissolved H$_2$S (Ohmoto, 1972). Under reducing conditions, where H$_2$S is the dominant aqueous sulfur species (see pyrite and pyrrhotite stability fields in Fig. 1), precipitated sulfides will have $\delta^{34}$S values that are very similar to the sulfur in the ore fluid.

Sulfur in Archean orogenic ore fluids could have been derived from three sources: 1) pre-existing sulfides in the host greenstone sequences or in subducted or subcreted oceanic crust, 2) sulfur-bearing magmatic volatiles, or 3) dissolved sulfur in seawater (Kerrick, 1986). Sulfides in komatiite-hosted nickel deposits and sedimentary, mafic and ultramafic rocks in the Yilgarn Craton, which represent the most likely major sulfur reservoirs prior to gold mineralisation, have published $\delta^{34}$S values that are generally in a restricted range from +1 to +5‰ (Donnelly et al. 1978; Seccombe et al. 1981; Lambert et al. 1984). Sulfur in magmas usually has $\delta^{34}$S values near zero (Ohmoto and Rye, 1979), but magmatic fluids derived from them may be reduced or oxidized depending on the oxidation state of the magmas, and extensive open-system degassing can lead to local enrichment of $^{34}$S (Marini et al. 1998). Ohmoto and Goldhaber (1997) suggest that seawater sulfate in the Archean had $\delta^{34}$S values between 2 and 10‰.

The range of $\delta^{34}$S values from these potential sulfur sources, excluding oxidised magmatic fluids, is approximately 0 to +10‰, which is similar to the range of $\delta^{34}$S values in ore-related sulfides in most Archean orogenic gold deposits (e.g., McCuaig
and Kerrich, 1998). Therefore, determining the source of sulfur in Archean orogenic gold fluids, based on $\delta^{34}S$ values in sulfide minerals, is normally impossible because of the overlapping $\delta^{34}S$ ranges from the potential sources. It is a key premise of this paper that only sulfides with anomalously negative $\delta^{34}S$ can potentially provide clues to source and/or anomalous ore-fluid behaviour at the depositional site.

**Sulfides analysed in this study**

*Sample selection*

A total of 79 samples from 21 deposits in the Eastern Goldfields Province were analysed in this study and combined with existing data. A regional study was completed on 55 samples from 20 deposits, selected from most of the major gold districts in the Eastern Goldfields Province. All samples are from well-documented PhD and BSc Honours collections at the Edward de Courcy Clarke Geological Museum at the University of Western Australia. The regional study was designed to determine any broad relationships between sulfur isotope variability and deposit characteristics such as hydrothermal alteration assemblages, ore-fluid composition, and structural style of mineralisation over a range of deposit sizes.

The Victory-Defiance deposit was selected for a case study because: 1) it is a world-class orogenic gold deposit, containing a pre-mining resource of approximately 250 tonnes of gold; 2) gold mineralisation is hosted in a variety of rock types and structural styles (Clark et al. 1986); 3) it is known to have a large range of sulfur isotope values (Palin and Xu, 2000); and 4) pyrite samples from the well-mineralised 32 Shear Zone, the subject of a detailed lead isotope study by Ho et al. (1994), were available. Twenty-four samples from Victory-Defiance were analysed in this study and combined with existing data.

*Analytical techniques*

Analytical techniques used in this study include Nd-YAG laser ablation of *in-situ* sulfides (Huston et al. 1995) and conventional digestion techniques for pyrite separates (Robinson and Kusakabe, 1975). All results are reported as $\delta^{34}S$ values in parts per thousand (per mil = ‰), relative to Canyon Diabolo Triolite (CDT). A total of 126 *in-situ* laser ablation analyses and 25 conventional analyses of pyrite separates.
were completed for this study. All analytical work was completed at the Central Science Laboratory and the ARC Centre of Excellence in Ore Deposits at the University of Tasmania.

**Regional sulfur isotope study**

*Introduction*

Analytical results from the study are summarised in Table 1 and Figures 2 and 3. Eight deposits are selected from the regional study for more detailed discussion in this section: six deposits with positive average $\delta^{34}S_{(py)}$ values, and two deposits with negative average $\delta^{34}S_{(py)}$ values. For each deposit, a brief overview of host rocks, structural style of mineralisation, ore-fluid characteristics and inferred ore-depositional mechanisms is shown in Table 4. A discussion of sulfur isotope values is given below.

*Deposits with positive average $\delta^{34}S_{(py)}$ values*

Deposits discussed in this section are Sunrise Dam, North Royal, Golden Kilometre, Great Eastern, Lady Bountiful and Hunt (Fig. 2) in order of decreasing size. Photographs of rock samples from these deposits, with $\delta^{34}S_{(py)}$ values, are shown in Figure 4. These deposits were selected because they have ore-related pyrites with dominantly positive average $\delta^{34}S$ values, based on results of this study, although several deposits also have ore-related pyrites with anomalously positive or negative $\delta^{34}S_{(py)}$ values.

The average $\delta^{34}S_{(py)}$ value in gold-related pyrites from the *Sunrise Dam* deposit (Table 4), based on results from this study (n=4) and Brown (2002; n=17) is +1.1‰ (±3.5), with a total range from −8.2 to +4.0‰. The rare negative $\delta^{34}S_{(py)}$ values occur in the more gently-dipping Sunrise Shear Zone, where samples from the same magnetite-bearing shale unit show a large difference in $\delta^{34}S_{(py)}$ values, ranging from +2.5 (Fig. 4A) to −6.8‰ (Fig. 4B).

Nine laser ablation $\delta^{34}S_{(py)}$ analyses, from both quartz veins and proximal wall-rock alteration halos at the *North Royal* deposit (Table 4), include eight values ranging from +0.3 to +5.8‰, and one anomalous value of +10.4‰ (Fig. 4C) from the
transition zone between inner chlorite-biotite and outer chlorite-bearing alteration assemblages, which shows a large range of $\delta^{34}S_{(py)}$ values, from +4.6‰ to +10.4‰, in adjacent pyrites. The average for all nine analyses is +4.1‰ (±3.0).

Gebre-Mariam (1994) reported two $\delta^{34}S$ values in gold-related pyrite, +3.2 and +3.7‰ from the Golden Kilometre deposit (Table 4). Of eight analyses from this study, seven $\delta^{34}S_{(py)}$ values range from +2.6 to +6.9‰, with one anomalous value of -4.3‰ in a quartz vein, less than 10 mm from two pyrites with $\delta^{34}S$ values of +2.6 and +3.3‰ (Fig. 4D). The average $\delta^{34}S_{(py)}$ value for all gold-related pyrites is +3.2‰ (±3.0), with a total range from -4.3 to +6.9‰.

Results of a previous conventional stable-isotope study at the Great Eastern deposit (Table 4) show $\delta^{34}S_{(py)}$ values of –0.6 to +2.1‰, with no apparent difference in values between the two mineralisation styles (n=12; Mikucki, 1997). Results from this study include laser ablation analyses of two pyrites from a sample of late-stage chlorite-hematite, gold-telluride mineralisation, with $\delta^{34}S_{(py)}$ values of +2.5 and +1.5‰ (Fig. 4E). The combined average $\delta^{34}S_{(py)}$ value in gold-related pyrites is +0.9‰ (±0.9).

At the Lady Bountiful deposit (Table 4), nine laser ablation and five conventional $\delta^{34}S_{(py)}$ analyses (average +3.2‰ ±2.3) include thirteen ranging from –1.1 to +4.8‰, in both quartz veins and proximal alteration halos, and one anomalous value of +9.5‰ in a mineralised quartz vein (Fig. 4F), which is hosted in granodiorite, near the contact with a layered sill (Cassidy, 1992). The pyrite in the central portion of the vein has a $\delta^{34}S$ value of +3.6‰, whereas a pyrite grain 3 mm away near the vein margin has the anomalous $\delta^{34}S$ value of +9.5‰, a difference of 5.8‰.

At the Hunt deposit, previous studies, which indicate a narrow range of $\delta^{34}S$ values of three gold-related pyrites (+4.4 to +8.0‰; Lambert et al. 1984) agree with new results with $\delta^{34}S_{(py)}$ values ranging from +3.4 to +4.9‰ (n=5) in vein-related wallrock alteration (Fig. 4G) and auriferous quartz veins (Fig. 4H). The average $\delta^{34}S_{(py)}$ value in gold-related pyrites is +4.7‰ (±1.5), with a total range from +3.4 to +8.0‰.
**Deposits with negative average \(\delta^{34}\text{S}_{(\text{py})}\) values**

Both the large New Celebration and small Porphyry deposits have negative average \(\delta^{34}\text{S}\) values in ore-related pyrites.

At *New Celebration* (Table 4), \(\delta^{34}\text{S}_{(\text{py})}\) values range from –8.6 to +5.5‰ (Fig. 5), with an average value of –3.0‰ (±5.2). There is a large range in the tholeiitic mafic schist with pre-gold magnetite alteration, with \(\delta^{34}\text{S}_{(\text{py})}\) values of –5.5 and –4.8‰ in proximal alteration, and a value of +5.5‰ in distal alteration. Negative \(\delta^{34}\text{S}_{(\text{py})}\) values from the felsic porphyry unit with abundant pre-gold hematite alteration range from -8.6 to -6.0‰ in proximal alteration with a value of –1.4‰ in distal alteration. A sample of distal footwall ultramafic schist has a \(\delta^{34}\text{S}_{(\text{py})}\) value of +3.9‰. There is a broad negative correlation between whole-rock gold values and pyrite \(\delta^{34}\text{S}\) values (Table 2 and Figure 6).

The small *Porphyry* deposit (Table 4) has an anomalously large range of \(\delta^{34}\text{S}_{(\text{py})}\) values, from –10.2 to +10.0‰ (n=19), second only to the giant Golden Mile deposit (Clout, 1989). The average value is –3.1‰ (±5.8). The largest shifts in \(\delta^{34}\text{S}_{(\text{py})}\) values occur within, and adjacent to, the mineralised shear zones. More negative \(\delta^{34}\text{S}_{(\text{py})}\) values correspond to higher gold grades (> 3 g/t) and more intense shear-fabric development and hematite alteration (Fig. 7A, B). With increasing distance from the lodes, gold grades, hematite alteration and shear fabric development decrease and \(\delta^{34}\text{S}_{(\text{py})}\) values increase, approaching 0‰ (Fig. 7C, D). Weakly mineralised samples adjacent to the lode have the most positive \(\delta^{34}\text{S}\) values, approaching +10.0‰ (Fig. 7E, F). There is a broad negative correlation between whole-rock gold values and pyrite \(\delta^{34}\text{S}\) values (Table 3 and Figure 8).

**Summary of regional study**

Analytical results and characteristics of the eight deposits in the regional study are summarised in Table 4. Six deposits have ore-related pyrites with positive average \(\delta^{34}\text{S}\) values, ranging from 0.9‰ (±0.9) at Great Eastern to 4.1‰ (±3.0) at North Royal, whereas *Porphyry* has an average \(\delta^{34}\text{S}_{(\text{py})}\) value of –2.1‰ (±6.0) and *New Celebration* has an average \(\delta^{34}\text{S}_{(\text{py})}\) value of –3.0‰ (±5.2). In the last two deposits, there is also a larger and more consistent variation in \(\delta^{34}\text{S}_{(\text{py})}\), with ranges of 20.2‰ at
Porphyry and 14.1‰ at New Celebration. At Sunrise Dam, there is also a relatively large range in $\delta^{34}$S$_{(py)}$ (12.2‰), although the average value is +1.1 (±3.5). The large range at Sunrise Dam is due to rare occurrences of negative $\delta^{34}$S$_{(py)}$ values in magnetite-rich shales in the gently-dipping Sunrise Shear Zone. Likewise, relatively large variations in $\delta^{34}$S$_{(py)}$ values at Lady Bountiful (10.6‰) and North Royal (10.1‰) are the result of rare occurrences of pyrites with anomalously positive $\delta^{34}$S values within and adjacent to veins. At Golden Kilometre, the single negative $\delta^{34}$S$_{(py)}$ value from this study (–4.3‰) occurs in a vein.

A distinctive feature in the quartz-monzonite hosted, gently-dipping shear-zones at Porphyry is the occurrence of ore-related pyrites with negative $\delta^{34}$S values in samples with higher gold grades and stronger hematite alteration. At New Celebration, mineralised pyrites with negative $\delta^{34}$S values occur in sub-horizontal quartz-carbonate veins (Fig. 5A) that cross-cut mafic schist, with abundant pre-gold magnetite alteration, and felsic porphyry dykes, with abundant pre-gold hematite alteration. A common feature is the association of negative $\delta^{34}$S values with pre-gold Fe-oxide alteration, at least at New Celebration. At both Porphyry and New Celebration, there is also a broad negative correlation between whole-rock gold values and pyrite $\delta^{34}$S values (Figures 6 and 8).

There are no obvious explanations, in terms of any one measurable component, for the variations in $\delta^{34}$S values of ore-related pyrites in the regional study. However, there are some indicative relationships. First, there are indications that more negative $\delta^{34}$S values correlate with higher gold grades, which is at least partly related to variations from proximal to distal alteration assemblages or proximity to veins. Second, there are variations related to contrasting host rocks, with rock with pre-existing Fe-metasomatism (e.g., New Celebration, Porphyry) showing more negative $\delta^{34}$S values and greater ranges. Third, there are indications that structural style may be important. All of the deposits with mean negative $\delta^{34}$S values from the regional dataset in Table 1 (Porphyry, New Celebration, Golden Mile) are hosted in shear zones, whereas deposits dominated by vein arrays (e.g., Granny Smith, Mt Charlotte) have positive mean $\delta^{34}$S values. Furthermore, there are indications that shear zone orientation may be important, with the gently-dipping Porphyry deposit showing
extreme variation in $\delta^{34}S$ values despite its small size, and the more negative $\delta^{34}S$ values from Sunrise Dam being from ore-related pyrites associated with the gently-dipping Sunrise Shear Zone.

**Deposit-scale study at Victory-Defiance**

*Introduction*

Results from the regional study suggest that there are potentially relationships between $\delta^{34}S_{(py)}$, proximity to high-grade ore zones, host rock composition and structural style of mineralisation. Victory-Defiance was selected for a case study to test these relationships because it is a world-class deposit with a variety of host rocks and structural styles of mineralisation, and with a large range of $\delta^{34}S_{(py)}$ (Palin and Xu, 2000).

The Victory-Defiance samples analysed in this study are those used for a lead isotope study of pyrites in the 32 Shear Zone. Ho et al. (1994) originally selected this Zone because it has a range of mineralisation styles and host rocks, and mineralisation is interpreted to have occurred during a single structural event from a chemically homogenous ore-fluid (Clark et al. 1989). Analytical results from Ho et al. (1994) not only include lead isotopic ratios, but also weight percent pyrite and gold analyses of pyrite separates. The combination of data from this study and that of Ho et al. (1994) thus provides an opportunity to determine potential causes of variations in $\delta^{34}S_{(py)}$ values in a world-class orogenic gold system.

*Deposit geology*

Victory-Defiance (Roberts and Elias, 1990) is the second largest deposit, after the Golden Mile, along the Boulder-Lefroy Shear Zone, with pre-mining resources of over 250t gold (Watchorn, 1998). Gold mineralisation is hosted in brittle-ductile shear zones, quartz breccia zones and brittle quartz-vein arrays (Fig. 9), in the Defiance Dolerite, Paringa Basalt and Kapai Slate; minor host rocks include the Flames Porphyry and Tripod Hill Komatiite (Clark et al. 1986). At the time of gold mineralization, the principal compressional stress ($\sigma_1$) was subhorizontal (Clark et al. 1986). Proximal alteration assemblages include quartz-albite-ankerite/dolomite-sericite-pyrite(-biotite) in basalt and dolerite, tremolite-biotite-talc-quartz-pyrite-
dolomite in komatiite, and quartz-albite-sericite-pyrite-ankerite(-magnetite-chlorite) in Kapai Slate and felsic intrusions (Clark et al. 1989). Geochronological studies (both U-Pb in rutile and Ar/Ar in sericite) constrain the timing of mineralisation to 2627 ±14 Ma (Clark, 1987; Kent, 1994). Fluid inclusion and mineral equilibria studies (Clark et al. 1989) indicate a low to moderate salinity (8-9 wt% NaCl equivalent), H₂O-CO₂±CH₄ hydrothermal fluid, with P-T conditions of 170-200 MPa and 370-390°C. Gold mineralisation is interpreted to be the result of sulfidation reactions in iron-rich host rocks during fluid-rock interaction (Clark et al. 1989), as well as phase separation and wall-rock carbonation (Palin and Xu, 2000). Recently, it has been suggested that gold deposition is the result of mixing of fluids with different redox states (Neumayr et al. 2005).

**Distribution of sulfur isotopes**

δ³⁴S(py) values at Victory-Defiance from this study are combined with those of Xu (1999) in Table 5. Samples analysed for this study are mainly from the gently-dipping (15-30°) 32 Shear Zone (n=23), whereas samples analysed by Xu (1999; n=21) are from the southern and eastern parts of the deposit. By combining the results from these two studies into a more comprehensive data set, the spatial distribution of variations in δ³⁴S(py) is more apparent. The average δ³⁴S(py) value from the combined dataset (n=44) is –2.2‰ (± 2.8), with a total range of –6.8 to +5.1‰.

Figure 9 shows the spatial distribution of gold-related δ³⁴S(py) values at Victory-Defiance in different structures. The most consistently negative δ³⁴S(py) values and the largest range of values (–6.3 to +0.2‰) are along the gently-dipping Repulse Fault. More steeply-dipping faults in the hangingwall of the Repulse Fault (Victoria, Britannia and Sirius Faults) have more positive δ³⁴S(py) values, ranging from –2.5 to +2.7‰. The largest range of δ³⁴S(py) values is in the 31, 32, and 33 Shear Zones, which are gently-dipping structures in the footwall of the Repulse Fault, and include δ³⁴S values ranging from -4.4 to +5.1‰. There are no significant relationships between δ³⁴S(py) values and host rocks (Table 5).
Sulfur isotopes, weight percent pyrite and gold grades

Data for this section are shown in Table 5 and Figure 10. There is a broad positive correlation between weight percent pyrite and gold value of pyrite separates for most rock types (Fig. 10A). There is also a broad positive correlation between weight percent pyrite and $\delta^{34}$S$_{py}$ values (Fig. 10B). In general, the samples with the lowest weight percent pyrite have the most negative $\delta^{34}$S$_{py}$ values and the lowest gold values. There is a broad negative correlation between gold values of pyrite separates and pyrite $\delta^{34}$S values (Fig. 10C). Palin and Xu (2000) document a similar negative correlation between whole rock-gold values, from core and mine samples, and pyrite $\delta^{34}$S values at Victory-Defiance. We have shown similar relationships between whole rock-gold values and pyrite $\delta^{34}$S values at New Celebration (Figure 6) and Porphyry (Figure 8).

Summary of sulfur isotope data

The following trends are apparent in the combined new and existing $\delta^{34}$S data from the Eastern Goldfields Province.

1) The $\delta^{34}$S values have a total range from about -10‰ to +12‰, with considerable overlap between sulfides from different deposits between -4‰ and +4‰, centred on 0‰ (Fig. 3), the approximate mean of most potential Archean sulfur reservoirs.

2) The majority of orogenic gold deposits have gold-related pyrites with mean $\delta^{34}$S values between 0 and +4‰ with a relatively restricted range of values, normally less than 8‰ if obvious outliers are excluded (Fig. 3). However, other deposits have mean $\delta^{34}$S values between -2 and -4‰, commonly with far greater ranges in $\delta^{34}$S values (Fig. 3): normally greater than 10‰ and potentially in excess of 22‰ (e.g., Golden Mile: Fig. 3).

3) There is no obvious consistent geographic relationship between gold deposits in the two groups (Fig. 2). Three of the deposits with negative means and large ranges of $\delta^{34}$S, Golden Mile, New Celebration and Victory-Defiance, occur in the southern part of the Kalgoorlie Terrane (Fig. 2) adjacent to the Boulder-Lefroy Shear Zone. However, Mt. Charlotte, which is sited adjacent to the Golden Mile, and Hunt and Junction, which are close to Victory-Defiance, fall into the groups with positive mean $\delta^{34}$S values and limited ranges of isotope ratios (Fig. 3).
4) There is no consistent relationship between the mean and total range of $\delta^{34}$S values of a deposit and its size, although many of the larger deposits do have large ranges in $\delta^{34}$S (Table 4). A major discrepancy is provided by the Porphyry deposit. There is a better correlation between gold grade and negative means and greater ranges of $\delta^{34}$S values.

5) Importantly, there is potentially a better fit between the structural style of deposit and range of $\delta^{34}$S values (Table 4). There is a strong tendency for shear-zone hosted deposits to have a greater range of $\delta^{34}$S values than stockwork or rock-hosted (disseminated) deposits. Pre-existing hematite or magnetite alteration also appears to favour the deposition of pyrites with negative $\delta^{34}$S values in some deposits (e.g., New Celebration; Fig 5A).

6) Most importantly, the study at Victory-Defiance also suggests that, with a subhorizontal $\sigma_1$, the more dilational, more gently-dipping shear zones have more negative mean $\delta^{34}$S values, and a larger range of $\delta^{34}$S, than structures oriented such that they were compressional during gold mineralisation (Fig. 9). In this respect, it is interesting that the gently-dipping Porphyry shear zone hosts pyrites with the greatest range of $\delta^{34}$S values outside the Golden Mile, and that the gently-dipping Sunrise Shear Zone hosts ore-related pyrites with the most negative $\delta^{34}$S values at Sunrise Dam. This suggests the possibility that more dilational fluid-dominated systems produce a greater range of oxidation states than rock-dominated systems.

7) At Victory-Defiance, a) gold value correlates broadly with pyrite content (Fig. 10A); b) samples with low pyrite content generally have more negative $\delta^{34}$S values (Fig. 10B); and c) the pyrites themselves with negative $\delta^{34}$S values have high gold values (Fig. 10C). In combination, these data suggest that normal sulfidation processes with significant pyrite formation produce more normal $\delta^{34}$S values, whereas other processes that produce smaller volumes of sulfide produce gold-rich pyrites with more negative $\delta^{34}$S values.

8) In most cases where there are large variations in $\delta^{34}$S values, these can occur on the centimetre to millimetre scale, with adjacent pyrites having markedly contrasting $\delta^{34}$S values (e.g., Fig 4C, 4F). This suggests very local controls on fluid oxidation state and consequent $\delta^{34}$S values.
Discussion

Introduction

The average $\delta^{34}\text{S}$ values of potential Archean sulfur reservoirs (i.e., pre-existing sulfides in host rocks, dissolved sulfate in seawater and sulfur-bearing magmatic volatiles) overlap between approximately 0 and $+10\%$. This range of positive $\delta^{34}\text{S}$ values cannot directly account for the negative $\delta^{34}\text{S}_{(py)}$ values of pyrites that occur in some orogenic gold deposits. Rather, their formation requires variable proportions of oxidised and reduced sulfur species in the ore fluid. The various processes that could produce such variations are discussed below.

Magmatic source

A potential source of oxidised sulfur species is felsic intrusions (Cameron and Hattori, 1987). However, such oxidised solutions would have to remain internally buffered during transport and gold precipitation. Ridley and Diamond (2000) suggest that orogenic ore-fluid compositions are unlikely to reflect the fluid source, given implied fluid travel distances, but rather reflect the influence of fluid-rock interactions along fluid pathways and ore-depositional processes at the deposit site. More importantly, there is no published evidence for coeval igneous rocks in the Eastern Goldfields Province that could have supplied oxidised magmatic-hydrothermal fluids (e.g., Witt and Vanderhor, 1998; Hagemann and Cassidy, 2000). Where detailed geochronological studies have been carried out (Salier et al. 2005), the orogenic gold deposits are significantly younger than intrusions of the high-Ca, mafic and alkaline suites of Champion and Cassidy (2002), the most likely to have produced oxidised fluids. These results support the view that Archean orogenic ore fluids were initially reduced and, under certain conditions, became oxidised along some pathways or at some depositional sites (Lambert et al. 1984; Phillips et al. 1986; Golding et al. 1990; Evans et al. 2006). In addition, the correlation between high gold values and negative $\delta^{34}\text{S}$ values in ore-related pyrites at Porphyry, New Celebration and Victory-Defiance, as shown in this study, suggests that whatever process caused oxidation of the primary ore fluid and formation of ore-related pyrites with negative $\delta^{34}\text{S}$ values in some deposits, also played a potentially important role in gold precipitation (cf. Palin and Xu, 2000). Ore-depositional processes that can potentially cause oxidation of
orogenic ore-fluids are discussed below, in relation to specific deposits analysed in this study.

**Mixing with magmatic fluid**

Although Mikucki (1998) considered that fluid mixing was not an important gold-depositing process, except at very high crustal levels, fluid mixing models (e.g. Walshe et al. 1999; Hall et al. 2001; Neumayr et al. 2005) have recently been proposed for Yilgarn orogenic gold systems. The models invoke mixing between a ubiquitous, deeply-derived, relatively reduced fluid from a distal source and a more proximal, locally oxidizing magmatic fluid.

Mixing of oxidised and reduced fluids contemporaneously in the same or adjacent fault zones, even though well established for epithermal gold deposits (Henley and Ellis, 1983) is presently not supported by fluid inclusion nor stable isotope data-sets (Hagemann and Cassidy, 2000). In addition, as discussed above, there is currently no geochronological data available that supports formation of oxidized granites that are contemporaneous with reduced fluids that form orogenic gold deposits. There is a case for gold mineralisation that broadly overlaps with the initiation of crustal melting and emplacement of the low-Ca granite suite of (Champion and Cassidy, 2002), as shown, for example, by Qui and McNaughton (1999) and Salier et al. (2005). However, these granitoids are generally reduced, not oxidised.

**Reaction with pre-existing oxidized alteration assemblages**

This type of process has recently been proposed by Neumayr et al. (2005) for the St. Ives gold camp. A significant change in the redox state of the hydrothermal fluids during gold mineralization is interpreted to be due to reaction between a ubiquitous, deeply-derived reduced ore fluid and the products of reactions (e.g. hematite or magnetite) between reduced amphibolite host rocks and oxidised fluids released from granitoids underneath and within the greenstone belt rocks. This early magmatic alteration of reduced basalts and subsequent reduced hydrothermal fluid flow in the same fault corridor is also described by Kenworthy and Hagemann (2005) for the Darlot gold deposits. Whether such early oxidised alteration assemblages are part of the orogenic gold event or related to a completely separate earlier event has not been resolved, although available geochronology supports the later. It may also not be
necessary for the oxidized alteration assemblages to be related to magmatic processes (cf. Huston et al. 2001). Whatever the timing, such reactions between reduced ore fluid and earlier alteration is supported, for example, at New Celebration where ore-related pyrites with negative δ\(^{34}\)S values occur predominantly in two host rock types: mafic schist, with ubiquitous pre-gold magnetite alteration; and felsic porphyry dykes, with abundant pre-gold hematite alteration. The most likely explanation is that the interaction of the primary ore fluid with these Fe\(^{3+}\)-rich rocks resulted in ore-fluid oxidation at, or near, the site of gold deposition, which, in turn, resulted in deposition of sulfides with negative δ\(^{34}\)S values. A potential analogy is the Archean orogenic-gold Francoeur 3 deposit in Quebec, which has negative δ\(^{34}\)S values in gold-related pyrite. Couture and Pilote (1993) interpret gold mineralisation at Francoeur 3 to be the result of fluid-rock interaction and progressive changes in ore-fluid oxidation state, associated, in part, with reaction of the orogenic ore-fluid with pre-gold hematite alteration.

**Mixing of two modified fluids from a single source**

In a detailed study of orogenic ore-fluid evolution in the Yilgarn Golden Crown deposit, Uemoto et al. (2002) show that gold mineralisation is associated with mixing between two modified components of a single orogenic ore-fluid. In this genetic model, an H\(_2\)O-CO\(_2\) ore fluid from a single source is interpreted to have migrated upwards along a shear zone. In the northern end of the deposit, the fluid reacted with graphitic shale and became a relatively reduced H\(_2\)O-CO\(_2\)±CH\(_4\) fluid. The addition of CH\(_4\), from reaction with the shale, raised the solvus to higher P-T conditions and, in combination with a local decrease in fluid pressure due to fracture opening, enhanced phase separation and gold precipitation. In addition, reaction with the graphitic shale could have caused a decrease in a\(_{\text{H}_2\text{S(aq)}}\), accounting for somewhat higher gold grades at the shale contact. In other parts of the deposit, the primary ore fluid reacted with dolerite and became a relatively oxidised H\(_2\)O-CO\(_2\) fluid. Mixing of the two evolved ore-fluid components in the upper parts of the deposit is interpreted to have oxidised the reduced ore fluid and promoted gold precipitation in the mixing zone.

Although this type of fluid mixing has not been documented for any of the deposits investigated in this study (see Table 4), it could account for the occurrence of distinct
oxidised and reduced fluids in the same orogenic-gold system, as the result of interaction of a typical orogenic ore-fluid with variably reduced and oxidised rocks in the host rock sequence. However, it is unlikely to have resulted in sufficiently oxidized fluids to cause the highly negative $\delta^{34}S_{(py)}$ shifts elsewhere as magnetite, not hematite, is stable in the metamorphic assemblage and pyrrhotite, pyrite and arsenopyrite are stable in the muscovite alteration zone.

Reactions with host rocks

Orogenic fluids in the Yilgarn craton are thought to have been broadly controlled by sulphate-sulphide or by carbonate-methane fluid buffers, depending upon the temperature and initial composition (Mikucki and Ridley, 1993). However, the high oxidation states deduced for some gold deposit fluids require mechanisms to depart from regional fluid buffers. From the example of Uemoto et al. (2002), it is evident that wall-rock reactions can modify the oxidation state of the ore fluid. Also, sulfidation of Fe-bearing minerals (e.g. Phillips and Groves, 1983) is widely accepted as a major gold-depositional process and sulfidation of Fe-oxides has been suggested as a mechanism to raise the oxidation state of ore fluids (e.g. Phillips et al. 1986; Evans et al. 2006). The association of negative $\delta^{34}S$ values with pre-existing Fe-oxide alteration at deposits such as Porphyry demonstrates that this is a plausible oxidation mechanism, but the fact that pyrites from deposits clearly formed by sulfidation of Fe-oxides (e.g. Mt Charlotte, Water Tank Hill, Wallaby) do not necessarily have negative $\delta^{34}S$ values requires that it cannot be a universal mechanism.

A more universal wall-rock reaction is carbonation because the ore fluid is ubiquitously CO$_2$-rich. During wall-rock carbonation, the reaction of CO$_2$-bearing hydrothermal fluids with ferric-iron bearing minerals (e.g., magnetite) forms Fe-bearing carbonates, characteristic of orogenic gold deposits (McCuaig and Kerrich, 1998). This reaction can result in significant oxidation of the ore fluid (Palin and Xu, 2000; Palin et al. 2001), leading to negative shifts in $\delta^{34}S$ of H$_2$S, as the proportion of HSO$_4$ to H$_2$S in the solution increases, with resultant negative $\delta^{34}S$ values in gold-related pyrite. Thus, it is possible that, under certain conditions, orogenic ore-fluids become oxidised as a result of carbonation reactions, rather than sulfidation, with Fe-oxides in wall-rocks (Phillips et al. 1986; Phillips et al. 1996). This process can explain the negative $\delta^{34}S$ values in ore-related pyrites in magnetite-rich mafic host
rocks at Victory-Defiance and New Celebration, but their lack in other rocks exceedingly rich in magnetite (e.g. BIF) where elements such as Ca and Mg may be too low for effective stabilisation of abundant ore-related carbonates.

Phase separation

Phase separation offers another avenue for departure from fluid buffers, resulting in oxidation of fluids (Rye, 1993). In all Yilgarn deposits that have received detailed fluid inclusion study, there is evidence for phase separation in ore fluids (Table 4). During phase separation, reduced gases, such as H₂, CH₄, and H₂S, are preferentially partitioned into a vapour phase, which increases the ratio of SO₄ to H₂S in the residual ore fluid, leaving it relatively oxidised (Drummond and Ohmoto, 1985). Under equilibrium conditions, phase separation leads to relatively ³⁴S-depleted H₂S in the residual ore fluid, and results in the precipitation of sulfide minerals with more negative δ³⁴S values (Ohmoto and Rye, 1979; Ohmoto, 1986). Removal of H₂S from the ore fluid into the vapour phase during phase separation also causes a decrease in the total activity of sulfur (aΣS) in gold ore fluids, which destabilises gold-bisulfide complexes and shifts the fluid from the pyrite stability field to the pyrite-hematite equilibrium curve (Fig. 11). This results in a rapid decrease in gold solubility and the precipitation of pyrite in equilibrium with hematite. Therefore, rapid pressure changes, and associated phase separation, are potentially efficient mechanisms for ore fluid oxidation, and hence gold deposition. Cassidy (1992) and Witt (1995) suggest phase separation as the main cause of gold deposition and hematite alteration in orogenic gold deposits in low-Fe host rocks. This process can explain the occurrence of gold mineralisation at Porphyry and the wide range of δ³⁴S values of ore-related pyrites within it.

At Sunrise Dam, there is evidence for intermittent phase separation in fluid inclusions from the Sunrise Shear Zone (Brown, 2002). Phase separation is interpreted to be related to hydraulic fracturing associated with competency contrasts between felsic volcaniclastic sedimentary rocks and more brittle magnetite-rich shale units (Brown, 2002). The occurrence of the shale units as thin beds within the host rock sequence suggests that fracturing related to competency contrasts, and associated phase separation, may have occurred only locally. This would account for the rare occurrences of negative δ³⁴S values: one of seven samples from the Sunrise Shear
The average $\delta^{34}S$ value in gold-related pyrites at Sunrise Dam is $+1.1\%$ ($\pm3.5$) consistent with the dominant gold-depositional mechanism being wall-rock sulfidation (Brown, 2002).

Phase separation has also been interpreted as a potential gold-depositional mechanism at Lady Bountiful and North Royal. Based on analytical results from this study, there are rare occurrences of ore-related pyrites with more positive $\delta^{34}S$ values in these two deposits. In a detailed study of the Mt Charlotte deposit, Harbi (1997) provides evidence for phase separation under both equilibrium and disequilibrium conditions, in different parts of the hydrothermal system. During phase separation under disequilibrium conditions, H2S in the residual ore fluid becomes relatively enriched in $^{34}S$, which results in the formation of sulfide minerals with more positive $\delta^{34}S$ values (Ohmoto and Rye, 1979).

At Victory-Defiance, the large range of $\delta^{34}S$ values in ore-related pyrites and a negative correlation between $\delta^{34}S_{(py)}$ values and gold grade in mafic host rocks (Fig. 10C) indicates an increase in fluid oxidation during mineralisation. Previous studies at Victory-Defiance (Clark et al. 1989) show that wall-rock sulfidation is a significant ore-forming process. However, this process alone cannot produce the degree of fluid oxidation necessary to explain the range in sulfur isotopes (Mikucki and Groves, 1990). Based on fluid-rock reaction path calculations (Palin and Xu, 2000; Palin et al. 2001), the two dominant in-situ mechanisms that potentially caused oxidation of originally reduced ore fluids at Victory-Defiance were carbonation of wall-rock magnetite and phase separation.

**Structural style: rock-dominated vs fluid-dominated systems**

Figure 12 shows the relationships between the total range of $\delta^{34}S$ values of ore-related pyrites and the structural style of mineralisation at studied deposits. There is a strong tendency for deposits hosted in shear zones to have greater ranges and more negative mean $\delta^{34}S$ values than stockwork-style or rock-hosted deposits such as disseminations and replacements: for example, eight of the ten deposits with $\delta^{34}S$ ranges of 10‰ or more are hosted in shear zones. While it must be remembered that the ranges are based on different population sizes, it is important that the relationship with structural
style is stronger than that with deposit size or any other single factor considered in this study.

As a specific, well-documented example, the structural setting at Victory-Defiance appears to have been a critical factor in controlling the distribution of $\delta^{34}\text{S}$ values of ore-related pyrites. As discussed above, large fluid pressure fluctuations can lead to oxidation of ore fluids and cause gold deposition. At Victory-Defiance, pyrites with negative $\delta^{34}\text{S}$ values occur in gently-dipping structures whereas those with more positive $\delta^{34}\text{S}_{(py)}$ values occur in steeply-dipping structures (Fig. 13). This suggests a potential relationship between the $\delta^{34}\text{S}$ value of ore-related pyrites, structures and fluid pressure fluctuations during fault-valve cycles. These cycles are controlled by the progressive build-up of fluid pressures between rupture events in fault systems that localise fluid flow (Sibson et al. 1988). Structural analysis and fluid inclusion studies in the Val d’Or district (Robert et al. 1995) indicate large fluid pressure fluctuations in laminated and extensional veins during mineralisation. Other studies use fluid inclusion evidence for phase separation to link large fluid-pressure fluctuations to gold deposition in high grade (>10 g/t) veins at the Pamour, Hollinger-McIntyre and Sigma deposits (Walsh et al. 1988; Guha et al. 1991). During sub-horizontal shortening (Clark et al. 1986; Verncombe et al. 1989), the gently-dipping structures at Victory-Defiance would be in the optimal orientation for dilation and focused fluid flow during faulting, whereas the steeply-dipping structures would be sites of compression or transpression, with more transient fluid flow. This relationship suggests that different fluid flow regimes in broadly dilational and compressional structures influence physical and chemical conditions in the ore fluid, and hence $\delta^{34}\text{S}$ values in gold-related pyrites.

At the Revenge deposit, located 5 km northwest of Victory-Defiance, Nguyen et al. (1998) demonstrate that fault-valve activity influenced the formation of optimally-oriented, gently-dipping, shear zones in a transitional brittle-ductile regime. Large fluid pressure fluctuations are interpreted to have controlled the localisation of fluid flow and associated gold mineralisation along active shear zones. At Revenge, there are also relationships between $\delta^{13}\text{C}$ of gold-related carbonate minerals and orientations of mineralisation-hosting structures (Nguyen, 1997). This again suggests
that different fluid flow regimes in different structures can influence the isotopic signature of ore fluids that advect within them.

The degree of dilatancy of ore-hosting structures probably reflects the degree to which fluid-dominated or rock-buffered processes acted. In dilatant shear zones, internal fluid-dominated processes, such as phase separation, caused pulsed variations in oxidation state. However, in less-dilatant structures, the fluids fractured the rock by processes such as crack-seal or hydraulic fracturing such that continuous reactions with wallrocks led to largely rock-buffered systems.

Summary

Based on the discussion above, variations in $\delta^{34}$S values of ore-related pyrites can be caused by the inferred dominant ore-depositional processes in orogenic gold systems: fluid-rock interaction, phase separation and a variety of fluid mixing. In the seismogenic regime, fluid pressure fluctuations and consequent reversals in pressure gradients influence the operation of these processes and cause episodic gold deposition at different stages in the seismic cycle (Cox, 1999). For example, pre-failure fluid discharge from faults enhances fluid-rock interaction in host rocks adjacent to faults, while fluid pressures increase beneath low permeability seals that cap the hydrothermal system. At this stage of the seismic cycle, wall-rock sulfidation reactions in iron-rich host rocks may generate disseminated gold mineralisation under rock-buffered conditions. In addition, wall-rock carbonation of Fe$^{3+}$-rich host rocks (e.g., magnetite-rich dolerite at the Golden Mile, New Celebration and Victory-Defiance) could cause oxidation of orogenic gold fluids (Phillips et al. 1986; Palin and Xu, 2000; Evans et al. 2006) during this pre-failure stage.

During and immediately after faulting in the seismic cycle, rapid fluid pressure fluctuations can cause phase separation, resulting in both ore fluid oxidation and gold precipitation, as discussed above. Pressure fluctuations are most severe at dilational sites, and, importantly, results from this study suggest that the larger variations in $\delta^{34}$S values are commonly associated with more dilational structures in the ore environment where internal fluid-dominated processes may be dominant.
In the immediate post-failure stage of the seismic cycle, fluid mixing between primary ore fluids and modified equivalents, which have reacted with wall-rocks, may cause oxidation and gold deposition. During the pre-failure discharge of fluids from faults, reactions between the primary ore fluid and variably reduced or oxidised wall rocks (e.g., graphitic shale or dolerite; Uemoto et al. 2002) can change the oxidation state of the ore fluid. During shear failure and dilation, pressure changes cause these modified ore fluids to be drawn back into faults which are pathways for the primary ore fluid. Subsequent back-mixing between the two fluids will result in gold deposition.

It is evident that a variety of processes, all of which are described from detailed research on one or more Yilgarn deposits, can explain the highly oxidised nature of some Archean orogenic gold deposits, without appeal to exotic fluid sources, such as those derived from magmatic systems (cf. Walshe et al. 1999; Hall et al. 2001).

*Sulfur isotopes and gold endowment*

A plot of gold endowment and total variation in $\delta^{34}S_{(py)}$ values (Fig. 12) shows that many larger orogenic gold deposits (>30 tonnes Au) have larger ranges of $\delta^{34}S_{(py)}$ values (greater than approximately 10‰), although this is not a consistent relationship. This broad relationship is potentially an indication of the influence of multiple ore-forming processes (e.g., wall-rock sulfidation, wall-rock carbonation and phase separation) in complex ore systems at deposits such as Victory-Defiance and the Golden Mile, as discussed above. Large ranges of $\delta^{34}S_{(py)}$ values in smaller deposits may indicate the influence of a single dominant ore-depositional process (e.g., phase separation at Porphyry). Most of the larger deposits with large ranges of $\delta^{34}S_{(py)}$ values are dominantly shear-zone hosted, rather than disseminated, quartz-vein or stockwork-hosted, suggesting that multiple ore-forming processes are more likely to occur in mineralising systems where larger fluid volumes circulated through more-continuous structural permeability paths and where fluid-dominated systems, rather than rock-buffered systems, were predominant.

The determination of $\delta^{34}S$ values in sulfide minerals requires detailed sample preparation and analysis, which is well beyond the scope of most exploration programs. However, multiple ore-depositional processes at a single deposit location are potentially critical factors for large gold endowment and high gold grade.
Therefore, the recognition of more than one potential gold-precipitation mechanism in an orogenic gold system is important. Analysis of $\delta^{34}\text{S}$ values in sulfides would complement structural, alteration and fluid inclusion studies that similarly seek to identify multiple ore-forming processes. Sulfur isotopic compositions alone cannot uniquely define potential endowment, as shown by the fact that the Porphyry deposit has an extreme range in $\delta^{34}\text{S}_{(\text{py})}$ values but is quite small. However, in concert with an understanding of other factors in the ore environment, they can be a useful indicator.

**Conclusions**

Based on the results of this and previous studies, there is abundant evidence for *in-situ* oxidation of orogenic ore fluids associated with different gold-depositional processes. Phase separation and fluid-rock interaction are the most common processes recorded by a variety of researchers for deposits examined in this study. The former, fluid-dominated process appears to produce greater shifts in fluid oxidation state. Mixing of two modified components of a single ore fluid is also an effective process of oxidation and gold deposition (Uemoto et al. 2002), although this mechanism is not documented by any author for the deposits studied here. Similarly, only fluid inclusion studies from deposits at high crustal levels (e.g., Wiluna, Hagemann; 1992; Racetrack, Gebre-Mariam, 1994) suggest mixing of external fluids in orogenic gold systems in the Eastern Goldfields Province.

The influence of more than one gold-depositional mechanism during the formation of a single deposit has the potential to increase gold endowment. Therefore, the recognition of multiple gold-depositional processes is significant in the study of, and exploration for, world-class orogenic gold deposits. Analysis of $\delta^{34}\text{S}_{(\text{py})}$ provides one method for recognising the influence of multiple ore-forming processes.

The structural setting of a deposit is potentially the most important factor controlling ore fluid oxidation, and hence the distribution of $\delta^{34}\text{S}_{(\text{py})}$ values. At Victory-Defiance, pyrites with negative $\delta^{34}\text{S}$ values occur more commonly in gently-dipping dilational structures, compared to steeply-dipping structures. In this study, it is proposed that these differences are associated with fluid-pressure fluctuations during fault-valve cycles, which establish different fluid-flow regimes in structures with different orientations. Rapid fluid-pressure fluctuations during faulting can cause the
preferential partitioning of reduced gas phases from the ore fluid, and are an effective method of orogenic ore-fluid oxidation. In addition, at different stages of the progressive fault-valve cycle, different gold-precipitation mechanisms are dominant. For example, fluid-rock interaction with rock-buffered reactions will be the dominant mechanism during pre-failure discharge of fluids from faults. Fluctuations in fluid-pressure during, and immediately after, faulting can cause fluid-dominated processes such as phase separation and back-mixing of modified ore-fluid components. Any, or all, of these three gold-depositional mechanisms can induce oxidation in orogenic gold fluids under appropriate conditions.

Negative average $\delta^{34}$S values and large variations in $\delta^{34}$S values of ore-related pyrites in world-class orogenic gold deposits are interpreted to be the result of multiple mechanisms of gold precipitation within a single and widespread orogenic ore fluid (Ridley and Diamond, 2000) in specific structural settings, rather than the result of different ore fluids. Magmatic fluids from shallow-level felsic intrusions, although not completely ruled out as an important source of oxidised ore-fluids (cf. Cameron and Hattori, 1987), do not appear to be necessary to account for negative $\delta^{34}$S values of ore-related pyrites in orogenic gold deposits in the Eastern Goldfields Province. Available studies suggest, instead, that they pre-date gold mineralisation but induced early hematite or magnetite alteration that modified potential host rocks and made them more reactive to orogenic gold fluids.

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Figure 1. Plot of oxygen fugacity (log $fO_2$) against pH showing gold solubility contours (0.01, 0.1, 1.0, and 10.0 ppm) for gold-bisulfide complexes, modified from Roberts (1987). Neutral solutions with low concentrations of total sulfur are capable of transporting gold in comparatively high concentrations as a sulfide complex. The solubility of gold in this state increases with $fO_2$ up to the boundary between the fields of reduced and oxidised sulfur. At higher oxygen fugacities, sulfate is the dominant species, and with the decrease in the activity of the reduced sulfur species, the solubility of gold decreases markedly (see arrow). Therefore, oxidation of fluids is an efficient mechanism for the precipitation of gold. Isotopic contours are drawn as $H_2S$ values. They were drawn with the aid of Zhang and Spry (1994), assuming $mNa^+=1$, $mK^+=0.1$ and $mCa^{2+}=0.01$, and total $S=0$ per mil.
Figure 2. Map of the Eastern Goldfields Province (modified from Knox-Robinson et al., 1996), showing locations of deposits with sulfur isotope data from this study and previous studies. Data are shown in Table 1. Greenstones are dark grey and granitoids are light grey. Map grid is in AMG coordinates, in metres.
Figure 3. Total range of $\delta^{34}$S values in ore-related pyrites by deposit, and average $\delta^{34}$S$_{(py)}$ values (short vertical lines), arranged from north to south and corresponding to locations in Figure 2. Dashed lines correspond to $\delta^{34}$S$_{(py)}$ ranges based on limited data (i.e., one sample or analysis). The grey area corresponds to the range of average $\delta^{34}$S$_{(py)}$ values based on analytical results of this study and data compiled from previous studies (see Table 1).
Figure 5. Photographs of host rocks from the New Celebration deposit. Scale bar in (C) and (E) is in millimetre increments. (A) Underground mine exposure of mineralised quartz-carbonate±pyrite veins, with yellow feldspar-ankerite-pyrite selvedges, crosscutting dark tholeiitic mafic schist with pre-gold magnetite alteration and orange felsic porphyry with pre-gold hematite alteration (from Williams, 1994). (B) Underground mine exposure of sub-vertical lenses of hematite-altered felsic porphyry in black tholeiitic mafic schist, and cross-cutting, sub-horizontal, quartz-carbonate-chlorite veins with hematite-altered selvedges (from Williams, 1994). (C) Mineralised felsic porphyry (sample 121784, 3.65 g/t Au) and δ^{34}S_{(py)} values. (D) Euhedral pyrite from sample in (C). (E) Weakly mineralised tholeiitic mafic schist (sample 121776, < 0.01 g/t Au) and δ^{34}S_{(py)} value. (F) Euhedral pyrite from sample in (E).
Figure 6. Plot of whole rock gold values vs pyrite $\delta^{34}\text{S}_{(py)}$ values from the New Celebration deposit, from data in Table 2.
Figure 6. Photographs and SEM images of quartz-monzonite host rock from the Porphyry deposit. Scale bar in photographs is in millimetre increments. (A) Well-mineralised sample (#101935, 7.4 g/t Au) with strong hematite alteration and well-developed shear fabric defined by pyrite and sericite. (B) Anhedral pyrite from sample in (A). (C) Weakly-mineralised sample (#101958, 0.5 g/t Au) from shear zone margin, with weak hematite alteration and minor fabric development. (D) Euhedral pyrite from sample in (C). (E) Quartz monzonite (#101951, < 0.01 g/t Au) with very weak fabric development, from approximately 10m below mineralised shear zone. (F) Small euhedral pyrite from sample in (E).
Figure 8. Plot of whole rock gold values vs pyrite $\delta^{34}\text{S}_{(py)}$ values from the Porphyry deposit, from data in Table 3.
Figure 9. Cross section of the Victory-Defiance area, view to the northwest (modified from Vanderhor and Groves, 1998), showing spatial distribution of $\delta^{34}S_{\text{py}}$ values listed in Table 5. Distinct average values occur in different structures (see discussion in text).

Repulse Fault  
(gently-dipping shear zone)  
mean $\delta^{34}S_{\text{py}} = -4.4‰$  
STD = 1.6‰  
median = -4.7‰  
range = 6.5‰ (-6.3 to +0.2)  
n = 17

31, 32 and 33 Shear Zones  
(gently-dipping footwall structures)  
mean $\delta^{34}S_{\text{py}} = -1.2‰$  
STD = 2.9‰  
median = -2.6‰  
range = 9.5‰ (-4.4 to +5.1)  
n = 15

Victory, Britannia and Sirius Faults  
(steeply-dipping hangingwall structures)  
mean $\delta^{34}S_{\text{py}} = -0.8‰$  
STD = 1.8‰  
median = -1.3‰  
range = 5.2‰ (-2.5 to +2.7)  
n = 10

Legend
Pdy – Proterozoic dyke
Apf – felsic porphyry
Abp – Paringa Basalt
Aod – Defiance Dolerite
Agd – xenolithic dolerite
Aks – Kapai Slate
Abd – Devon Consuls Basalt
Aut – Tripod Hill Komatiite
Figure 10. Plots of weight percent pyrite, gold value and $\delta^{34}$S value from Victory-Defiance ore-related pyrites. Data are from this study and Ho et al. (1994) as shown in Table 5. (A) Weight percent pyrite vs gold value of pyrite separate, showing broad positive correlation. (B) Weight percent pyrite vs $\delta^{34}$S$_{py}$ values, showing broad positive correlation. (C) Gold values of pyrite separates vs $\delta^{34}$S values, showing broad correlation between higher gold grades and more negative $\delta^{34}$S$_{py}$ values.
Figure 11. Plot of oxygen fugacity (log $f_{O_2}$) and activity of total sulfur ($a\Sigma S$), showing gold solubility contours for bisulfide complexes, modified from Mikucki and Groves (1990). During phase separation in a reduced ore fluid, reduced gases such as H$_2$S, CH$_4$ and H$_2$ are preferentially partitioned into a vapour phase, which reduces $a\Sigma S$ and leaves a relatively oxidised ore fluid (Drummond and Ohmoto, 1985). The resulting shift from the pyrite stability field to the pyrite-hematite equilibrium curve destabilises the gold-bisulfide complex and causes a significant decrease in gold solubility (see arrow across the steep gold-solubility gradient). In this case, gold mineralisation would be accompanied by increased hematite alteration. Isotopic contours are drawn as H$_2$S values. They were drawn with the aid of Zhang and Spry (1994), assuming, mNa$^+$=1, mK$^+$=0.1 and mCa$^{2+}$=0.01, and total S=0 per mil.
Figure 12. Plot showing broad relationship between gold endowment and total range of $\delta^{34}$S$_{(py)}$ values, by dominant structural style of mineralisation, from data compilation in Table 1. Individually identified deposits are those with a pre-mining resource of >30 tonnes Au and/or a range of $\delta^{34}$S values in ore-related pyrites greater than 10‰.
Figure 13. Plots showing more negative $\delta^{34}$S$_{(py)}$ values and larger variation in gently dipping faults, compared to steeply dipping faults, at Victory-Defiance (see cross section in Figure 9 for locations). Data from Table 5.
Table 1. List of gold deposits in the Eastern Goldfields Province, arranged from north to south, indicating sources of sulfur isotope data used in this study. Deposit locations are shown in Figure 2. All δ^{34}S values are from ore-related pyrite. Pre-mining endowment figures are from Townsend et al. (2000). Analytical methods are listed: CONV is conventional digestion and LA is laser ablation.

<table>
<thead>
<tr>
<th>Deposit Name</th>
<th>Pre-mining Endowment (tonnes Au)</th>
<th>Number of Samples/Analyses</th>
<th>Min and Max δ^{34}S_{py}‰ Values (total range)</th>
<th>Data Sources</th>
<th>Analytical Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wiluna</td>
<td>86</td>
<td>10/10</td>
<td>-2.5 to +1.0 (3.5)</td>
<td>Hagemann (1992)</td>
<td>CONV</td>
</tr>
<tr>
<td>Great Eastern</td>
<td>15</td>
<td>13/14</td>
<td>-0.6 to +2.5 (3.1)</td>
<td>this study; Mikucki (1997)</td>
<td>LA/CONV</td>
</tr>
<tr>
<td>Tarmoola</td>
<td>100</td>
<td>10/10</td>
<td>0.0 to +4.0 (4.0)</td>
<td>Duuring (2002)</td>
<td>CONV</td>
</tr>
<tr>
<td>Leonora Gold Blocks</td>
<td>1</td>
<td>1/1</td>
<td>+7.1</td>
<td>this study</td>
<td>LA</td>
</tr>
<tr>
<td>Trump Mine</td>
<td>1</td>
<td>1/2</td>
<td>+2.7 to +2.9 (0.2)</td>
<td>this study</td>
<td>LA</td>
</tr>
<tr>
<td>Forrest Mine</td>
<td>1</td>
<td>1/2</td>
<td>+0.6 to +2.6 (2.0)</td>
<td>this study</td>
<td>LA</td>
</tr>
<tr>
<td>Harbour Lights</td>
<td>10</td>
<td>2/3</td>
<td>-1.1 to +5.1 (6.2)</td>
<td>this study</td>
<td>LA</td>
</tr>
<tr>
<td>Sons of Gwalia</td>
<td>130</td>
<td>3/5</td>
<td>+0.7 to +3.2 (2.5)</td>
<td>this study</td>
<td>LA</td>
</tr>
<tr>
<td>Lancefield</td>
<td>46</td>
<td>18/18</td>
<td>-6.4 to +3.2 (9.6)</td>
<td>Hronsky (1993)</td>
<td>CONV</td>
</tr>
<tr>
<td>Granny Smith</td>
<td>50</td>
<td>7/11</td>
<td>+0.3 to +4.5 (4.2)</td>
<td>Ojala (1995)</td>
<td>CONV</td>
</tr>
<tr>
<td>Wallaby</td>
<td>200</td>
<td>6/9</td>
<td>-0.7 to +6.2 (6.9)</td>
<td>Salier et al. (2004, 2005)</td>
<td>LA</td>
</tr>
<tr>
<td>Sunrise Dam</td>
<td>250</td>
<td>19/21</td>
<td>-8.2 to +4.0 (12.2)</td>
<td>this study; Brown (2002)</td>
<td>LA/CONV</td>
</tr>
<tr>
<td>Porphyry</td>
<td>11</td>
<td>13/19</td>
<td>-10.2 to +10.0 (20.2)</td>
<td>this study</td>
<td>LA</td>
</tr>
<tr>
<td>Sand King</td>
<td>2</td>
<td>10/11</td>
<td>+0.9 to +6.0 (5.1)</td>
<td>this study; WMC (unpublished data)</td>
<td>LA/CONV</td>
</tr>
<tr>
<td>Golden Kilometre</td>
<td>17</td>
<td>8/13</td>
<td>-4.3 to +7.0 (11.3)</td>
<td>this study; Gebre-Mariam (1994)</td>
<td>LA/CONV</td>
</tr>
<tr>
<td>Lady Bountiful</td>
<td>11</td>
<td>9/14</td>
<td>-1.1 to +9.5 (10.6)</td>
<td>this study</td>
<td>LA/CONV</td>
</tr>
<tr>
<td>Ora Banda</td>
<td>18</td>
<td>1/2</td>
<td>+1.7 to +3.0 (1.3)</td>
<td>this study</td>
<td>LA</td>
</tr>
<tr>
<td>Racetrack</td>
<td>13</td>
<td>5/6</td>
<td>+1.6 to +7.3 (5.7)</td>
<td>this study; Gebre-Mariam (1994)</td>
<td>LA/CONV</td>
</tr>
<tr>
<td>Golden Swan</td>
<td>1</td>
<td>1/2</td>
<td>+3.4 to +5.4 (2.0)</td>
<td>this study</td>
<td>LA</td>
</tr>
<tr>
<td>Royal Standard</td>
<td>1</td>
<td>1/1</td>
<td>3.6</td>
<td>this study</td>
<td>LA</td>
</tr>
<tr>
<td>Paddington</td>
<td>200</td>
<td>1/2</td>
<td>+2.7 to +2.9 (0.2)</td>
<td>this study</td>
<td>LA</td>
</tr>
<tr>
<td>Kanowna Belle</td>
<td>130</td>
<td>5/14</td>
<td>-5.4 to 10.9 (16.3)</td>
<td>Ross (2002)</td>
<td>LA</td>
</tr>
<tr>
<td>Mt Charlotte</td>
<td>160</td>
<td>34/34</td>
<td>-3.8 to +8.9 (12.7)</td>
<td>Clout (1989); Harbi (1997)</td>
<td>LA/CONV</td>
</tr>
<tr>
<td>Golden Mile</td>
<td>2500</td>
<td>224/224</td>
<td>-9.8 to 12.7 (22.5)</td>
<td>Clout (1989); Hagemann et al. (1999)</td>
<td>LA/CONV</td>
</tr>
<tr>
<td>New Celebration</td>
<td>100</td>
<td>5/8</td>
<td>-8.6 to +5.5 (14.1)</td>
<td>this study</td>
<td>LA</td>
</tr>
<tr>
<td>Hunt</td>
<td>10</td>
<td>6/10</td>
<td>+1.0 to +8.0 (7.0)</td>
<td>this study; Lambert et al. (1984)</td>
<td>LA</td>
</tr>
<tr>
<td>Victory-Defiance</td>
<td>250</td>
<td>28/58</td>
<td>-6.3 to +5.1 (11.4)</td>
<td>this study; Palin and Xu (2000)</td>
<td>LA/CONV</td>
</tr>
<tr>
<td>Junction</td>
<td>60</td>
<td>6/6</td>
<td>+2.2 to +5.1 (2.9)</td>
<td>Polito (1999)</td>
<td>CONV</td>
</tr>
<tr>
<td>Higginsville</td>
<td>10</td>
<td>1/2</td>
<td>+7.3 to +7.9 (0.6)</td>
<td>this study</td>
<td>LA</td>
</tr>
<tr>
<td>Chalice</td>
<td>18</td>
<td>5/14</td>
<td>+1.8 to +3.5 (1.7)</td>
<td>Bucci (2001)</td>
<td>CONV</td>
</tr>
<tr>
<td>North Royal</td>
<td>55</td>
<td>4/9</td>
<td>+0.3 to +10.4 (10.1)</td>
<td>this study</td>
<td>LA/CONV</td>
</tr>
</tbody>
</table>
Table 2. δ³⁴S values of ore-related pyrites (in order from most negative to most positive) and whole-rock gold values at New Celebration. Gold values from Williams (1994). δ³⁴S\(_{py}\) values from this study.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Sample Description</th>
<th>δ³⁴S(_{py}) ‰</th>
<th>Whole-rock Au (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>121784</td>
<td>mineralised felsic porphyry intrusion, albite-hematite alteration</td>
<td>-6.0, -8.6</td>
<td>3.7</td>
</tr>
<tr>
<td>121788</td>
<td>mineralised tholeiitic mafic schist, alkali feldspar-albite-ankerite alteration</td>
<td>-5.5, -4.8</td>
<td>5.0</td>
</tr>
<tr>
<td>121763</td>
<td>felsic porphyry intrusion, sericite alteration, 19.5m from mineralised shear zone</td>
<td>-1.4</td>
<td>0.3</td>
</tr>
<tr>
<td>121766</td>
<td>ultramafic schist, biotite-dolomite-chlorite alteration, 10m below mineralised shear zone</td>
<td>+3.9</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>121776</td>
<td>tholeiitic mafic schist, chlorite-calcite-albite alteration, 39.5m from mineralisation</td>
<td>+5.5</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>
Table 3. $\delta^{34}$S values of ore-related pyrites (in order from most negative to most positive) and whole rock gold values, in quartz-monzonite host rocks at Porphyry. Gold values from Allen (1986). $\delta^{34}$S$_{(py)}$ values from this study.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Sample Description</th>
<th>$\delta^{34}$S$_{(py)}$ ‰</th>
<th>Whole rock Au (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101956</td>
<td>sheared quartz monzonite, strong hematite alteration, visible gold</td>
<td>-10.2, -9.4</td>
<td>5.0</td>
</tr>
<tr>
<td>101929</td>
<td>sheared quartz monzonite, moderate hematite alteration</td>
<td>-9.7, -7.7</td>
<td>0.3</td>
</tr>
<tr>
<td>101935</td>
<td>sheared quartz monzonite, strong hematite alteration, visible gold</td>
<td>-8.4, -7.8</td>
<td>7.4</td>
</tr>
<tr>
<td>101987</td>
<td>sheared quartz monzonite, strong hematite alteration</td>
<td>-8.3</td>
<td>3.2</td>
</tr>
<tr>
<td>101984</td>
<td>sheared quartz monzonite, weak hematite alteration</td>
<td>-5.6</td>
<td>1.4</td>
</tr>
<tr>
<td>101990</td>
<td>quartz monzonite, weak hematite alteration</td>
<td>-4.3</td>
<td>0.6</td>
</tr>
<tr>
<td>101955</td>
<td>sheared quartz monzonite, moderate hematite alteration</td>
<td>-2.8</td>
<td>1.0</td>
</tr>
<tr>
<td>101931</td>
<td>sheared quartz monzonite, strong hematite alteration</td>
<td>-2.2, -4.1</td>
<td>0.9</td>
</tr>
<tr>
<td>101958</td>
<td>sheared quartz monzonite, weak hematite alteration</td>
<td>-1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>101951</td>
<td>grey quartz monzonite, 10 m below shear zone</td>
<td>+10.0, +7.1</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>
Table 4. Summary of deposit characteristics and δ\(^{34}\)S values of ore-related pyrites from regional study of deposits in the Eastern Goldfields Province, Yilgarn Craton. The first six deposits, listed in order of decreasing gold endowment, have positive average δ\(^{34}\)S values, whereas the last two have negative average δ\(^{34}\)S values.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Pre-mining Endowment (tonnes Au)</th>
<th>Max and Min δ(^{34})S Values from this and Previous Studies, n = Total Number of Analyses</th>
<th>Total Range of δ(^{34})S Values</th>
<th>Pre- and Mean δ(^{34})S Value and STD</th>
<th>Structural Style of Mineralisation</th>
<th>Host Rocks</th>
<th>Ore-Fluid Characteristics</th>
<th>Inferred Ore-Depositional Mechanisms</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunrise Dam</td>
<td>250</td>
<td>-8.2 to +4.0 (n=21)</td>
<td>12.2</td>
<td>+1.1 (±3.5)</td>
<td>variably dipping brittle-ductile shear zones (Western Lodes ~70° and Sunrise Shear Zone ~30°)</td>
<td>felsic to intermediate volcaniclastic and sedimentary rocks, with thin magnetite-rich shale units, and rhyodacite porphyry dikes</td>
<td>H(_2)O-C(_2)O±CH(_4) &lt;2 to 21 wt% NaCl equivalent 110-140 MPa 280-320°C</td>
<td>fluid-wallrock interaction and minor phase separation</td>
<td>Brown and Tornatora (2001) Brown (2002) Brown et al. (2002a,b)</td>
</tr>
<tr>
<td>North Royal</td>
<td>55</td>
<td>0.3 to +10.4 (n=9)</td>
<td>10.1</td>
<td>+4.1 (±3.0)</td>
<td>laminated quartz veins in steep to subvertical, brittle-ductile shear zones</td>
<td>tholeiitic basalt and gabbro dikes</td>
<td>CO(_2)-rich low-salinity &lt;300 MPa 425-475°C</td>
<td>fluid-wallrock interaction and phase separation</td>
<td>McCuaig et al. (1993) McCuaig (1996)</td>
</tr>
<tr>
<td>Golden Kilometre</td>
<td>17</td>
<td>-4.3 to +3.4 (n=10)</td>
<td>7.7</td>
<td>+3.2 (±3.0)</td>
<td>brittle, laminated quartz-carbonate veins and breccias</td>
<td>Fe- and Ti-rich quartz gabbro</td>
<td>H(_2)O-C(_2)O(_4)CH(_4) 3.7 wt% NaCl equivalent 50-190 MPa 275-375°C</td>
<td>fluid-wallrock interaction and phase separation</td>
<td>Witt (1992b) Gabre-Mariam (1994)</td>
</tr>
<tr>
<td>Great Eastern</td>
<td>15</td>
<td>-0.6 to +2.6 (n=14)</td>
<td>3.2</td>
<td>+0.9 (±0.9)</td>
<td>steep, brittle-ductile shear zones, brittle vein arrays and breccias</td>
<td>tonalite, diorite and granodiorite</td>
<td>H(_2)O-C(_2)O(_4)H(_2) 3.5 to 7.9 wt% NaCl equivalent 50-200 MPa &gt;350°C</td>
<td>fluid-wallrock interaction and mixing with surface water</td>
<td>Cassidy (1992) Młucki (1997)</td>
</tr>
<tr>
<td>Lady Bountiful</td>
<td>11</td>
<td>-1.1 to +9.8 (n=14)</td>
<td>10.6</td>
<td>+3.2 (±2.3)</td>
<td>laminated quartz veins, brittle quartz-vein arrays and breccias</td>
<td>granodiorite, gabbro and quartz gabbro</td>
<td>H(_2)O-C(_2)O(_4)CH(_4) 7 to 10 wt% NaCl equivalent 50-200 MPa 200-350°C</td>
<td>phase separation</td>
<td>Cassidy (1992) Cassidy and Bennett (1993)</td>
</tr>
<tr>
<td>New Celebration</td>
<td>100</td>
<td>-8.6 to +5.5 (n=8)</td>
<td>14.1</td>
<td>-3.0 (±5.2)</td>
<td>steep to sub-vertical brittle-ductile shear zones</td>
<td>mafic schist, tab chlortite schist and felsic porphyry dikes</td>
<td>H(_2)O-C(_2)O(_4)CH(_4) 6 to 23 wt% NaCl equivalent 300-490 MPa 300-450°C</td>
<td>fluid-wallrock interaction</td>
<td>Williams (1994) Townsend et al. (2000) Hodge et al. (2005)</td>
</tr>
</tbody>
</table>
Table 5. $\delta^{34}$S values from Victory-Defiance ore-related pyrites, from this study and Xu (1999). Samples listed in lithostratigraphic order of host rocks (see Fig. 7). Data for weight percent pyrite and Au ppm of pyrite separates are from Ho et al. (1994). Sample numbers are from respective studies. Host structures are shown in Figure 7.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Host Rock</th>
<th>$\delta^{34}$S$_{pyr}$ ‰</th>
<th>Host Structure</th>
<th>Pyrite (wt%)</th>
<th>Au (ppm)</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>104360BA</td>
<td>Flames Porphyry</td>
<td>-3.9</td>
<td>Repulse Fault</td>
<td>6.5</td>
<td>1</td>
<td>Ho et al. (1994); this study</td>
</tr>
<tr>
<td>104358AcI</td>
<td>Flames Porphyry</td>
<td>-3.7</td>
<td>Repulse Fault</td>
<td>1.8</td>
<td>16</td>
<td>Ho et al. (1994); this study</td>
</tr>
<tr>
<td>104361A</td>
<td>Flames Porphyry</td>
<td>-3.9</td>
<td>Repulse Fault</td>
<td>1.0</td>
<td>45</td>
<td>Ho et al. (1994); this study</td>
</tr>
<tr>
<td>VO15</td>
<td>Flames Porphyry</td>
<td>-4.7</td>
<td>Repulse Fault</td>
<td>6.0</td>
<td>16</td>
<td>Ho et al. (1994); this study</td>
</tr>
<tr>
<td>104350BB</td>
<td>Flames Porphyry</td>
<td>-2.2</td>
<td>Victory Fault</td>
<td>16.4</td>
<td>85</td>
<td>Ho et al. (1994); this study</td>
</tr>
<tr>
<td>104350AE</td>
<td>Flames Porphyry</td>
<td>-2.0</td>
<td>Victory Fault</td>
<td>49.8</td>
<td>161</td>
<td>Ho et al. (1994); this study</td>
</tr>
<tr>
<td>CD2193, 274.6m</td>
<td>Paringa Basalt</td>
<td>-2.0</td>
<td>32 Shear Zone</td>
<td></td>
<td></td>
<td>Ho et al. (1994); this study</td>
</tr>
<tr>
<td>104364CAl</td>
<td>Paringa Basalt</td>
<td>-3.6</td>
<td>32 Shear Zone</td>
<td>7.5</td>
<td>9</td>
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