Global Geochemical Fingerprinting Points to a Mantle Dynamics Coupled with the Supercontinent Cycle

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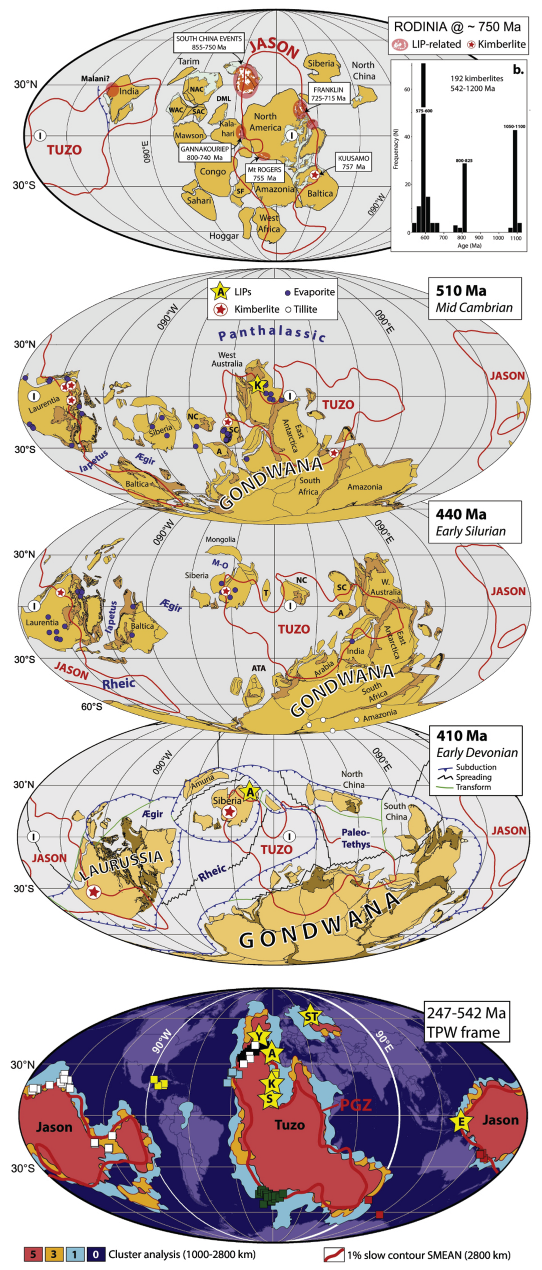
Background and Study aims

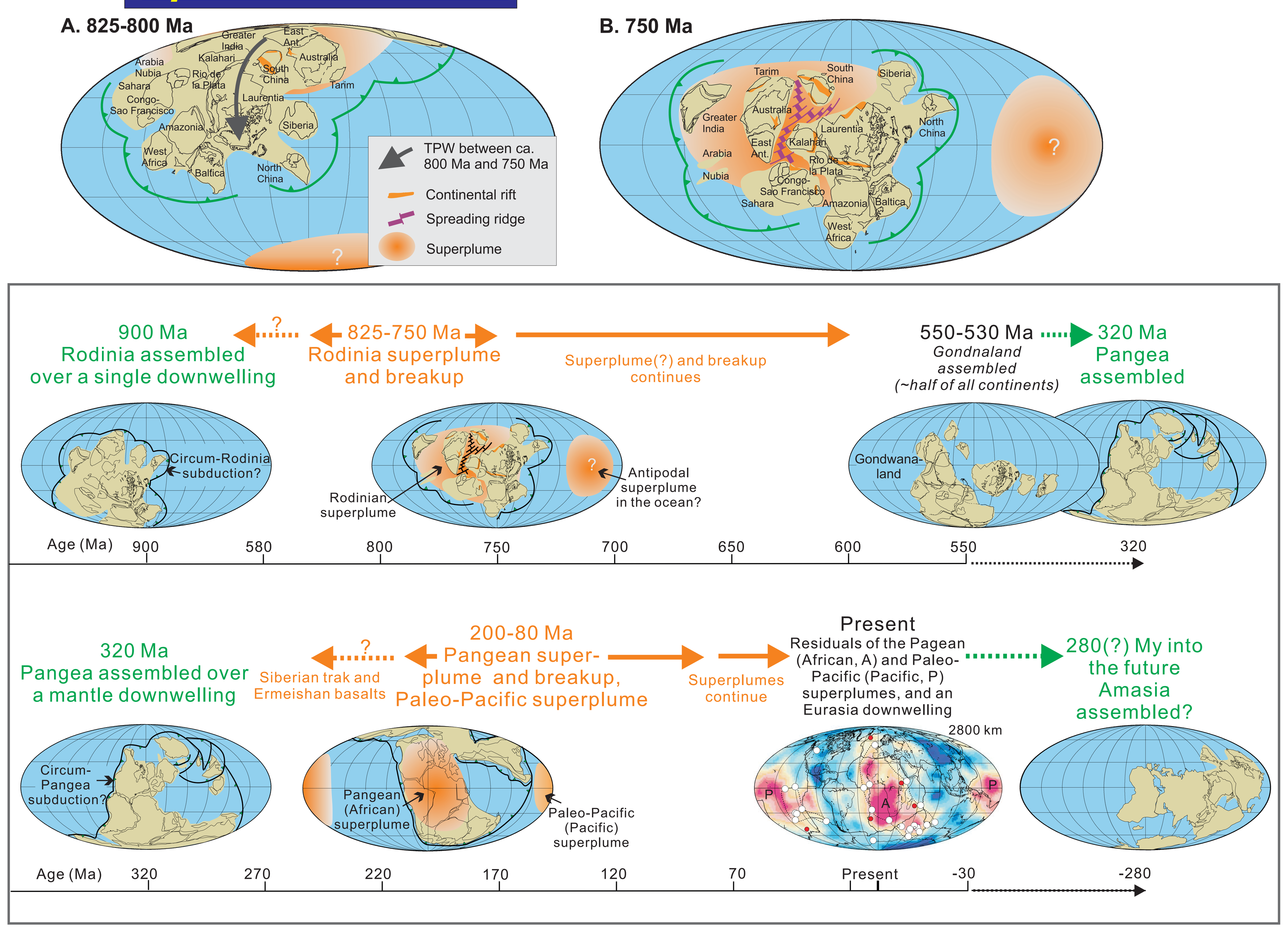
The plate tectonic theory developed last century works well on Earth's outer shell, but how this system interacts with mantle plumes, and if they are part of the same geodynamic system in Earth history, remains unclear. Seismic studies have revealed that Earth's present-day lower mantle is dominated by two antipodal large low shear velocity provinces (LLSVPs), also known as the African and Pacific superplumes, surrounded by high-velocity zones with subducted cold slabs (Dziewonski et al., 2010,EPSL). It has been further shown that almost all known mantle plumes since around 300 million years ago (Ma) were generated atop or near the edges of these two LLSVPs (Torsvik et al., 2014,PNAS). On the other hand, the assembly and breakup of supercontinents are controlled by global-scale mantle dynamics and constant feedback between surface and deep mantle processes (Anderson, 1994,Geology). It has been further established that the African LLSVP (whether or not in its present geometry) was located underneath the supercontinent Pangaea since 300 Ma (Burke and Torsvik, 2004,EPSL), and that there was a close link between mantle plumes and Pangaea breakup (Courtillot et al., 1999,EPSL). However, how long the LLSVPs have been present, how such LLSVPs interact with tectonic plates in Earth history, and whether they are **fixed in the deep mantle** (Dziewonski et al., 2010; Torsvik et al., 2010, 2014) or part of a **dynamic system associated with the supercontinent** cycle since at least the Proterozoic (Li et al., 2008, 2019,PR; Li and Zhong, 2009,PEPI), remain topics of debate. Tracing mantle plume signatures throughout Earth history is fundamental for answering those questions and testing the stable vs. dynamic/cyclic nature of the LLSVPs, and thus achieving a better understanding of the coupling between Earth's mantle dynamics and plate tectonics.

Fixed LLSVPs Model



Torsvik (2019,Tectonophysics)

Dynamic LLSVPs Model



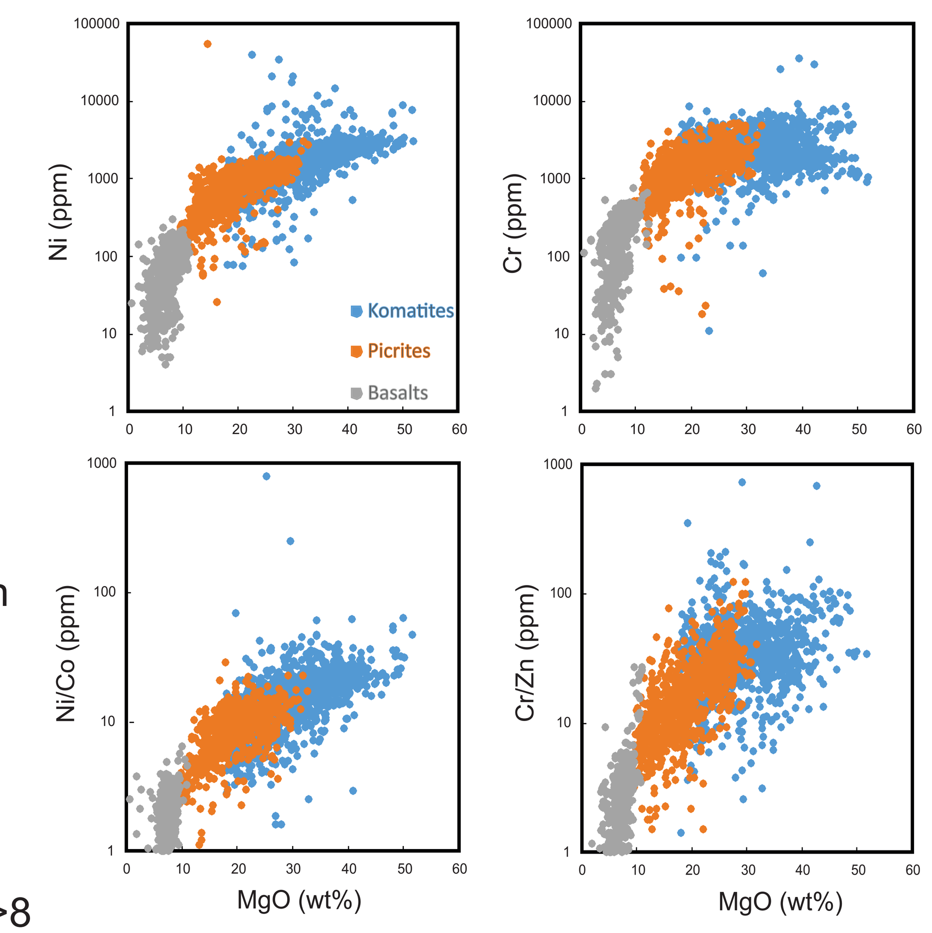
Li and Zhong (2009,PEPI)

Basaltic magmatism and Earth's mantle

>The main components of basaltic magmatism:
Fe-Mg silicate minerals (Ol & Px) and spinel
>Transition elements (Ni, Cr, Co, Zn, Mn, Fe) have partition coefficients with Fe-Mg silicate minerals and spinel >1:
-strongly melt-composition dependent.
-highly sensitive to the earliest magmatic differentiation stages.

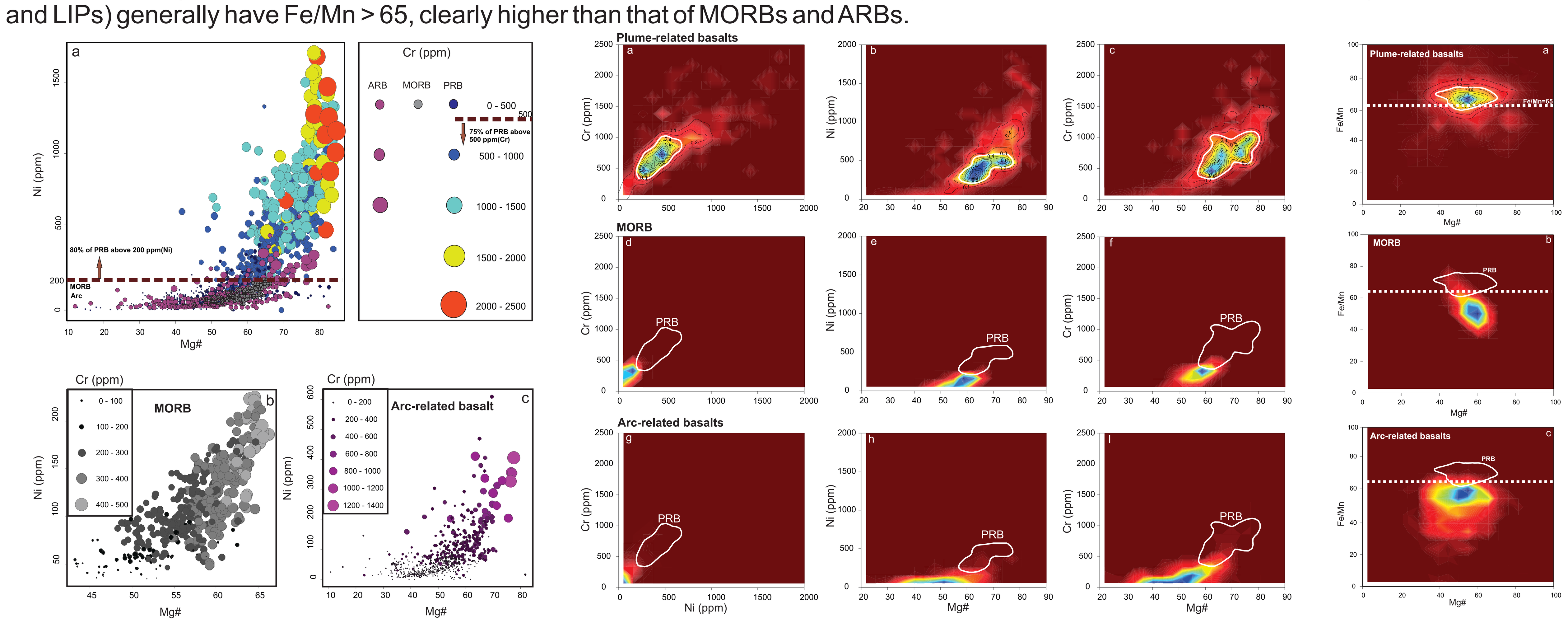
Ni and Cr as tracers for mantle plume products

>Mg and its ratio to other elements (i.e., Mg/Fe) are commonly used as tracers for the differentiation of silicate rocks and an indicator for mantle temperature (Herzberg et al., 2007,G3).
>Ambient mantle temperature below the ridges and sub-arc to be ~1350 °C.
>~200–300 °C over the ambient mantle temperature are expected for mantle plumes.
>Komatiites (>18 wt% MgO and T~ 1600 °C),
>Picrites (> 12 wt % MgO and T ~ 1500 °C; from OIBs and LIPs)
>Normal basalts (< 12 wt % MgO and T ~ 1350 °C; from present-day MORBs and ARBs)
>>>Plume magmatism is characterized by Ni > 200 ppm, Cr > 500 ppm, and Ni/Co and Cr/Zn both >8



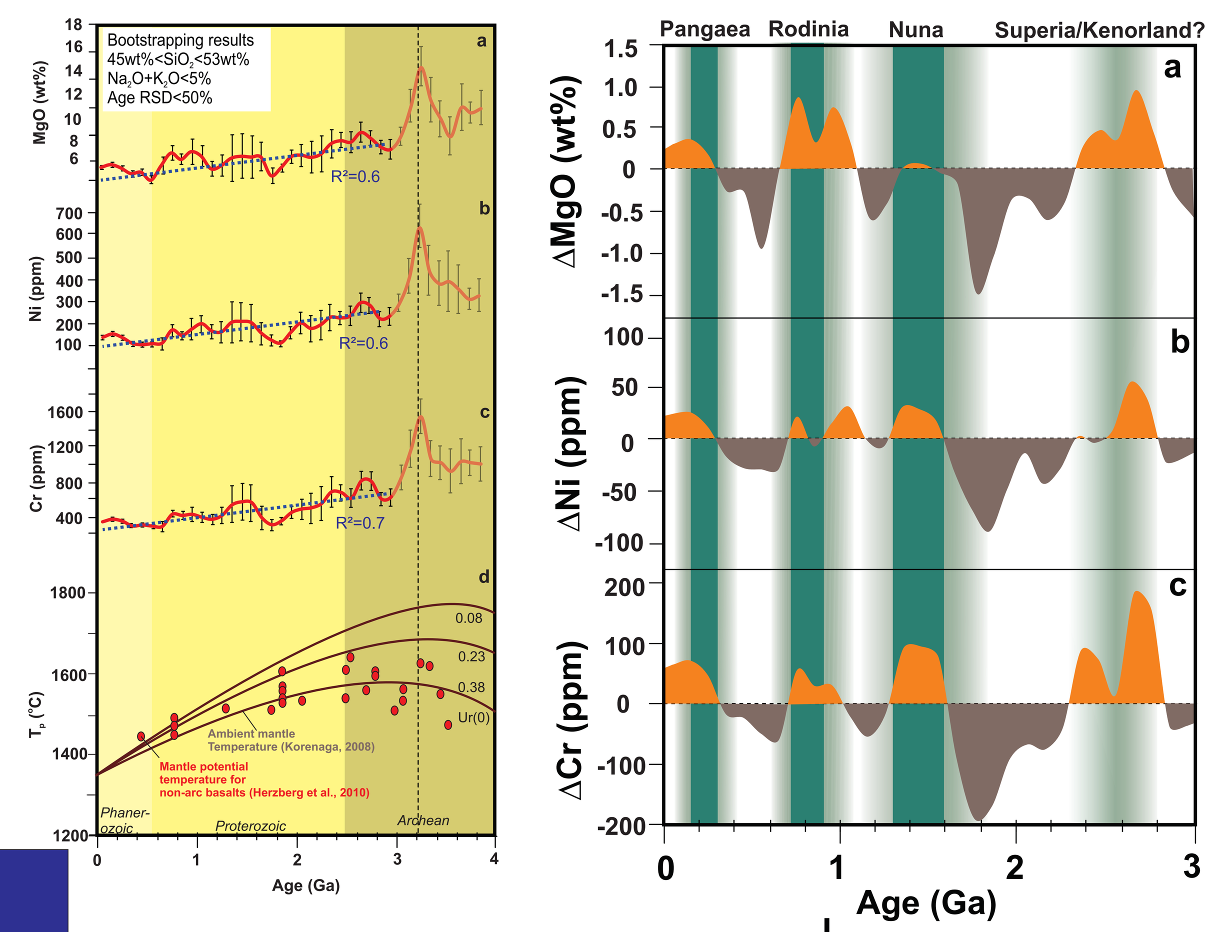
Basaltic rock datasets

To further verify the inferred plume characteristics, we produced covariation plots for Ni and Cr, and Mg# (100*MgO/ (MgO + FeO_T)) vs. Ni and Cr of basalt datasets (45 wt% < SiO_2 < 53 wt% and Na_2O+K_2O <5 wt %) from Cenozoic OIBs and LIPs and present-day MORBs and ARBs. Much like komatiites and picrites, 70 % of the plume basalts (PB) datasets have Ni > 150 ppm and Cr > 300 ppm whereas non-plume magmatism (MORBs and ARBs) are mostly below these limits. Thus, we argue that high Ni and Cr contents in basalts implies a plume signature. In addition, consistent with previous studies of some OIBs from the Pacific superplume (Humayun et al., 2004,Science), we found that plume basalts (OIBs and LIPs) generally have Fe/Mn > 65, clearly higher than that of MORBs and ARBs.



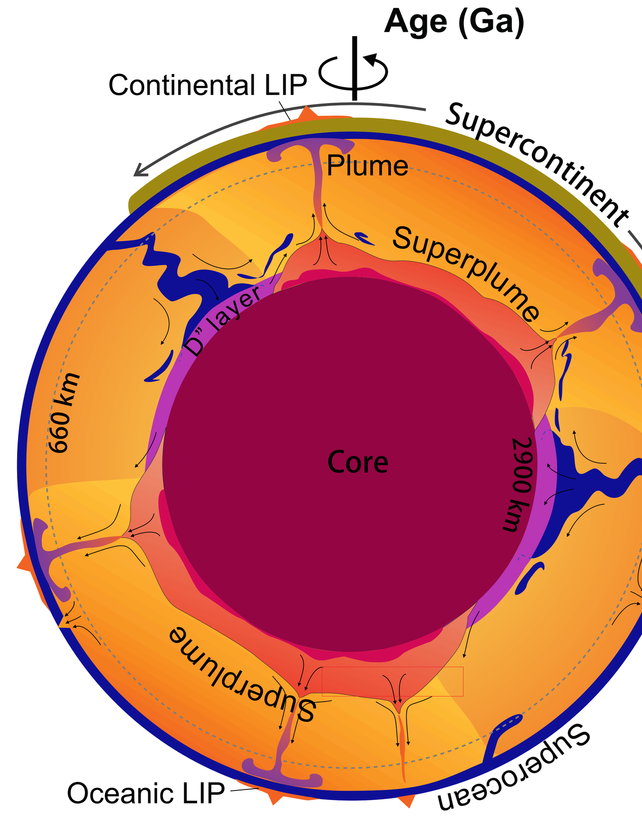
Time variations in mantle plume intensity

The bootstrapped analysis revealed a first-order decrease in MgO, Ni and Cr since the Archean similar to that shown by Keller and Schoene (2012,Nature), readily explainable by Earth's secular cooling (including the lowering of the mantle potential temperature).The second-order variability of MgO, Ni and Cr, previously largely ignored (Keller and Schoene, 2012, 2018,EPSL; Condie, 2018,GF), is more intriguing. The curves consistently show major positive peaks at ~2.8–2.3 Ga, ~1.6–1.3 Ga, ~1.0–0.7 Ga, and ~0.3–0.0 Ga. The most straightforward interpretation of these second-order variations is that they reflect changes in mantle potential temperature/degree of melting, which may be a consequence of either mantle plumes, or thermal insulation in the upper mantle (Anderson, 2000), or both. Plume is possibly a more dominant factor because it allows the higher Ni (>150 ppm) and Cr (>300 ppm) contents of the basalts to be sourced from the fertile lower mantle peridotites (i.e., Ni = 2,500 – 3,200 ppm and Cr = 2,600 – 7,500 ppm) (Herzberg et al., 2007,G3, 2013, Nature) rather than the depleted upper mantle peridotites (i.e., Ni = 1,960 ppm and Cr = 2,500 ppm) (Salters and Stracke, 2004,G3).



Implications for mantle dynamics coupled with the supercontinent cycle

Our results allow us to test the fixed vs. dynamic models for the two LLSVPs in the lower mantle. In the fixed LLSVPs model (Torsvik et al., 2010,Nature, 2014), the LLSVPs are stable features anchored to the core-mantle boundary (CMB) since early Earth. Their positions and shapes would therefore not have been linked to the subduction girdle and thus to plate motion in general (Li and Zhong, 2009). As such, one would expect the formation of plume basalts to be stochastic in Earth history, implying a semi-uniform occurrence of plume magmatism over geological time, i.e., plume intensity unrelated to the supercontinent cycle. Alternatively, if supercontinents indeed preferentially form on the global subduction girdle (cold downwelling mantle) as suggested by some (Mitchell et al., 2012,Nature), and both the antipodal LLSVPs and the subduction girdle are fixed and long-lived features, then one would expect an anticorrelation between plume intensity and supercontinental tenure (we note that the pre-Cretaceous global plume record is dominated by continental LIPs). In contrast, according the dynamic LLSVPs model (Li and Zhong, 2009), the formation of antipodal LLSVPs is linked to circum-supercontinent subduction that leads to the formation of the subduction girdle; the subduction girdle subsequently divides the hot and dense lower mantle into the two antipodal LLSVPs (Li and Zhong, 2009). Such a dynamic LLSVP model therefore predicts an increase in the intensity of plume magmatism during the tenure and breakup stage of the supercontinent cycle, and thus a periodicity positively correlated with the supercontinent cycle



Li et al. (2008)
Li and Zhong (2009)