# Helium, argon, heat and gold: Noble gas studies of the Ailaoshan gold province, China

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Analyses of He and Ar in ancient mineralising fluids, using fluid inclusions in pyrite as 'bottles' for the palaeofluids, can be used to trace atmospheric (meteoric), crustal and mantle contributions to the fluid and heat budget of extinct hydrothermal systems. Crushing pyrite grains *in vacuo* is an effective method of releasing the trapped fluids, which can be analysed using conventional noble gas techniques. We present analyses of noble gases from three gold deposits from the same deep-seated fault in the Ailaoshan Gold Province, China. The results demonstrate the palaeofluids were a mixture between a mantle-derived, magmatic fluid and two different groundwaters. Stable isotope compositions are consistent with a predominantly magmatic origin for the fluids and do not identify any meteoric component: it is the specific isotopic and abundance characteristics of He and Ar that allow unequivocal identification of both a mantle-derived component and a meteoric component to these fluids.

It can also be shown that direct injection of high enthalpy, magmatic fluids occurred at one of the deposits, whereas heat was advected into the hydrothermal cell via low enthalpy fluids at the other two deposits.

## Fluid compositions

He and Ar isotopes correlate, and can be modelled as mixing between a high $^3$He-high $^{40}$Ar 'magmatic' fluid and modified air saturated water (asw) that had atmospheric Ar ($^{40}Ar/^{36}Ar = 295.5$), but radiogenic He ($^3He/^4He = 0.001\ R_a$, where $R_a = 1.39 \times 10^{-6}$; Fig. 1). Modern groundwaters commonly have He and Ar characteristics similar to the modified asw fluid, and it is likely this fluid represents an ancient groundwater. A separate modified asw fluid, characterised by higher He/Ar ratios and atmospheric $^{40}Ar/^{36}Ar$, is involved in the genesis of two of the deposits (Zhenyuan and Mojiang) (Fig. 2).

The excellent correlations in He and Ar isotope space (Figs. 1,2) makes it possible to constrain endmember fluid compositions prior to mixing in the hydrothermal system.

The first groundwater had $^4$He excesses of $\approx 4 \times 10^{-5}$ cm$^3$ STP g$^{-1}$ $H_2O$. This would require $\approx 5$ Ma to accumulate in typical crustal rocks. The absence of excess $^{40}$Ar constrains the fluid temperature to $< 200$°C.

The magmatic fluid had a $^3He/^4He$ ratio of 1.23 Ra prior to mixing with modified asw. This $^3He/^4He$ is significantly lower than potential mantle He sources (which likely had $^3He/^4He$ of 6–8 $R_a$). It appears the

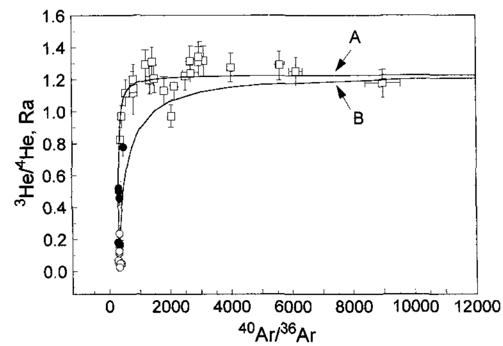


FIG. 1. He and Ar isotopes are consistent with binary mixing between a high $^3He/^4He$-high $^{40}Ar/^{36}Ar$ fluid and a fluid with atmospheric $^{40}Ar/^{36}Ar$, but radiogenic He. The third fluid component cannot be distinguished in this diagram. Daping: squares; Zhenyuan: filled circles; Mojiang: open circles. Curves A and B are for different magmatic fluids mixing with modified asw. The curvature of the line, r, is the ratio of $(^4He/^{36}Ar)_{magmatic}/(^4He/^{36}Ar)_{mod.\ asw} = 1400$ (line A) and 140 (line B).

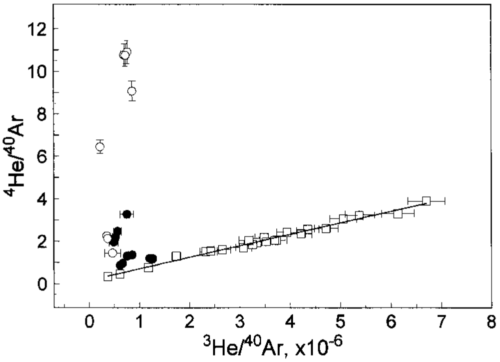


FIG. 2. Fluids from Daping lie on a binary mixing trajectory such that: $^3He/^{40}Ar = ^4He/^{40}Ar * (5.41 \pm 0.16) \times 10^5 + (0.16 \pm 0.06)$ ($r^2 = 0.98$) where the intercept ~ $^4He/^{40}Ar$ of the low temperature groundwater. All Zhenyuan and Mojiang compositions have higher $^4He/^{40}Ar$ for a given $^3He/^{40}Ar$ compared to the Daping correlation. This is interpreted to be due to mixing with a second, high He/Ar groundwater. Symbols as Fig. 1.

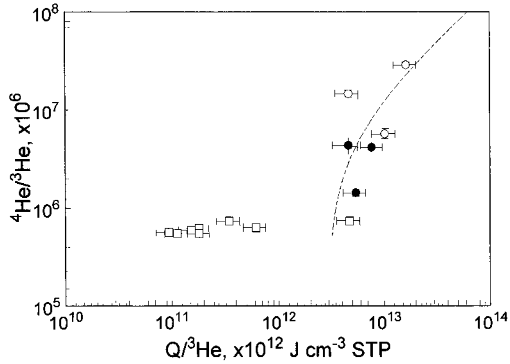


FIG. 3. Two distinct thermal regimes exist. Daping samples have high and variable $^3$He/heat ratios reflecting direct injection of mantle-derived heat. Zhenyuan and Mojiang have more consistent and lower $^3$He/heat ratios that correlate with $^4$He. The line corresponds to a $^4$He/heat ratio of $6 \times 10^{-7}$ cm$^3$ STP J$^{-1}$. Symbols as Fig. 1. Errors in the heat estimate include the range of fluid inclusion homogenisation temperatures.

parent magma to these volatiles assimilated significant crustal $^4$He and $^{40}$Ar, in a ratio broadly compatible with He and Ar produced in ancient crust.

The second groundwater, sampled only by Zhenyuan and Mojiang deposits, mixed with a fluid composed of a variable mixture of a) and b), consequently correlations are poor; the endmember fluid had $^4He/^{40}Ar \geqslant 11$, corresponding to $[^4He] \geqslant 3 \times 10^{-3}$ cm$^3$ STP g$^{-1}$ $H_2O$.

## He and heat

Turner and Stuart demonstrated that, for binary mixing between a high enthalpy, $^3$He – rich magmatic fluid and a cold aqueous fluid with a known concentration of $^{36}$Ar (= asw concentration), the He/heat ratio of the resulting hydrothermal fluid can be estimated by:

$$^3He_m/Q_m = {}^3He_m/{}^{36}Ar_{asw} \,.\, [^{36}Ar]_{asw}/(C_p.\theta)$$

($C_p$,$\theta$ are specific heat capacity and temperature difference respectively; subscript m refers to mantle-derived, asw to air saturated water). Using this relationship, Turner and Stuart (1992) showed that the He/heat ratios of fluids trapped in hydrothermal vent minerals were similar to fluids emanating from the vent.

Assuming fluid inclusion homogenisation temperatures in coexisting quartz are representative of fluid temperature, $^3$He/Heat ratios can be estimated. $^3$He/heat ratios in fluids trapped at Daping ($0.5-29 \times 10^{-12}$ cm$^3$ STP J$^{-1}$) are consistent with direct injection of magmatic volatiles into the hydrothermal circulation. However, $^3$He/heat in Zhenyuan and Mojiang fluids was considerably lower ($0.06-0.6 \times 10^{-12}$ cm$^3$ STP J$^{-1}$). Furthermore, the enthalpies of these fluids correlate with the second, high [$^4$He] groundwater (Fig. 3). There was no direct injection of magmatic volatiles in the Zhenyuan and Mojiang hydrothermal systems, but the heat was transported into the system by low enthalpy, high [$^4$He] groundwater fluids.

## References

Turner, G. and Stuart, F.M. (1992) *Nature*, **357**, 581–3.