

# Tracing the sources of CO<sub>2</sub> in metamorphic belts with Ne and Ar: A fluid inclusion case study, northeast Australia.

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**Abstract:** The Proterozoic Mary Kathleen Fold Belt of the Mt Isa Inlier preserves a metasomatic history that spans 100's of Myr. Late-Isan (~1550 Ma) Na-Ca alteration extends for 100's of km along the Pilgrim Fault and is associated with CO<sub>2</sub>-H<sub>2</sub>O-NaCl fluids of unusually high salinity. Previous stable isotope and noble gas studies have drawn conflicting conclusions as to the origin of metamorphic volatiles. In this study we use combined Ne and Ar isotopic analysis, targeted on two distinct fluid inclusion assemblages to reconcile the existing data.

The CO<sub>2</sub>-dominated and H<sub>2</sub>O-dominated fluid inclusion assemblages selected define two discrete mixing trends on a <sup>40</sup>Ar/<sup>36</sup>Ar versus <sup>20</sup>Ne/<sup>22</sup>Ne diagram. H<sub>2</sub>O-dominated fluid inclusion assemblages have <sup>40</sup>Ar/<sup>36</sup>Ar of between 300 and 2700, and <sup>20</sup>Ne/<sup>22</sup>Ne between 9.8 and 8.4. This spread in data is consistent with mixing between noble gases derived from the atmosphere and produced in the crust, typical of crustal rocks or fluids. In contrast, CO<sub>2</sub>-dominated fluid inclusion assemblages have <sup>40</sup>Ar/<sup>36</sup>Ar of between 500 and 14,100 and <sup>20</sup>Ne/<sup>22</sup>Ne between 8.4 and 10.1. The maximum <sup>20</sup>Ne/<sup>22</sup>Ne value is only just above the atmospheric value; however, the spread in data is consistent with mixing of CO<sub>2</sub> derived from the mantle and CO<sub>2</sub> derived from the carbonate-bearing host-rocks.

The data are consistent with a regionally dominant source of H<sub>2</sub>O-fluids from sedimentary formation waters but suggest mantle-derived magmatism as an important source of CO<sub>2</sub>. It is concluded that mantle melts are the likely heat source for high temperature, low pressure metamorphism in the Mt Isa Inlier.

## Introduction

Unravelling the origin of metamorphic volatiles is essential to understanding volatile transport through the Earth's crust and the nature of crustal deformation. Metamorphic volatiles are typically dominated by CO<sub>2</sub>-H<sub>2</sub>O-NaCl fluids that can be buffered either internally or externally. Possible sources of metamorphic CO<sub>2</sub> include carbonate-bearing meta-sedimentary rocks in the mid-upper crust, oxidation of graphite or volatilisation of carbonate in the basement, and the underlying mantle. Identifying input of mantle CO<sub>2</sub> is especially important because the heat from mantle melts could be a trigger for metamorphism.

The Mary Kathleen Fold Belt of the Mt Isa Inlier, northeast Australia, is one example of an amphibolite facies terrane in which CO<sub>2</sub>-rich fluids have a debated origin. Stable isotope data have been interpreted to favour a magmatic fluid origin: carbonate veins have  $\delta^{18}\text{O}$  similar to average crust and  $\delta^{13}\text{C}$  is between  $\sim 0$  and  $-7$  ‰ (Marshall et al., 2006; Oliver, 1995). However, recent argon and halogen data obtained for H<sub>2</sub>O-dominated fluid inclusion assemblages suggest a dominant role for sedimentary formation waters because the  $^{40}\text{Ar}/^{36}\text{Ar}$  is less than  $\sim 2700$  in most cases (Kendrick et al., 2008). The variability of the fluid inclusion assemblages, which are preferentially preserved in quartz on the edges of calcite veins, suggests multiple fluid origins are possible (Kendrick et al., 2008; Oliver, 1995).

In order to better understand the origin of these fluids, we have further investigated the noble gas isotope composition of quartz-hosted liquid-vapour and liquid carbon-dioxide fluid inclusions. Helium is not retained by quartz hosted fluid inclusions making it of limited value in this study. Instead we have evaluated combined Ne and Ar isotope analyses for understanding metamorphic fluid origins and identifying mantle components. Together, Ar and Ne are suitable for this purpose

because the  $^{40}\text{Ar}/^{36}\text{Ar}$  value varies between 296 in the atmosphere up to at least ~40,000 in the deep-crust or mantle and the  $^{20}\text{Ne}/^{22}\text{Ne}$  value varies from ~8 in the crust up to 12.5 in the mantle. These variations enable the distinction of crust versus mantle and atmospheric noble gases. Neon and Ar have the additional advantage over He, in that their transport is more closely coupled to that of the major volatiles. Therefore, the origin of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  can be more easily inferred from the combined Ne and Ar isotope systematics.

### **Geology and sample selection**

The amphibolite facies Mary Kathleen Fold Belt has a prolonged metamorphic/metasomatic history (Oliver, 1995; Oliver et al.). Metasomatism occurred sporadically from intrusion of the earliest Wonga Granites at ~1760 Ma, to the end of the Isan Orogeny at ~1500 Ma. Regional late-Isan Na-Ca alteration (albitisation) is focussed along the Pilgrim Fault and effects up to 20% of the Corella Formation host rocks (Fig 1). The scapolite-rich calc-silicate Corella Formation represents one possible source of  $\text{CO}_2$ , although O and C isotope data suggest they are not the only source (Marshall et al., 2006; Oliver et al., ; Oliver et al., 1993).

Carbonate veins associated with late-Isan alteration commonly form 'pods' with dimensions up to several hundred metres across. These 'pods' have been quarried previously and provide exceptional exposure. Titanite within carbonate veins and 'pods' have U-Pb ages of 1550-1530 Ma that overlap the 1550-1490 Ma Williams-Naraku Batholiths in the nearby Cloncurry District (Fig 1; (Page and Sun, 1998). The similarity of these ages suggests a possible relationship between regional alteration and intrusion of unexposed Batholiths hinting at a mantle heat source and possible involvement of mantle  $\text{CO}_2$  (Oliver et al., 2004).

Samples from the Tribulation and Knobby quarries (Fig 1) were selected because they contain ‘end-member’ populations of fluid inclusion. The three Tribulation Quarry samples are dominated by moderate salinity liquid-vapour fluid inclusions. Liquid-vapour-daughter fluid inclusions have a moderate abundance and CO<sub>2</sub> bearing fluid inclusions are rare (Kendrick et al., 2008). The two samples from the Knobby Quarry are dominated by up to 80 % liquid-CO<sub>2</sub> fluid inclusions. Aqueous fluid inclusions with variable salinity and mixed aqueous-carbonic fluid inclusions are also present (Fig 1; (Kendrick et al., 2008). Mixed aqueous-carbonic fluid inclusions in the Knobby samples contain daughter minerals indicating a high salinity. However, elsewhere in the Mary Kathleen Fold Belt, mixed aqueous-carbonic fluid inclusions have lower salinities (<20 wt %), indicating metamorphic CO<sub>2</sub> was intimately associated with low as well as high salinity fluids (see (Kendrick et al., 2008).

Based on previous noble gas analysis of irradiated samples, the samples selected contain 5-31 ppm K in the fluid inclusions and quartz matrix and 2-72 ppb U concentrated in the quartz matrix (Table 1; (Kendrick et al., 2008). CO<sub>2</sub> and H<sub>2</sub>O dominated fluid inclusions have similar <sup>36</sup>Ar concentrations of ~1-10 ppb (Kendrick et al., 2008).

### **Analytical methods and results**

Fluid inclusions are the main reservoir of noble gases in quartz (Kendrick et al., 2006b; Watson and Cherniak, 2003). However, because the quartz matrix contains K and U bearing mineral impurities, radiogenic <sup>40</sup>Ar\*<sup>1</sup> or nucleogenic <sup>21</sup>Ne\* plus <sup>22</sup>Ne\*, could have accumulated within the matrix after entrapment. To evaluate the

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<sup>1</sup> Asterix indicate a noble gas isotope with a non-atmospheric origin.

importance of the fluid inclusion and matrix reservoirs, quartz separates identical to those studied by microthermometry (Fig 1), were analysed by sequential *in vacuo* crushing in modified nupro valves: *in vacuo* crushing releases noble gases from the fluid inclusions most easily.

Extracted noble gases were purified over a period of 10 minutes using SAES St 707 and St 101 getters and Ar, Kr and Xe were then separated from Ne (and He) by sublimation onto a charcoal finger at liquid nitrogen temperatures over a second 10 minute period. Neon was expanded into the MAP 215 noble gas mass spectrometer at the University of Melbourne and isotopically analysed in 11 cycles of measurement over a period of 50 minutes. Subsequently, Ar, Kr and Xe were analysed simultaneously in 9 cycles of measurement over a period of 50 minutes. The instrument was calibrated with aliquots of air and corrections were made for machine blank and mass discrimination.

Despite the similar concentration of  $^{36}\text{Ar}$  in  $\text{CO}_2$  and  $\text{H}_2\text{O}$ -dominated fluid inclusions indicated previously (Kendrick et al., 2008), significantly more Ne was extracted from samples dominated by  $\text{CO}_2$  fluid inclusions than samples dominated by  $\text{H}_2\text{O}$  fluid inclusions (Table 1). This could be explained because the  $^{20}\text{Ne}/^{36}\text{Ar}$  is higher in  $\text{CO}_2$  fluid inclusions than in  $\text{H}_2\text{O}$  fluid inclusions (Fig 2) or because of different relative abundances of fluid inclusions in the quartz matrix of Knobby and Tribulation samples. As a result, Ne isotope measurements for Knobby samples dominated by  $\text{CO}_2$  fluid inclusions have a higher precision than for Tribulation samples dominated by  $\text{H}_2\text{O}$  fluid inclusions.

The majority of  $^{20}\text{Ne}/^{22}\text{Ne}$  analyses for samples dominated by both  $\text{H}_2\text{O}$  and  $\text{CO}_2$  fluid inclusions are lower than the atmospheric value of 9.8. The highest  $^{20}\text{Ne}/^{22}\text{Ne}$  value of  $10.07 \pm 0.16$  is only slightly above the atmospheric value (Fig 3).

The  $^{20}\text{Ne}/^{22}\text{Ne}$  value is not related to crush number (Table 1), suggesting that the variation results from decrepitation of different fluid inclusions at different stages of the experiment. In contrast, samples from Tribulation Quarry, which are dominated by  $\text{H}_2\text{O}$  fluid inclusions, yield some extremely elevated  $^{21}\text{Ne}/^{22}\text{Ne}$  values, with  $^{21}\text{Ne}/^{22}\text{Ne}$  increasing as a function of crushing step (Table 1). The systematic increase in  $^{21}\text{Ne}/^{22}\text{Ne}$  could indicate that some nucleogenic  $^{21}\text{Ne}^*$  was extracted from the quartz matrix and the exceptionally high  $^{21}\text{Ne}/^{22}\text{Ne}$  values are attributed to post-entrapment  $^{21}\text{Ne}^*$  ingrowth.

Post-entrapment  $^{21}\text{Ne}^*$  ingrowth is likely to have been more significant than  $^{22}\text{Ne}^*$  ingrowth because U is sited predominantly within the O-rich, F-poor quartz matrix (Kendrick et al., 2008). Furthermore, U and F are unlikely to be associated with each other in fluid inclusions because: aqueous fluid inclusions are Ca-rich implying they are F-poor because fluorite has a negligible solubility (Rimstidt, 1997); and,  $\text{CO}_2$  fluid inclusions could contain F but are unlikely to contain significant U. The  $^{21}\text{Ne}/^{22}\text{Ne}$  values are most reliable for the Knobby samples which have an elevated Ne concentration because they are dominated by  $\text{CO}_2$  fluid inclusions. The  $^{21}\text{Ne}/^{22}\text{Ne}$  values determined for Ne-poor Tribulation samples probably become less representative of the fluid inclusion composition as crushing progresses (Table 1; Fig 3). In contrast, the  $^{20}\text{Ne}/^{22}\text{Ne}$  values obtained by *in vacuo* crushing are interpreted to be close to the fluid inclusion initial value in every case.

The correction for post-entrapment *in situ* production of radiogenic  $^{40}\text{Ar}^*$  is less than 6% for the Knobby and Tribulation samples, and very little radiogenic  $^{40}\text{Ar}^*$  was released by *in vacuo* crushing (Kendrick et al., 2008). As a result the  $^{40}\text{Ar}/^{36}\text{Ar}$  values are also close to the fluid inclusions initial values (Table 1). The total range determined here is 600-2400 for  $\text{H}_2\text{O}$ -dominated fluid inclusions in the Tribulation

samples and 700-14,100 for CO<sub>2</sub>-dominated fluid inclusions in Knobby samples. The range determined for the CO<sub>2</sub> fluid inclusions is even greater than the 1500-7300 range reported previously (Kendrick et al., 2008).

## **Discussion**

The maximum <sup>40</sup>Ar/<sup>36</sup>Ar value determined for H<sub>2</sub>O-dominated fluid inclusions remains <2700 (Table 1) compatible with a dominant origin of these H<sub>2</sub>O-rich fluids from sedimentary formation waters or upper-crustal metamorphic fluids (Kendrick et al., 2008). In contrast, the maximum <sup>40</sup>Ar/<sup>36</sup>Ar values determined for CO<sub>2</sub>-dominated fluid inclusions is now 14,100 (Table 1), which is double that determined previously, and is higher than is easily explained by a CO<sub>2</sub> source exclusively within the Corella Formation (cf. (Kendrick et al., 2008).

The <sup>40</sup>Ar/<sup>36</sup>Ar value is plotted against the <sup>20</sup>Ne/<sup>22</sup>Ne value in Figure 3. H<sub>2</sub>O-dominated fluid inclusions have <sup>40</sup>Ar/<sup>36</sup>Ar and <sup>20</sup>Ne/<sup>22</sup>Ne values that define a trend between the atmosphere and a <sup>40</sup>Ar\*- plus <sup>22</sup>Ne\*-rich reservoir representative of sedimentary rocks. This trend is interpreted to characterise both sedimentary formation waters and sedimentary rocks which each contain a mixture of atmospheric and crustal (<sup>22</sup>Ne\* + <sup>40</sup>Ar\*) noble gases. CO<sub>2</sub> fluid inclusions lie on an unrelated trend in which <sup>20</sup>Ne/<sup>22</sup>Ne is positively correlated with <sup>40</sup>Ar/<sup>36</sup>Ar (Fig 4).

The mixing trend can be modelled using the general mixing equation of (Langmuir et al., 1978) and interpreted in two different ways: In model one, CO<sub>2</sub> was derived from both the Corella Formation and the mantle. In this model the 'best fit' mixing curve with an r-value of less than one indicates that the <sup>22</sup>Ne/<sup>36</sup>Ar value of CO<sub>2</sub> derived from the Corella Formation was higher than that of CO<sub>2</sub> derived from the mantle. If mantle CO<sub>2</sub> had a <sup>36</sup>Ar concentration of ten times less than the crustal CO<sub>2</sub>,

the maximum measured  $^{40}\text{Ar}/^{36}\text{Ar}$  value of 14,100 would indicate that 84% of the  $\text{CO}_2$  (in that analysis) had a mantle origin. The proportion of mantle  $\text{CO}_2$  would be progressively lower in analyses with lower  $^{40}\text{Ar}/^{36}\text{Ar}$  values (see Fig 4). In the second model,  $\text{CO}_2$  is derived exclusively from the mantle and acquires crustal noble gases through interaction with sedimentary formation waters. In this case the r-value of less than one implies that the sedimentary formation waters had a higher  $^{22}\text{Ne}/^{36}\text{Ar}$  value than the mantle  $\text{CO}_2$ , or that Ne partitioned into the  $\text{CO}_2$  preferentially relative to Ar.

The alternative models are difficult to distinguish on the basis of  $^{40}\text{Ar}/^{36}\text{Ar}$  and  $^{20}\text{Ne}/^{22}\text{Ne}$  alone (Fig 4). However, model one is supported by the stable isotope composition of carbonate veins which have  $\delta^{13}\text{C}$  values varying between  $\sim 0\text{‰}$ , which is similar to the Corella Formation, and  $-7\text{‰}$  which is representative of the mantle/magmatic end-member (Fig 9 of (Marshall et al., 2006)). In addition, model two is not favoured by the  $F^{129}\text{Xe}$  and  $F^{84}\text{Kr}$  values of both  $\text{CO}_2$  and  $\text{H}_2\text{O}$  dominated fluid inclusion assemblages that are intermediate between air and air-saturated water (Fig 2). The  $F^{129}\text{Xe}$  and  $F^{84}\text{Kr}$  values should be fractionated, and the noble gas concentration of the  $\text{CO}_2$  fluid inclusions much higher than the  $\text{H}_2\text{O}$  fluid inclusions, if the mixing trend resulted from interactions of mantle-derived  $\text{CO}_2$  and sedimentary formation waters.

## **Conclusions**

The noble gas data conclusively demonstrate  $\text{CO}_2$  and  $\text{H}_2\text{O}$  fluid inclusions in the Knobby and Tribulation Quarries had independent origins (Fig 4). Sedimentary formation waters or metamorphic fluids derived from upper-crustal rocks are indicated as a major source of  $\text{H}_2\text{O}$  and some  $\text{CO}_2$ . However, combined Ne and Ar isotopic analysis has been demonstrated as a useful means to identify mantle  $\text{CO}_2$

components and provides strong independent evidence for the involvement of mantle derived CO<sub>2</sub> in the Mary Kathleen Fold Belt. The presence of mantle derived CO<sub>2</sub> suggests the mantle, or mantle melts, were a major source of heat for metamorphism.

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**Table 1. Noble gas data for Knobby and Tribulation Quarry quartz samples**

Crush	$^{20}\text{Ne}/^{22}\text{Ne}$	$^{21}\text{Ne}/^{22}\text{Ne}$	$^{40}\text{Ar}/^{36}\text{Ar}$
<b><i>Knobby Quarry – CO<sub>2</sub> dominated fluid inclusions</i></b>			
02CC38 (XX mg), 2 ppb U, 24 ppm K			
1	9.25 ± 0.10	0.082 ± 0.002	9503 ± 152
2	9.79 ± 0.17	0.093 ± 0.002	
3	9.22 ± 0.60	0.097 ± 0.001	14,061 ± 395
4	9.23 ± 0.10	0.133 ± 0.003	9941 ± 137
5	10.07 ± 0.16	0.182 ± 0.005	14,104 ± 1198
02CC108 (XX mg), 20 ppb U, 31 ppm K			
1	9.04 ± 0.06	0.141 ± 0.002	745 ± 2
2	9.07 ± 0.07	0.147 ± 0.005	3980 ± 100
3	9.07 ± 0.10	0.167 ± 0.004	5479 ± 68
4	8.76 ± 0.19	0.182 ± 0.008	8205 ± 34
5	8.73 ± 0.18	0.173 ± 0.004	5759 ± 7
<b><i>Tribulation Quarry – H<sub>2</sub>O dominated fluid inclusions</i></b>			
02CC05 (XX mg), 72 ppb U, 5 ppm K			
1a	9.48 ± 0.48	0.040 ± 0.004	746 ± 2
2a	9.52 ± 0.28	0.063 ± 0.003	984 ± 9
3a	9.92 ± 0.50	0.215 ± 0.011	1030 ± 2
02CC85 (XX mg), 5 ppb U, 19 ppm K			
1b	9.49 ± 0.11	0.054 ± 0.002	933 ± 1
2b	9.65 ± 0.50	0.194 ± 0.007	1636 ± 13
3b	8.64 ± 0.53	0.320 ± 0.010	1697 ± 13
4b	7.42 ± 0.54	1.024 ± 0.063	1902 ± 19
5b	8.52 ± 0.53	1.189 ± 0.076	2439 ± 44
02CC82 (XX mg), 8 ppb U, 14 ppm K			
1c	8.81 ± 0.36	0.120 ± 0.005	1294 ± 191
2c	7.82 ± 0.41	0.636 ± 0.038	683 ± 1
<b><i>Reference values</i></b>			
Sed. Fm. W.	9.8-8.3	0.029-0.300	300-2000
Mantle	12.5		40,000

Fig 1 Kendrick et al., 2008

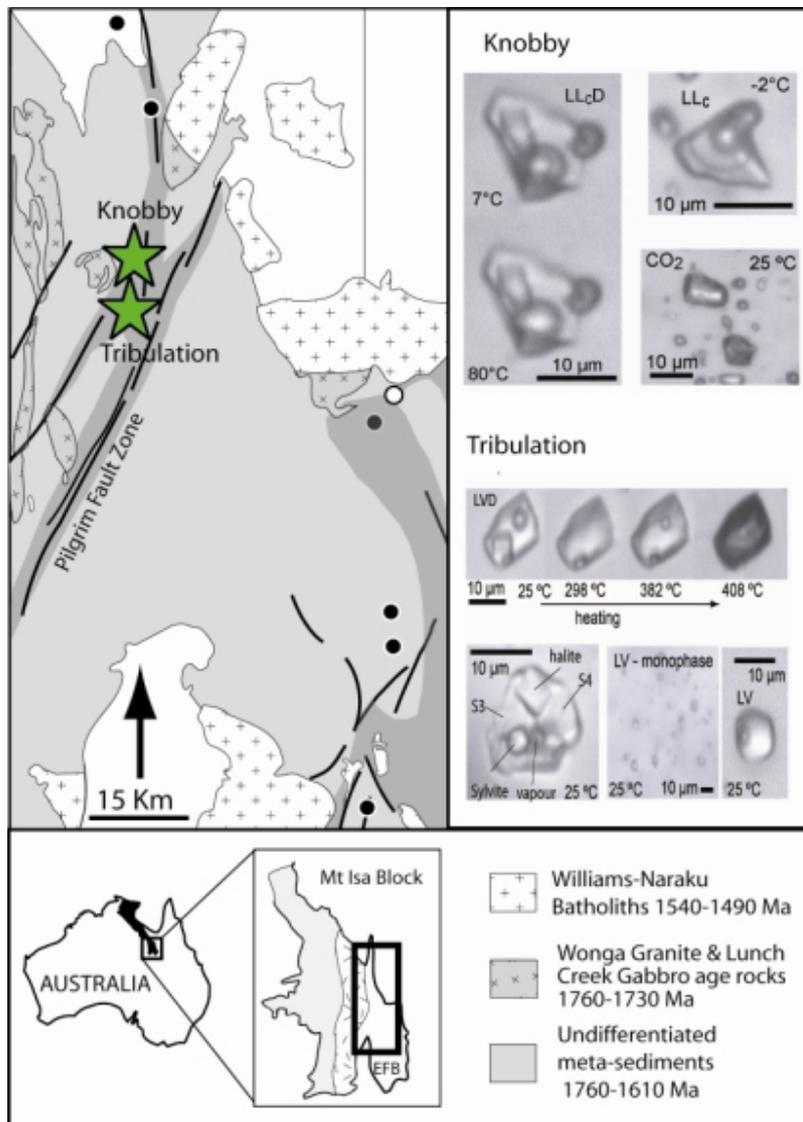
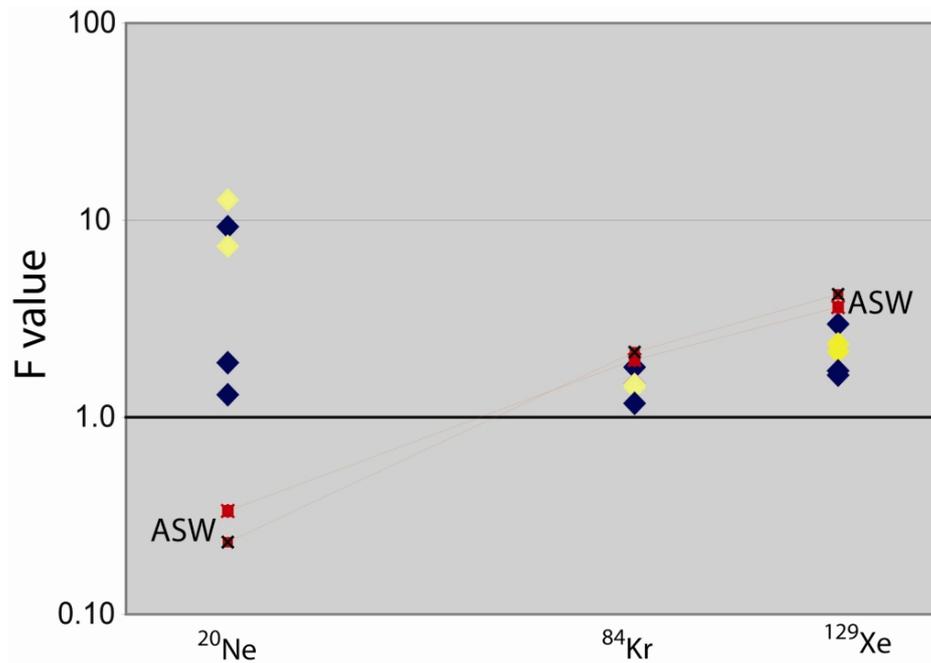


Fig 1. Locality map showing the location of the Tribulation and Knobby Quarries in the Mary Kathleen Fold Belt of the Mt Isa Inlier, and fluid inclusions typical of these localities: Knobby Quarry samples contain ~80% high-density liquid CO<sub>2</sub> fluid inclusions; Tribulation Quarry samples are dominated by moderately saline (10-30 wt %) H<sub>2</sub>O fluid inclusions (see (Kendrick et al., 2008).

**Fig 2 Kendrick et al., 2008**



*Fig 1. Fractionation values for  $^{20}\text{Ne}$ ,  $^{84}\text{Kr}$  and  $^{129}\text{Xe}$  relative to  $^{36}\text{Ar}$  in air for  $\text{H}_2\text{O}$  and  $\text{CO}_2$  dominated fluid inclusion assemblages in the Mary Kathleen Fold Belt.  $FNg = (Ng/^{36}\text{Ar})_{\text{sample}} / (Ng/^{36}\text{Ar})_{\text{air}}$ . Air has an F value of one. Relative to Ar, air-saturated water (ASW) is depleted in Ne and enriched in Kr and Xe.*

Fig 3 Kendrick et al., 2008

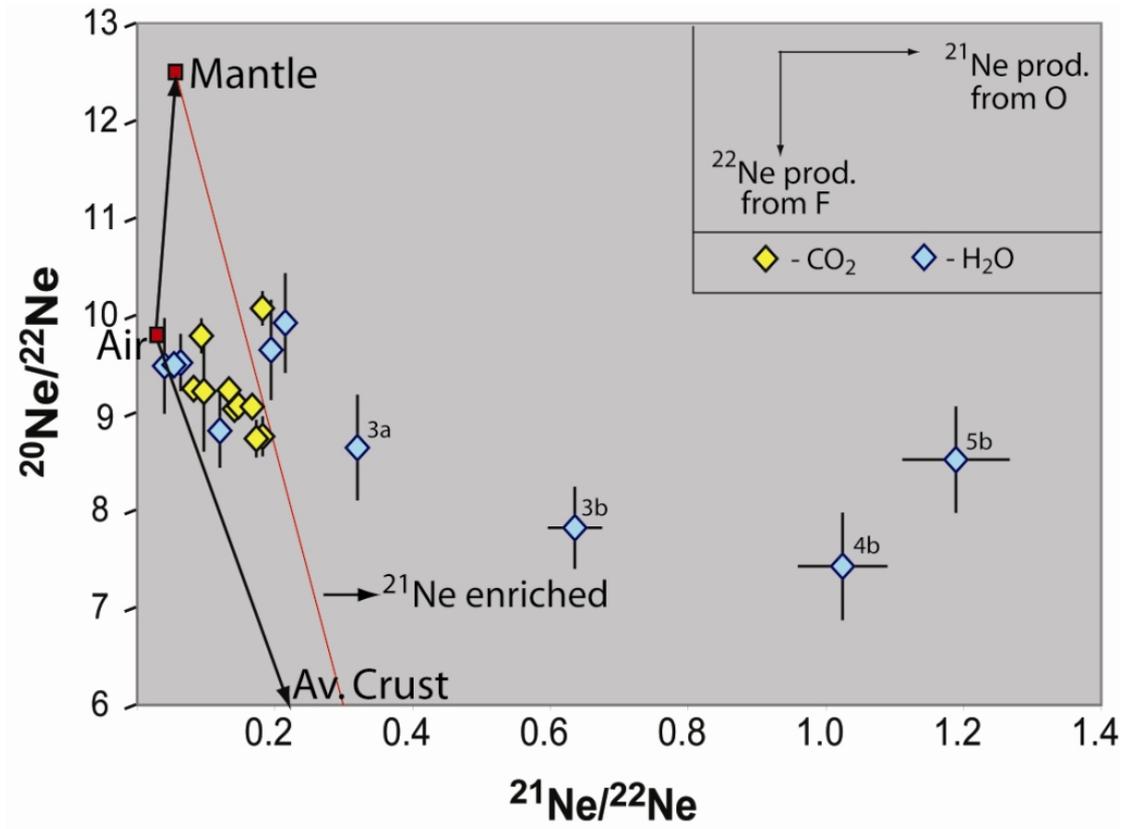


Fig 3. Ne three isotope plot for  $\text{H}_2\text{O}$  and  $\text{CO}_2$ -dominated fluid inclusion assemblages in the Mary Kathleen Fold Belt. The highest  $^{21}\text{Ne}/^{22}\text{Ne}$  values are obtained in the last crushes of the Ne-poor Tribulation Quarry samples (Table 1).

Fig 4 Kendrick et al., 2008

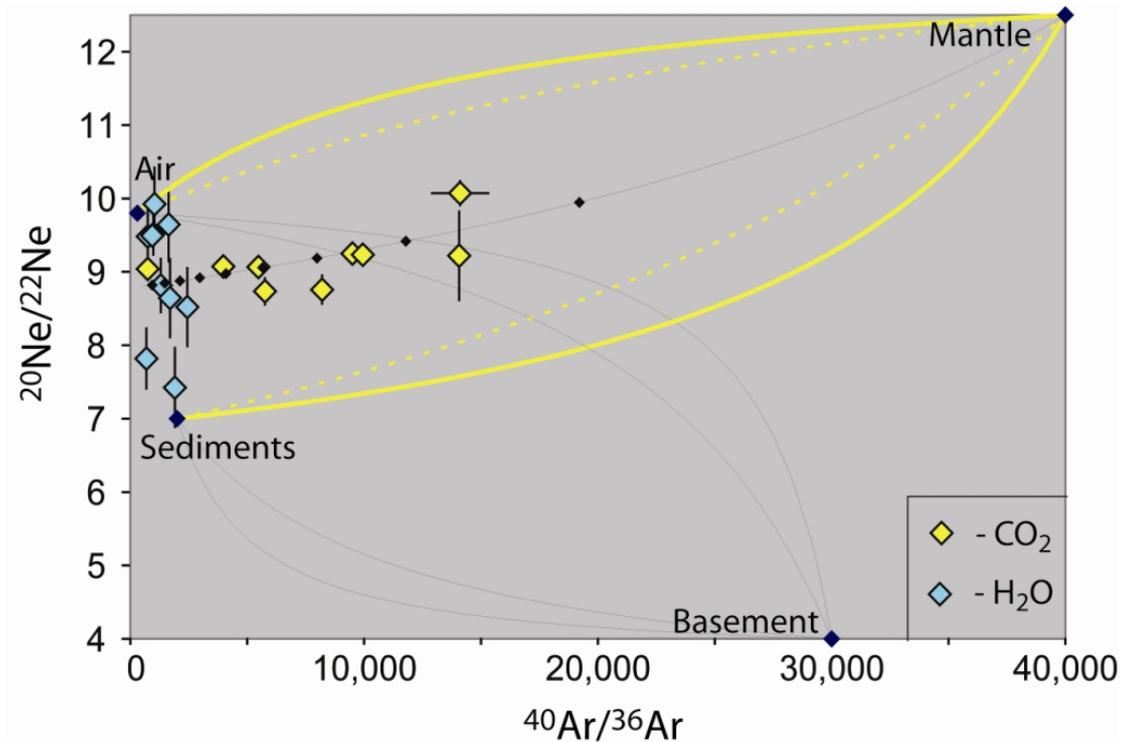


Fig 4.  $^{40}\text{Ar}/^{36}\text{Ar}$  versus  $^{20}\text{Ne}/^{22}\text{Ne}$  diagram for  $\text{H}_2\text{O}$  and  $\text{CO}_2$  dominated fluid inclusion assemblages in the Mary Kathleen Fold Belt.  $\text{H}_2\text{O}$ -dominated fluid inclusions define a mixing line between atmosphere and crustal noble gases. Mixing envelopes are shown between these fluids and the mantle and basement. The best fit mixing line between these fluids and the mantle has an  $r$  value of 0.5. 10% divisions are calculated based on the following end-member compositions: sedimentary  $\text{CO}_2$  has a  $^{36}\text{Ar}$  concentration of 1-10 ppm, 10 times the mantle concentration of 0.1-1 ppm, a  $^{40}\text{Ar}/^{36}\text{Ar}$  of 500 and  $^{20}\text{Ne}/^{22}\text{Ne}$  of 8.4. The mantle has  $^{40}\text{Ar}/^{36}\text{Ar}$  of 40,000 and  $^{20}\text{Ne}/^{22}\text{Ne}$  of 12.5. The composition of the basement is based on the maximum  $^{40}\text{Ar}/^{36}\text{Ar}$  value measured in several ore deposits of the Mt Isa Inlier (Kendrick et al., 2008; Kendrick et al., 2006a; Kendrick et al., 2007) and the assumption that the  $^{20}\text{Ne}/^{22}\text{Ne}$  value would be lower than in the sedimentary formation waters.

## References

- Kendrick, M. A., Baker, T., Fu, B., Phillips, D., and Williams, P. J., 2008, Noble gas and halogen constraints on regionally extensive mid-crustal Na-Ca metasomatism, the Proterozoic Eastern Mt Isa Block, Australia: *Precambrian Research*, v. in press.
- Kendrick, M. A., Duncan, R. J., and Phillips, D., 2006a, Noble gas and halogen constraints on mineralizing fluids of metamorphic versus surficial origin: Mt Isa, Australia: *Chemical Geology*, v. 235, p. 325-351.
- Kendrick, M. A., Mark G., and Phillips, D., 2007, Mid-crustal Fluid Mixing in a Proterozoic Fe oxide-Cu-Au deposit: Evidence from Ar, Kr, Xe, Cl, Br, I, Ernest Henry, Australia.: *Earth and Planetary Science Letters*, v. 256, p. 328-343.
- Kendrick, M. A., Miller, J. M., and Phillips, D., 2006b, Part I. Decrepitation and degassing behaviour of quartz up to 1560 C: Analysis of noble gases and halogens in complex fluid inclusions assemblages.: *Geochimica et Cosmochimica Acta*, v. 70, p. 2540-2561.
- Langmuir, C. H., Vocke, R. D. J., Hanson, G. N., and Hart, S. R., 1978, A general mixing equation with applications to iclandic basalts: *Earth and Planetary Science Letters*, v. 37, p. 380-392.
- Marshall, L. J., Oliver, N. H. S., and Davidson, G. J., 2006, Carbon and oxygen isotope constraints on fluid sources and fluid-wallrock interaction in regional alteration and iron-oxide-copper-gold mineralisation, eastern Mt Isa Block, Australia: *Mineralium Deposita*.
- Oliver, N. H. S., 1995, Hydrothermal History of the Mary Kathleen Fold Belt, Mt Isa Block, Queensland.: *Australian Journal of Earth Science*, v. 42, p. 267-279.
- Oliver, N. H. S., Butera, K. M., Rubenach, M. J., Marshall, L. J., Cleverley, J. S., Mark, G., Tullemans, F., and Esser, D., The protracted hydrothermal evolution of the Mount Isa Eastern Succession: A review and tectonic implications: *Precambrian Research*, v. In Press, Corrected Proof.
- Oliver, N. H. S., Cartwright, I., Wall, V. J., and Golding, S. D., 1993, The stable isotope signature of kilometre-scale fracture-dominated metamorphic fluid pathways, Mary Kathleen, Australia: *Journal of Metamorphic Geology*, v. 11, p. 705-720.
- Oliver, N. H. S., Cleverley, J. S., Mark, G., Pollard, P. J., Fu, B., Marshall, L. J., Rubenach, M. J., Williams, P. J., and Baker, T., 2004, Modeling the role of sodic alteration in the genesis of iron-oxide-copper-gold deposits, eastern Mt Isa block, Australia.: *Economic Geology*, v. 99, p. 1145-1176.
- Page, R. W., and Sun, S.-S., 1998, Aspects of geochronology and crustal evolution in the Eastern Fold Belt, Mount Isa Inlier.: *Australian Journal of Earth Sciences*, v. 45, p. 343-362.
- Rimstidt, J. D., 1997, Gangue mineral transport and deposition, *in* Barnes, H. L., ed., *Geochemistry of Hydrothermal Ore Deposits*: New York, John Wiley and Sons, p. 487-517.
- Watson, E. B., and Cherniak, D. J., 2003, Lattice diffusion of Ar in quartz, with constraints on Ar solubility and evidence of nanopores.: *Geochimica et Cosmochimica Acta*, v. 67, p. 2043-2062.

