Further evidence for \( \sim 8 \) kbar amphibolite facies metamorphism in the Marymia Inlier, Western Australia

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Pressure estimates for amphibolite-facies metamorphism of Plutonic Gold Mine (Plutonic), Marymia Inlier, Western Australia, were recently revised significantly upwards from \( \sim 4 \pm 2 \) kbar/550–600°C to \( \geq 8 \) kbar/\( \sim 600^\circ C \), based on the calculated stability fields for mineral assemblages in garnet-free mafic rocks. These conditions are anomalous in the context of the Yilgarn Craton. Here, we present new mineral equilibria calculations for rare garnet-bearing rock types from Plutonic that confirm those higher pressure estimates, and provide confidence that the determinations of metamorphic conditions based only on results from metamorphosed mafic rocks are robust and reliable. Taken together, the new estimates (7.3–8.2 kbar/580–590°C) from the garnet-bearing rocks, and the existing results from the mafic rocks, provide evidence that, most probably during the late Archean, rocks now exposed along the northern margin of the Yilgarn Craton underwent substantial increases in pressure, which was likely followed by rapid exhumation.

KEY WORDS: mineral equilibria, Plutonic Gold Mine, Theriak/Domino, thermobarometry, THERMOCALC.

INTRODUCTION

The Marymia Inlier is an Archean basement high located between the Pilbara and Yilgarn cratons in Western Australia, and surrounded by Proterozoic basins (Figure 1). Plutonic Gold Mine (Plutonic) is located in the Plutonic Well Greenstone Belt (PWGB; Figure 1), a northeast–southwest-trending, \( \sim 50 \) km-long and \( \sim 10 \) km-wide granite–greenstone terrane within the Marymia Inlier. The early history of the belt is comparable with that of other greenstone sequences in the Yilgarn Craton. Later features, including uplifting to form the basement high, are attributed to suturing events during the Paleoproterozoic Capricorn Orogeny (ca 1830–1770 Ma) that brought together the Pilbara and Yilgarn cratons to form the West Australian Craton (e.g. Tyler & Thorne 1990; Bagas 1999; Vielreicher et al. 2002; Cawood & Tyler 2004; Pirajno et al. 2004).

Peak metamorphism at Plutonic is dated between 2660 and 2630 Ma (Vielreicher & McNaughton 2002; Vickery 2004). Metamorphic pressure and temperature (P–T) conditions at this time in the wider Yilgarn Craton are generally interpreted to lie along anticlockwise P–T paths with peak pressures of \( \sim 4 \) kbar (Goscombe et al. 2009), based on data from rocks located \( \sim 1000 \) km to the south of the Marymia Inlier. Gazley et al. (2011a) presented P–T results from garnet-free mafic rocks at Plutonic that indicated that the rocks in this part of the Marymia Inlier were affected by considerably higher pressures. Here we present P–T estimates from two rare garnet-bearing rocks from Plutonic that support and even more tightly constrain the estimates obtained from the garnet-free mafic rocks, and in combination suggest that the northern margin of the Yilgarn Craton was affected by a relatively high-pressure metamorphic episode, most probably during the late Archean.

GEOLOGICAL SETTING

Comprehensive reviews of the geological setting of the local Plutonic area and the deposit geology have recently been presented in Gazley et al. (2011a,b, 2012, 2014a,b) and Duclaux et al. (2011, 2012, 2013) and are briefly summarised. Known economic concentrations of Au at Plutonic occur mainly within the Mine Mafic Package that consists predominantly of garnet-free metabasaltic rocks, which are typically of high Fe- to high Mg-tholeiite (Upper Mine Mafic Package) and calc-alkaline composition (Lower Mine Mafic Package) (e.g. Morgan 2004; Gazley 2011). Intercalated metasediments are volumetrically minor and typically consist of metamorphosed graphitic shales, shales and cherts; garnet-bearing assemblages are rare. The entire sequence was deposited prior to ca 2680 Ma based on U–Pb age of zircons from cross-cutting felsic intrusions (Vickery 2004). The sequence was metamorphosed to amphibolite-facies conditions (\( \sim 600^\circ C \); Vielreicher et al. 2002; Vickery 2004;
Gazley et al. (2011a) between 2660 and 2630 Ma (Vielreicher & McNaughton 2002; Vickery 2004). A late-stage, greenschist-facies hydrothermal event at Plutonic is constrained by a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1725 $\pm$ 26 Ma from titanite in a chlorite–carbonate vein (Gazley 2011). This age is the same as an age for a metasomatic event dated at 1719 $\pm$ 14 Ma by U–Pb age of zircon overgrowths in a sample from the Marymia Deposit in the north of the PWGB (Vielreicher & McNaughton 2002). Available zircon data from Plutonic do not record a hydrothermal event at this age (Vickery 2004). The timing of Au mineralisation at Plutonic is controversial; recent work has suggested that the main Au mineralising event may be Proterozoic in age (with events ca 2200 Ma, ca 1830 Ma
and ca 1720 Ma) and not associated with amphibolite-facies conditions (e.g. Gazley 2011; Duclaux et al. 2012, 2013).

Until recently, peak metamorphism was based on interpreted qualitative mineral assemblage associations \( P_{\text{max}} < 3 \text{kbar}; \text{Vielreicher et al. 2002} \) and results of conventional geothermobarometry \( P_{\text{max}} \sim 4 \pm 2 \text{kbar}; \text{Vickery 2004} \) to have taken place at relatively low pressures at approximately 550°C (Vielreicher et al. 2002). Metamorphism was considered to have involved little overall change in crustal thickness (Bagas 1999).

Although garnet-bearing assemblages have traditionally been preferred for pressure–temperature studies, recent advances in activity–composition models for amphiboles (e.g. Diener et al. 2007; Bhadra & Bhattacharyya 2007; Diener & Powell 2012) have provided increased scope for interpreting \( P–T \) records using garnet-free mafic rocks such as those that make up nearly all of the Mine Mafic Package. This paper presents an examination of the volumetrically insignificant garnet-bearing assemblages that was undertaken to assess whether it is possible to more precisely constrain the peak pressure conditions.

**ANALYTICAL METHODS**

Electron probe microanalyses (EPMA) were obtained using wavelength-dispersive methods at Victoria University of Wellington, New Zealand, using a JEOL JXA-733. The accelerating voltage was 15 kV, and the sample current was 12 nA. Spot sizes of 1–20 \( \mu \text{m} \) were used depending on the volatile and/or alkali content of the mineral being analysed. Photographs and back-scattered electron (BSE) images were used to locate and record the sites analysed during EPMA. The BSE images presented in this paper were obtained using a Phillips XL40 scanning electron microscope at the Australian Resources Research Centre, Perth, Australia.

Major-element analyses of whole-rock samples of MG027 and MG327 were carried out by X-ray fluorescence spectrometry (XRF) at SpectraChem Analytical Ltd, Wellington, New Zealand. Determinations of Fe\(^{2+}\) were conducted by titration at Albert-Ludwigs-Universität Freiburg, Germany, following the techniques outlined in Heinrichs & Herrmann (1990). Further details of both whole-rock and titration analyses are available in Gazley et al. (2011a).

Pressure–temperature pseudosequences for the two garnetiferous rock samples were calculated using Theriaik/Domino (de Capitani & Brown 1987; de Capitani & Petrakakis 2010) with the internally consistent thermodynamic dataset 5.5 of Holland & Powell (1998, updated 22 November 2003). Mineral stability and the topology of the pseudosequences were confirmed using THERMOCALC v. 3.37 (Powell & Holland 1988). Sample MG027 was calculated in the nine-component system MnNCFMASHT (MnO, Na\(_2\)O, CaO, FeO, MgO, Al\(_2\)O\(_3\), SiO\(_2\), H\(_2\)O, TiO\(_2\)) while MG327 was calculated in the 11-component system MnNCFMASHTO (MnO, Na\(_2\)O, CaO, K\(_2\)O, FeO, MgO, Al\(_2\)O\(_3\), SiO\(_2\), H\(_2\)O, TiO\(_2\), O). In both samples, CaO concentrations were modified to account for removal of Fe\(_2\)O\(_3\) (as apatite), and FeO was decreased to correspond for the amount of S that would otherwise have been in pyrrhotite. CaO is not corrected for the negligible amounts of calcite present in these rocks. In MG027, K\(_2\)O was ignored as it is predominantly present in hornblende in the rock, and this cannot be accommodated in the activity–composition model. The modelled composition for MG027 contains appreciable MnO in the bulk composition and insignificant ferric Fe in normalised amphibole chemistry as determined by EPMA. Accordingly, an ideal mixing model that includes pyrophane is used for ilmenite. This mixing model came standard with the Theriaik/Domino package as downloaded on 09/12/2013. Sample MG327 contains approximately 10% of its Fe content as ferric Fe (determined by titration), so for this sample the ilmenite–hematite activity-composition model of White et al. (2007) was used. The garnet-mixing model is from Holland & Powell (1998) and the amphibole-mixing model from Diener et al. (2007). A complete list of activity–composition models is available in the accompanying supplementary material.

**PETROGRAPHY AND MINERAL CHEMISTRY**

The two samples selected provide a rare opportunity to compare interpretations gained from pseudosection studies of garnet-bearing and garnet-free rocks from Plutonic. It is unlikely that any of the samples were affected by mineralising fluids, as Au mineralisation at Plutonic is associated with very narrow alteration haloes (e.g. Gazley 2011; Gazley et al. 2011b), and both samples were collected from sites distal to Au mineralisation. MG027 is an amphibole-rich garnet-bearing rock that is broadly mafic in composition. MG327 is a thin sedimentary layer that is intercalated with the mafic rocks of the Mine Mafic Package. The samples were collected from the main underground mine at Plutonic: MG027 from diamond drill hole UDD8252 at 7.1 m; and MG327 from diamond drill hole UDD1886 from 178.2 to 179.1 m. Representative BSE images for these two samples are shown in Figure 2 with bulk composition data presented in Table 1.

Sample MG027 is a coarse-grained garnet–hornblende rock that lacks plagioclase and contains late-stage chlorite replacing the garnet. Garnet crystals can be >1 cm across and the mole fraction of almandine \( X_{\text{alm}} \) is uniformly ~0.62 with \( X_{\text{spss}} \) [Mn / (Fe\(_T\) + Mg + Ca + Mn)] ranging from 0.16 to 0.19, and \( X_{\text{exs}} \) [Ca / (Fe\(_T\) + Mg + Ca + Mn)] ranging from 0.05–0.06. Quartz is present in the matrix of the rock, as is epidote, which has radiactive haloes in surrounding amphibole. Pyrrhotite is the dominant opaque phase in the matrix, with lesser ilmenite. The garnet contains inclusions of epidote, ilmenite and a tschermakitic hornblende, which is interpreted to be the stable amphibole throughout the highest-grade parts of the metamorphic history. Large amphibole crystals in the rock are sharply zoned with tschermakitic hornblende rims and subcalcic monoclino amphibole (cummingtonite) cores (Figure 2a). Ilmenite contains 1–2 wt% MnO.

Sample MG327 is a metasediment that contains small, subhedral garnet porphyroblasts (typically <3 mm) in a fine-grained matrix (typically <100 \( \mu \text{m} \)) of quartz, plagioclase, biotite, epidote, calcite,
Pressure–temperature pseudosections for MG027 and MG327 are presented in Figures 3 and 4, respectively. The input bulk compositions are based on XRF data and are presented in Table 1 along with bulk composition data for metabasaltic samples MG053 and MG313 from Gazley et al. (2011a) for comparison. The growth of garnet and absence of plagioclase in MG027 can be attributed to the higher MnO, and lower Na₂O and CaO contents compared with MG053 and MG313, despite overall similar mafic bulk compositions (Table 1). The Al₂O₃ concentration of MG327 (Table 1) is consistent with that of mafic sediment.

The peak metamorphic mineral assemblage in sample MG027 consists of garnet–hornblende–ilmenite (Figure 2a; Figure 3, shaded field) without plagioclase, hedenbergite, cummingtonite, chlorite or tremolite. This field lies between approximately 500 and 640°C and between approximately 7.5 and 12.0 kbar. The calculated abundance of garnet (~31 vol%) is greater than the amount present in the rock (~20 vol%) because the garnet has been partially replaced along grain margins and fractures by chlorite. The presence of cummingtonite in the cores of many of the hornblende grains in MG027 (Figure 2a) attests to the early prograde growth of amphibole at ~3 kbar and 530°C. Under these conditions calculated abundances of cummingtonite and hornblende are approximately equal. Overgrowth of cummingtonite cores by hornblende during peak metamorphism led to the zoned amphiboles that are preserved in MG027.

The peak metamorphic assemblage in sample MG327 that consists of biotite–epidote–garnet–plagioclase–Kfeldspar–ilmenite–quartz, best corresponds to the field shaded in Figure 4. A calculated abundance of K-feldspar at ~4 vol% in this field is slightly higher than is present in the rock and could result from minor K₂O mobility during metamorphism and the sensitivity of calculated K-feldspar abundances to K₂O. Decreasing the K₂O content from 1.66 to 1.41 wt% results in a calculated K-feldspar abundance of ~1.2 vol% that more closely matches the concentration in the rock but does not alter the location of the field boundaries significantly. Taken by itself, the narrow peak mineral stability field in MG327, which has a positive slope in P–T space, extends from approximately 430 to 650°C and from approximately 2.5 to 9.5 kbar but does not provide very useful P–T constraints. However, using the previously determined peak temperature of 600°C from hornblende–plagioclase thermometry (using the calibration of Holland & Blundy 1994) on this field (Gazley et al. 2011a), pressure estimates of 7.4–8.3 kbar are obtained. The fine plagioclase grain size and the wide variation in plagioclase composition rule out using traditional geothermobarometry methods to obtain estimates to compare with the P–T estimates derived from pseudosections. Peak metamorphic estimates can be further constrained by considering the overlapping peak assemblage of multiple P–T pseudosections from rocks that experienced the same metamorphic conditions. Gazley et al. (2011a) used this approach to constrain the peak metamorphic conditions at Plutonic to ~600 ± 50°C and ~8 ± 2 kbar. The two new P–T pseudosections presented here for garnet-bearing rocks...
Table 1  Bulk composition data for input into Theriak/Domino and THERMOCALC. LOI, loss on ignition. Fe\(^{3+}\) determined by titration for MG327 and MG313 (method described in Gazley et al. 2011a).

|       | MG027 |       | MG327 |       | MG053 |       | MG313 |
|-------|-------|-------|-------|-------|-------|-------|-------|
|       | wt%   | mol (%) ox. | mol element | wt%   | mol (%) ox. | mol element | wt%   | wt%   |
| SiO\(_2\) | 50.52 | 55.29 | 55.29 | 63.75 | 71.23 | 71.25 | 53.79 | 50.14 |
| Al\(_2\)O\(_3\) | 9.91 | 6.38 | 12.76 | 16.01 | 10.53 | 21.05 | 14.97 | 13.79 |
| CaO    | 7.94 | 9.29 | 9.29  | 6.54  | 7.80  | 7.80  | 9.48  | 9.98  |
| MgO    | 5.82 | 9.48 | 9.48  | 0.72  | 1.20  | 1.20  | 5.25  | 9.75  |
| MnO    | 0.80 | 0.74 | 0.74  | 0.16  | 0.15  | 0.15  | 0.16  | 0.19  |
| Fe\(_3\)O\(_4\)\(^b\) | 22.40 | –   | –     | 0.78  | –     | –     | 10.80 | 3.36  |
| FeO    | – | 17.85 | 17.85 | 3.72 | 4.00 | 4.00 | 2.74 | 2.54 |
| Na\(_2\)O | 0.73 | 0.77 | 0.77  | 2.77  | 3.00  | 5.99  | 2.74  | 2.54  |
| K\(_2\)O | 0.26 | –   | –     | 1.66  | 1.18  | 2.37  | 0.26  | 0.38  |
| TiO\(_2\) | 0.25 | 0.21 | 0.21  | 0.67  | 0.56  | 0.56  | 0.89  | 0.63  |
| SO\(_3\) | 0.72 | –   | –     | 0.16  | –     | –     | 0.01  | 0.06  |
| P\(_2\)O\(_5\) | 0.06 | –   | –     | 0.08  | –     | –     | –     | –     |
| O      | – | – | 168.28 | 0.33 | 192.86 | – | – | – |
| LOI   | 0.05 | –   | –     | 2.19  | –     | –     | 1.41  | 1.28  |
| Total | 99.46 | 99.21 | 99.76 | 99.03 | 99.76 | 99.03 | 99.03 | 99.03 |

\(^a\) Ca corrected for apatite based on P\(_2\)O\(_5\) concentration and Fe corrected for pyrrhotite (Fe\(_7\)S\(_8\)) based on SO\(_3\) concentration.

\(^b\) Fe analysed as Fe\(_3\)O\(_4\) (except as stated) and converted to FeO and O for input to Theriak/Domino.

Figure 3  A \(P\)–\(T\) pseudosection for garnetiferous mafic rock MG027. Only a selection of relevant assemblages are labelled. Mineral abbreviations follow the recommendations of Kretz (1983); liq, liquid. Shaded field: inferred peak metamorphic mineral assemblage.

Marymia Inlier P–T conditions 923
constrain the peak $P-T$ conditions to be $580-590^\circ C$ at $7.3-8.2$ kbar (Figure 5) with errors derived from $P-T$ pseudosections of $\pm 50^\circ C$ and $\pm 1$ kbar, in line with the recommendations of Powell & Holland (2008). The derived peak metamorphic conditions are also consistent with mineral compositions for garnet calculated in Theriak/Domino for these samples; MG027 calculated $X_{\text{aln}} = -0.64$, cf. measured $X_{\text{aln}} = -0.62$; MG327 calculated $X_{\text{aln}} = 0.42$, cf. measured $X_{\text{aln}} = 0.52-0.67$. A better match between the calculated $X_{\text{aln}}$ content in garnet in MG327 and the measured content can be achieved by decreasing the $K_2O$ content by a small amount, for example removing 0.25 wt% $K_2O$ results in a $X_{\text{aln}}$ content in garnet of $\sim 0.52$, further highlighting the sensitivity of this bulk composition to variations in $K_2O$ concentration.

These new constraints for peak metamorphic conditions are entirely consistent with those determined by Gazley et al. (2011a). Importantly our new $P-T$ pseudosections remove the need to rely on a conventional (hornblende–plagioclase) geothermometer to constrain peak pressure conditions at $\sim 8$ kbar, in a peak assemblage field that Gazley et al. (2011a) defined as extending from 5 to 9 kbar and from 500 to 630°C.

**DISCUSSION AND CONCLUSION**

The new results presented here confirm the interpretation of Gazley et al. (2011a) that amphibolite facies...
conditions (~600°C/~8 kbar, double the previously accepted pressure estimates) prevailed at the southern end of the Marymia Inlier, most probably during the late Archean. More significantly, we have increased the lower pressure constraints using the pseudosection data errors on pressure determinations of ~1 kbar (Powell & Holland 2008). Our new P–T determinations are consistent with the interpretation that the Marymia Inlier records an event that occurred along the northern margin of the Yilgarn Craton during the late Archean. However, the nature of this event remains uncertain; in large part because it remains unclear whether the Marymia Inlier is connected to the Yilgarn Craton at depth (Bagas 1999). Without such fundamental data, tectonic interpretations involving the Marymia Inlier can only be conjectural. Gazley et al. (2011a) argued for a steep pressure increase from ~3 to 4 kbar at ~500°C to ~6 kbar at ~600°C. Based on our thermodynamic modeling, the peak conditions were ~600°C and ~8 kbar. Early prograde conditions are constrained at ~3–4 kbar and ~500°C, as early cummingtonite is overgrown by hornblende in sample MG027 (Figure 3) and equates to a geothermal gradient of 35 and 45°C per km, consistent with the geothermal gradient derived for metamorphism across a large part of the Yilgarn at this time (Czarnota et al. 2010). Peak metamorphic conditions at Plutonic were at a significantly higher pressure but without a corresponding increase in temperature. This gives rise to an apparent geothermal gradient of only 20°C per km and therefore does not represent an equilibrium geotherm that would have resulted in peak temperatures in excess of 850°C. The lack of evidence that these rocks reached such high temperatures indicates that the rocks may have been exhumed rapidly following the high-pressure metamorphism.

ACKNOWLEDGEMENTS

This paper builds on research conducted during MFG’s PhD, which was funded by Barrick Australia Pacific Ltd. We are grateful for the in-depth comments of Alistair White and Steve Hollis on an early draft of this paper. The authors acknowledge the constructive reviews of John Ridley and an anonymous reviewer.

SUPPLEMENTAL DATA

Activity composition models for MG027 and MG327

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Received 8 January 2014; accepted 2 August 2014