

SUPPLEMENT DATA SD4

Effect of *T* and mineral assemblage changes

It has been demonstrated that garnet $\delta^{18}\text{O}$ shifts due to *T* variation are limited (i.e. typically < 1 ‰) even when important changes in stable mineral assemblage occur within prograde metamorphism (Kohn 1993; Vho et al. 2020). The investigated samples underwent a complex evolution with two overprinting metamorphic cycles at different conditions (*HT/LP* and *HP/LT*). The variation in mineral $\delta^{18}\text{O}$ that this change in *P-T* conditions may produce in closed systems (i.e. without infiltration of any external fluid) must be quantified in order to assess if a rock evolved as a closed or an open system.

The expected shift in garnet $\delta^{18}\text{O}$ between the *HT* and the *HP* metamorphic stages by growth in a closed system was calculated for certain metasediments for which a difference in $\delta^{18}\text{O}$ between pre-Alpine and Alpine garnet was actually measured (AV16-45, VC10-04, FG1249 and FG1315); the *P-T* conditions used for the calculation and the results are reported in Table S4-T1 (oxygen isotope fractionation factors taken from Vho et al. 2019). The stable mineral assemblage at each stage was calculated using single Gibbs minimization with Theriak (de Capitani and Brown 1987; de Capitani and Petrakakis 2010) and checked against the mineral modes observed in each sample. Variations in the reactive bulk composition for each successive stage caused by garnet core fractionation were considered following the strategy of Lanari et al. (2017). It is important to outline that the calculated $\delta^{18}\text{O}$ values of stable phases depend on the chosen fractionation factors and might be affected by an uncertainty in the order of 1 ‰. Nevertheless, the relative difference between mineral zones, i.e. the magnitude of the variation in $\delta^{18}\text{O}$ between different garnet growth stages, is the key variable for the following discussion. All data discussed below are reported in **Table S4-T1**

In the Val Chiusella metaquartzite VC10-04, starting from the measured bulk composition, the stable assemblage was modelled at 750°C and 0.85 GPa (representing the pre-Alpine *HT* stage, Regis et al. 2014). Given the modal abundance predicted for each mineral, their $\delta^{18}\text{O}$ in equilibrium with the measured garnet core $\delta^{18}\text{O}$ of 16.6 ‰ was calculated at 750°C. This results in a reconstructed bulk rock $\delta^{18}\text{O}$ of 19.7‰ (column "Bulk $\delta^{18}\text{O}$ "). The same calculation was performed for the same bulk

composition at 500° and 2.0 GPa (Alpine HP stage, Regis et al. 2014) maintaining a constant bulk rock $\delta^{18}\text{O}$. The resulting garnet composition, assuming no changes in bulk $\delta^{18}\text{O}$, is 15.7 ‰. When this value is compared to the actually measured $\delta^{18}\text{O}$ of the Alpine garnet rim (11.3 ± 0.7 ‰) the calculation demonstrates that the measured shift of ~ 5 ‰ $\delta^{18}\text{O}$ between garnet core and rim in sample VC10-04 from Chiusella Valley cannot be explained by changes in P - T conditions maintaining a closed system.

The same type of closed-system calculation was made for micaschist AV16-45 from Malone Valley based on garnet core stable at 700°C and 0.6 GPa (Regis et al. 2014) and with a $\delta^{18}\text{O}$ of 10 ‰. The calculation returns an Alpine garnet rim (450°C and 1.7 GPa) with a predicted $\delta^{18}\text{O}$ of 8.4 ‰, which is significantly different from the measured garnet rim composition of 6.1 ‰.

In both these samples, the $\sim 4 - 6$ ‰ $\delta^{18}\text{O}$ shift measured in garnet between the HT core and the HP rim points to an infiltration of an external fluid with a lower $\delta^{18}\text{O}$ value than the rock that must have occurred between the growth of the pre-Alpine garnet core and the Alpine rim. Quartz and phengite $\delta^{18}\text{O}$ values measured in AV16-45 (Table S4-T1 last column) support this hypothesis, being ~ 1 ‰ and ~ 2 ‰ lower than the values predicted for a closed system, respectively.

The blueschist AV16-44 from Malone Valley shows a similar behaviour to AV16-45. Measured $\delta^{18}\text{O}$ values in garnet rim1 of micaschist FG1249 and FG1315 from Lys Valley are only 0.3 ‰ and 0.7 ‰ higher than those predicted for a closed system, respectively. The Alpine rims show a slight increase in $\delta^{18}\text{O}$ in sample FG1249 and a slight decrease in sample FG1315, mimicking what observed for quartz (Engi et al. 2018). Hence, the fluid interacting with those lithologies likely did not have an oxygen isotope composition as far from equilibrium as the fluids that interacted with the samples from Malone Valley and Chiusella Valley.

Table S4-T1. Expected $\delta^{18}\text{O}$ variations in the stable mineral assemblages of the metasedimentary samples in case the rocks evolved as closed systems. Mineral abbreviations are from Whitney and Evans (2010). Fractionation factors are from Vho et al. (2020a). Measured garnet core and rim $\delta^{18}\text{O}$ are reported in bold.

Sample	Bulk $\delta^{18}\text{O}$ (‰)*	P-T stage 1	Min. vol%	Min. $\delta^{18}\text{O}$ (‰)**	P-T stage 2	Min. vol%	Closed system $\delta^{18}\text{O}$ (‰)	Measured $\delta^{18}\text{O}$ (‰)	
VC10-04	19.7	700 °C, 0.60 GPa ^b	Qz	65	20.1	550 °C, Qz	65	20.1	-
			Pl	14	19.0	2.00 GPa ^c Grt	20	15.7	11.3 ± 0.7
			Amp	11	17.2	(rim2***) Gln	15	16.7	-
			Grt	10	16.6	-	-	-	-
AV16-45	12.0	700 °C, 0.60 GPa ^b	Qz	43	13.4	450 °C, Qz	40	13.7	12.6 ± 0.2
			Kfs	20	12.2	1.70 GPa ^f Grt	13	8.4	6.1 ± 0.4
			Bt	13	10.2	(rim***) Ph	34	10.4	8.6 ± 0.6
			Gt	12	10.0	Pg	8	10.3	-
			Sil	7	11.6	Chl	5	8.6	-
			Pl	5	12.1	-	-	-	-
FG1249	11.8	730 °C, 0.60 GPa ^a	Qz	30	14.0	620 °C, Qz	36	12.8	13.9 ± 0.4 ^d
			Kfs	19	12.7	0.62 GPa ^a Ms	29	10.5	-
			Bt	14	10.9	(rim1) Pl	15	11.2	-
			Pl	13	12.6	Bt	13	9.2	-
			Sil	11	12.1	St	3	9.6	-
			Grt	11	10.6	Grt	2	8.8	9.5 ± 0.2
			Ilm	1	7.5	Ilm	1	5.1	-
FG1315	12.9	750 °C, 0.85 GPa ^a	Qz	41	14.2	650 °C, Qz	46	13.8	14.3 ± 0.8 ^d
			Ms	24	12.3	1.52 GPa ^a Ph	33	11.1	-
			Grt	14	10.9	(rim1) Pg	11	11.3	-
			Pl	12	13.2	Grt	6	10.0	10.2 ± 0.4
			Bt	5	11.2	Pl	2	12.7	-
			Sil	2	12.4	Bt	1	10.3	-
			Rt	1	9.2	Rt	1	8.0	-

* Calculated from the measured garnet core $\delta^{18}\text{O}$.

** Typical uncertainties of calculated $\delta^{18}\text{O}$ are in the order of 1‰ (2sd).

*** Volume percentage of garnet based on observations.

^a P-T conditions from Giuntoli et al. (2018).

^b Minimum P-T conditions from Regis et al. (2014).

^c P-T conditions from Regis et al. (2014).

^d (Engi et al. 2018).

^f P-T conditions retrieved from observed mineral assemblage.

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