\[ ^4\text{He}/\text{Heat Flux Ratios as New Indicators of Past Thermal and Tectonic Events – New Constraints on the Tectonothermal History of the Michigan Basin} \]

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\textbf{He/Heat Flux Ratio Indicator - Background}

For over two decades it has been assumed that transport properties for both heat and helium are similar in the crust and that transport for both tracers is in steady-state [1]. Because helium and heat production results from a common source, these assumptions led to an estimated crustal He flux of \(4.65 \times 10^{-14} \text{ mol m}^{-2} \text{ s}^{-1}\) based on heat flow considerations [1]. In addition, based on the observed low mantle He/heat flux ratio \((6.6 \times 10^{-14} \text{ mol J}^{-1})\) at the proximity of mid-ocean ridges, which is over an order of magnitude lower than the radiogenic production ratio \((1.5 \times 10^{-12} \text{ mol J}^{-1})\), it was concluded that the amount of U and Th required to support the oceanic radiogenic He flux would only provide \(\sim 5\%\) of the mantle heat flux. Consequently, the presence of a terrestrial “helium-heat imbalance” was suggested [1]. Estimated \(^4\text{He}/\text{heat flux ratios lower than radiogenic production ratios were thus interpreted as reflecting a He deficit in the crust or mantle original reservoir. To account for this “helium-heat imbalance”, the presence of a layered mantle (\(\sim 670 \text{ km}\)) was suggested in which removal of He is impeded from the lower mantle [1].

\textbf{Recent Findings}

By simultaneously carrying out 2-D simulations of groundwater flow, heat transfer and \(^4\text{He}\) transport in the Carrizo aquifer and surrounding formations in southwest Texas, the legitimacy of earlier assumptions was assessed [2]. Specifically, it was shown that the driving transport mechanisms for He and heat are of a fundamentally different nature for a high range of permeabilities \((k \lesssim 10^{-16} \text{ m}^2)\) found in metamorphic and volcanic rocks at all depths in the crust. More specifically, it was concluded that total \(^4\text{He}/\text{heat flux ratios lower than radiogenic production ratios do not reflect a He deficit in the crust or mantle original reservoir. Instead, they reflect the combined impact of air saturated water (ASW), advection, conduction, and diffusion when steady-state is reached for both tracers. The interplay between these different components and the extent to which each one influences this ratio depends in turn on hydraulic conductivities and therefore, permeabilities of the formations they cross in their movement upward, toward the surface.

Both, the presence of ASW (e.g., an atmospheric component provided by freshwater or seawater) in an advective dominated system \((k \gtrsim 10^{-16} \text{ m}^2)\), or \(^4\text{He}\) and heat transport in a diffusive/conductive dominated low permeability system will lead to
$^4$He/heat flux ratios lower than the radiogenic production ratio in a steady-state regime [2]. It was further concluded that only in the total absence of contact with ASW under a steady-state advective dominated regime for both $^4$He and heat transport is the $^4$He/heat flux ratio expected to equal the radiogenic production ratio. Simulations also suggest that $^4$He transport is in a transient state in recently formed crust for permeabilities $\leq 10^{-17}$ m$^2$. Under these conditions $^3$He/heat fluxes of up to several orders of magnitude lower than the radiogenic production ratios are expected.

In the absence of a thermal event, the maximum potentially observable $^4$He/heat flux ratio is one corresponding to the radiogenic crustal production ratio. The occurrence of a $^4$He/heat flux ratio greater than the crustal production ratio under all scenarios can only be the result of a past mantle or magmatic thermal event in which the released heat has already escaped while the released mantle He is still present in the system, and is slowly (with respect to heat) making its way toward the surface. These findings have given origin to a new indicator: the $^4$He/heat flux ratio. This indicator is particularly useful to identify the occurrence of past thermal events in systems such as the Michigan Basin in which low hydraulic conductivity/permeability but high thermal conductivity formations such as evaporites are present.

**Helium-heat signature in the Marshall Aquifer, Michigan Basin**

He concentrations and fluxes analyzed and estimated in the Marshall aquifer of the Michigan Basin revealed some surprising results [3]. Indeed, $^4$He excesses are unusually high for such shallow depths ($\leq$300 m), and reach over three orders of magnitude above those of ASW. First order estimated $^4$He fluxes in certain areas of the Marshall are far greater than those reported in other multi-layered basins around the world at far greater depths and also display $R/R_a$~0.15 ($R$ is the measured $^3$He/$^4$He, $R_a$ is the $^3$He/$^4$He atmospheric ratio) further suggesting the presence of a more significant and local mantle component. Corresponding $^4$He/heat flux ratios in these areas are also far greater than the crustal production ratio and point to the occurrence of a past thermal event of mantle or magmatic nature in which the released heat has already escaped and at least part of the released mantle $^4$He remains in the system. We are currently expanding this noble gas study in the Michigan Basin to confirm this theory.

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**References**

