Introduction: Among short-lived radioactive chronometers, the \(^{146}\text{Sm}-^{142}\text{Nd}\) system (with an half-life of 68 million years (Myr) [1]) is particularly suited to study the early stages of terrestrial planet differentiation. Since 3.5 billion years (Gyr) ago, all terrestrial rocks show a \(\mu\)\(^{142}\text{Nd}\) of 0 ± 3 (2\(\sigma\)) [2-5]. This indicates that early chemical heterogeneities resulting from the formation of ancient or primitive crust have been erased by efficient remixing into the Archean convecting mantle. From 3.9 to 3.5 Gyr, a progressive \(\mu\)\(^{142}\text{Nd}\) decrease in early Archean rocks from +20 to 0 is thought to illustrate this efficient remixing of the first primitive crust into the Archean convecting mantle [3].

In contrast to the present-day convecting mantle in Earth, several studies of martian meteorites have shown that the Mars mantle has retained large variations in \(\mu\)\(^{142}\text{Nd}\) from -27 to +71 to recent times [6-10]. This shows that the martian mantle still preserves chemical signatures inherited from the early planetary differentiation, and is thus poorly mixed.

Those differences in mixing states between Earth and Mars mantles have implications for our understanding of mantle convection and global evolution of planets. For Earth, the implied long mixing time of ~1 Gyr from the Hadean to Archean for the whole mantle is paradoxical. This is much longer than the rapid mixing time (<100 Myr) inferred for the Archean due to vigorous mantle convection related to Earth’s hotter thermal regime [11], and similar to the mixing time inferred for the present-day Earth’s mantle [12]. For Mars, how to preserve a poorly mixed mantle is still a matter of debate. Some have suggested that the martian mantle stopped convecting a long time ago in order to prevent convective mixing [13], while recent numerical modeling indicate that mantle convection is still active in Mars [14] where it should have erased the observed chemical heterogeneity that is still present.

Results: We found a resolvable positive \(^{142}\text{Nd}\) anomaly of \(\mu\)\(^{142}\text{Nd}\) = +7 ± 3 (2\(\sigma\)) relative to the modern convecting mantle in a 2.7 Gyr old tholeiitic lava flow from the Abitibi Greenstone Belt in the Canadian Craton [15]. Our result effectively extends the early Archean convective mixing time to > 1.8 Gyr, i.e. even longer than present-day mantle mixing timescale [12], despite a more vigorous mantle mixing timescale expected in the Archean.

Discussion: Different hypotheses have been examined to explain such a protracted mixing in the Archean, such as mantle overturn, two-layer convection or the existence of a dense layer at the bottom of the mantle. We postulate that the requirement of a delayed mixing in a strongly convective mantle is best explained by long periods of stasis in the global plate system (e.g. stagnant-lid regime), possibly with occasional episodes of subduction throughout the Hadean and Archean [16].

Our numerical model [15] confirms that in absence of continuous plate tectonics (e.g. mobile-lid regime), the convective mantle mixing is relatively inefficient in erasing the chemical heterogeneities inherited from the primordial differentiation of the early Earth (Fig. 1).

Figure 1: Mixing time versus Rayleigh number, from [15]. Even under average Archean conditions, the mixing time for stagnant-lid regime can be as long as ~2 Gyr, while for mobile-lid regime in an equivalent system the mixing time is ~150-500 Myr. At present, the mixing time of the Earth’s mantle is ~1 Gyr, and of Mars’s mantle, with a Rayleigh number of at least 2*10\(^5\) [14] but under stagnant-lid regime, is ~4 Gyr.
Using the mixing times from the numerical model and their evolution with time, it is possible to explain the 2.7 Gyr $^{142}$Nd anomaly in Theo’s Flow, if the tectonic regime of the Hadean and Archean was a stagnant-lid regime with only episodic subduction (Fig. 2). In this case, the timing for the onset of continuous modern plate tectonics (mobile-lid regime) would have occurred shortly before or after 2.7 Gyr.

**Figure 2**: Evolution of the mantle $^{142}$Nd signature with time, from [15]. The terrestrial average value (0 ± 3 µ-unit, 2σ) is indicated. Theo’s flow: open circle (this study), black circle represents the average for Theo’s flow; literature data: square [5], diamond [3], triangle [17]. From the known $^{142}$Nd compositions at 3.85 Gyr (Itsaq complex [3]), the initial heterogeneity is homogenized with time, depending on the plate tectonic regime, using the mixing times from Fig. 1.

The case of Mars. A major difference between the Earth and Mars when looking to short-lived isotopes is the fact that martian meteorites, even young ones, still largely preserve chemical clues about ancient differentiation events. Among those meteorites, shergottites retain isotopic evidences about a major differentiation event ~35 Myr after the formation of the solar system [8-10]. Similarly, nakhlites also reveal very early differentiation event(s) in Mars [7, 18, 19]. Convection within the martian mantle is so inefficient in mixing ancient chemical heterogeneities that some even suggested that Mars stopped convecting a long time ago [13]. Interestingly, the present model initially developed for terrestrial samples predicts that in absence of plate tectonics, a poorly-mixed mantle is actually an expected outcome. This is particularly relevant for Mars, as the planet has shown a stagnant-lid regime for at least the last 4 Gyr of its history [20]. According to the model developed here (Fig. 1), the absence of plate tectonics in Mars allows reconciling the paradox of a convective but poorly-mixed martian mantle.

**Conclusions**: The numerical modeling developed in this study shows that the mixing rate of a convective mantle is directly influenced by the plate tectonic regime of the planet. As such, a stagnant-lid regime can preclude efficient convective mixing. On Earth, the progressive decrease in $^{142}$Nd resulting from convective mixing of early-formed heterogeneities can be reconciled with the positive $^{142}$Nd anomaly observed in Theo’s Flow ($^{142}$Nd = +7 ± 3) if Earth was characterized during the Archean by a stagnant-lid regime, with short and episodic episodes of subduction. The paradox of a convective but poorly-mixed martian mantle can be also explained by stagnant-lid plate tectonic on Mars.