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Emergence of peraluminous crustal magmas and implications for the early Earth

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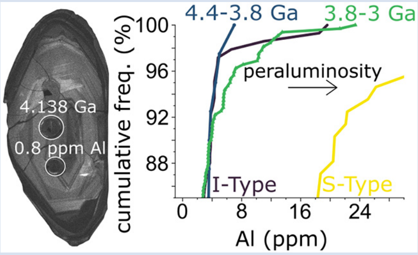
Abstract



Detrital zircons from the Jack Hills (JH) metasedimentary belt of Western Australia are a record of the first ~1.5 billion years of Earth history and can be used to help reconstruct the conditions of crust formation and secular changes therein. Beginning as early as *ca.* 4.3 Ga, but becoming more pronounced in the mid-Archean, a peraluminous signature begins to emerge from the JH zircon record. Combined with trace elements (P, REEs) and Ti-in-zircon thermometry, this increase in peraluminosity is likely the result of deep (>7 kbar) partial melting of hydrous mafic protoliths or partial melting of metasedimentary source material. In a geodynamic context, these results may suggest a gradual shift from a vertical tectonic regime toward a horizontal tectonic regime with potential subduction-like or collisional processes creating the necessary conditions for peraluminous melt generation beginning locally at least by ~3.6 billion years ago (Ga).

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Introduction

Continental crust and its derivatives (*e.g.*, detrital zircons) preserve a near continuous record of Earth's history from ~4.4 Ga to today (Voice *et al.*, 2011) that can be used to investigate both individual magmatic systems (*e.g.*, Reimink *et al.*, 2014) and secular changes in Earth's geodynamic and tectonic history (Bauer *et al.*, 2020). The ~3 Ga metasedimentary rocks from the JH in Western Australia contain detrital zircons that are the oldest known record of Earth's continents (Compston and Pidgeon, 1986). These ancient zircons retain multiple chemical fingerprints that have been combined to reconstruct a Hadean Earth that bore oxidised, water-rich silicic continents derived from mafic (±felsic) protoliths that interacted with low temperature (T) surface waters (Cavosie *et al.*, 2005; Watson and Harrison, 2005; Trail *et al.*, 2011; Burnham and Berry, 2017).

One outstanding problem in Earth's early history is the nature and timing of the transition from a stagnant lid or vertical tectonic regime (crust thickened by processes akin to modern oceanic plateaus; Van Kranendonk *et al.*, 2004; Reimink *et al.*, 2014) to a mobile lid or horizontal tectonic regime where crust can be thickened and rapidly recycled through subduction-like processes and/or shallow thrusting (Bauer *et al.*, 2020). Horizontal tectonics is associated with an increase in the depth of melt generation. The shift toward a horizontal tectonic regime should produce chemical signatures in the ancient rock record that reflect this geodynamic shift. One potential tool to evaluate this shift is the Al content of zircon crystals (X_{Al}^{Zrc}, in ppm by weight), which is strongly dependent on the peraluminosity of the melt from which the zircon crystallised (Wang and Trail, 2019).

Experiments and natural observations indicate that peraluminous melts (here defined as those with an aluminum saturation index [ASI = molar $Al_2O_3/(CaO + Na_2O + K_2O)$] > 1 (Shand, 1943) are the product of a limited number of petrogenetic processes. Here, we investigate X_{Al}^{Zrc} from the JH as an indicator of peraluminous melts and relate this to petrogenetic models in the context of geodynamic shifts in the first ~1.5 billion years of Earth's history.

Samples and Results

Zircons were collected from clastic metasedimentary units within the Jack Hills metamorphic belt (Weiss *et al.*, 2015). All zircons were separated from their host rock and mounted in epoxy using previously described techniques (Trail *et al.*, 2017; also see Supplementary Information). Care was taken to ensure the trace element compositions reported for zircons are primary structure bound signatures (*e.g.*, not metamict regions, mineral inclusions, secondary alterations). Data were discarded if: 1) Fe > 100 ppm, 2) analyses outside 100 ± 10 % concordance, and/or 3) light rare earth element index (LREE-I) < 50 (Bell *et al.*, 2019).

The cumulative zircon age distribution is similar to previously reported ages from the JH (*e.g.*, Crowley *et al.*, 2005), with notable age peaks at 3370 and 4050 Ma (Fig. 1). Exceptionally, site T145 contained a high proportion (15.5 %) of unaltered Hadean-aged zircons. Zircon titanium concentrations are similar

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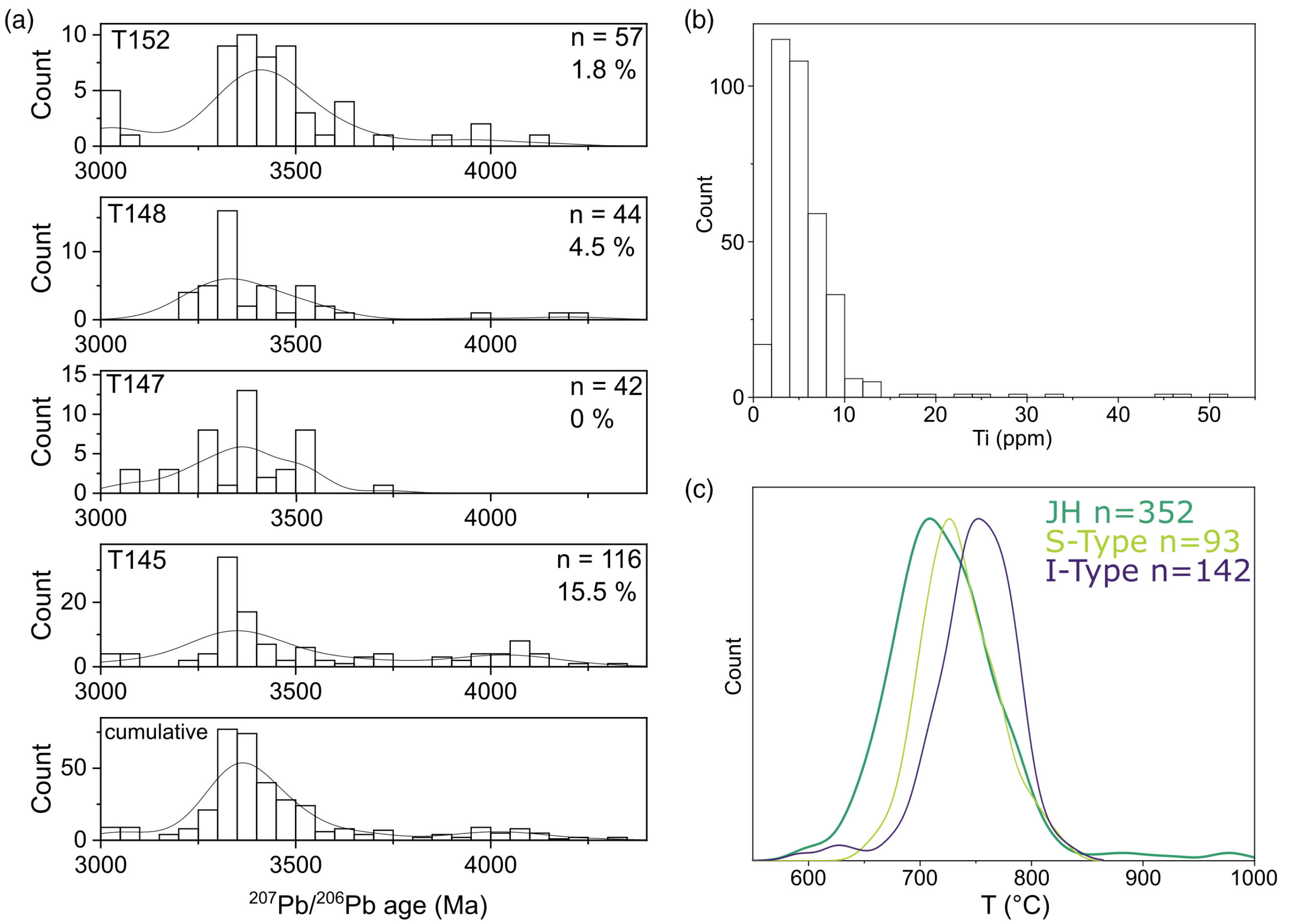

Figure 1 **(a)** $^{207}Pb/^{206}Pb$ JH zircon age distributions from multiple units. **(b)** Ti in JH zircons with **(c)** Ti-in-zircon temperatures, calculated assuming $a_{TiO_2} = 0.5$ and $a_{SiO_2} = 0.8$ (Ferry and Watson, 2007) with zircons from the LFB (Trail *et al.*, 2017).

to other studies of the JH (*e.g.*, Watson and Harrison, 2005), and broadly indicate crystallisation from cool, water saturated intrusive igneous systems (Fig. 1). Age *versus* X_{Al}^{Zrc} (Fig. 2) shows an increase in both the number of high Al (>4 ppm Al) and the average Al content of zircons beginning by ~3.6 Ga (Fig. 2).

Discussion

Al-in-zircon as a proxy for peraluminosity. X_{Al}^{Zrc} is influenced by melt composition, temperature and water content ($Al^{3+} + H^{+} = Si^{4+}$) (Trail *et al.*, 2017; Wang and Trail, 2019). These parameters will co-vary in a magmatic system, and a magmatic liquid cooling along a liquid line of descent will generally increase peraluminosity and water content with decreasing temperature (*e.g.*, Blatter *et al.*, 2013). However, JH zircons record a narrow range of temperatures (Fig. 1). These temperatures indicate crystallisation from a cool, water-rich silicic magma which suggests that variations in water activity play a subordinate role in regulating X_{Al}^{Zrc}. The weak correlation between Al and Ti (Fig. S-5) suggests T also plays a subordinate role to composition in regulating X_{Al}^{Zrc} within this population (Trail *et al.*, 2017). The dominant role of composition is further demonstrated in granitic zircons from the Lachlan Fold Belt (LFB), the type locality of I- and S-type granitic rocks [defined here as granitic rocks known to primarily form through igneous processes (I-type) *versus* those formed to a measurable extent by melting of metasedimentary precursors (S-types); *e.g.*, Chappell, 1999]. It should be noted that I-type magmas are often weakly peraluminous (ASI < 1.1), and as such bulk peraluminosity is not used here to define I- versus S-type magmas. In the LFB, even though Ti content of I-type zircons is slightly higher on average than S-types, the latter have significantly higher X_{Al}^{Zrc} (Fig. S-4)

Increasing peraluminosity results in increased alumina activity and a subsequent increase in X_{Al}^{Zrc}. For granitic zircons of the LFB, X_{Al}^{Zrc} exceeds 4 ppm when the bulk composition becomes peraluminous, likely reflecting this increase in alumina activity in the melt (Trail *et al.*, 2017). We use this 4 ppm value to discriminate between zircons that likely crystallised from peraluminous melts. It is worth noting that ~80 % of JH zircons have Al contents lower than the LFB I-types (Fig. 2b), which reflects the lower crystallisation T observed in the Ti content (Fig. 1c). Thus, this LFB based peraluminosity threshold likely underestimates the number of peraluminous JH zircons.

In the JH, there is a subtle but significant increase in X_{Al}^{Zrc} with decreasing age (Fig. 2b). The >3.8 Ga population yields X_{Al}^{Zrc} similar to I-type granitoids. In the 3.8–3 Ga population, likely peraluminous zircons (>4 ppm Al) have an average $X_{Al}^{Zrc} = 8.5$ ppm compared to $X_{Al}^{Zrc} = 5.5$ ppm in the >3.8 Ga group and $X_{Al}^{Zrc} = 7.8$ ppm in I-types. As the JH is a metasedimentary rock, this increase is akin to sedimentary mixing of metaluminous [ASI < 1, molar $Al_2O_3/(Na_2O + K_2O) > 1$] and peraluminous protoliths seen in modern sedimentary systems (Fig. S-7).

Origin of peraluminous zircons. The limited number of mechanisms to generate peraluminous melts makes their appearance in the JH record a useful event for interpreting

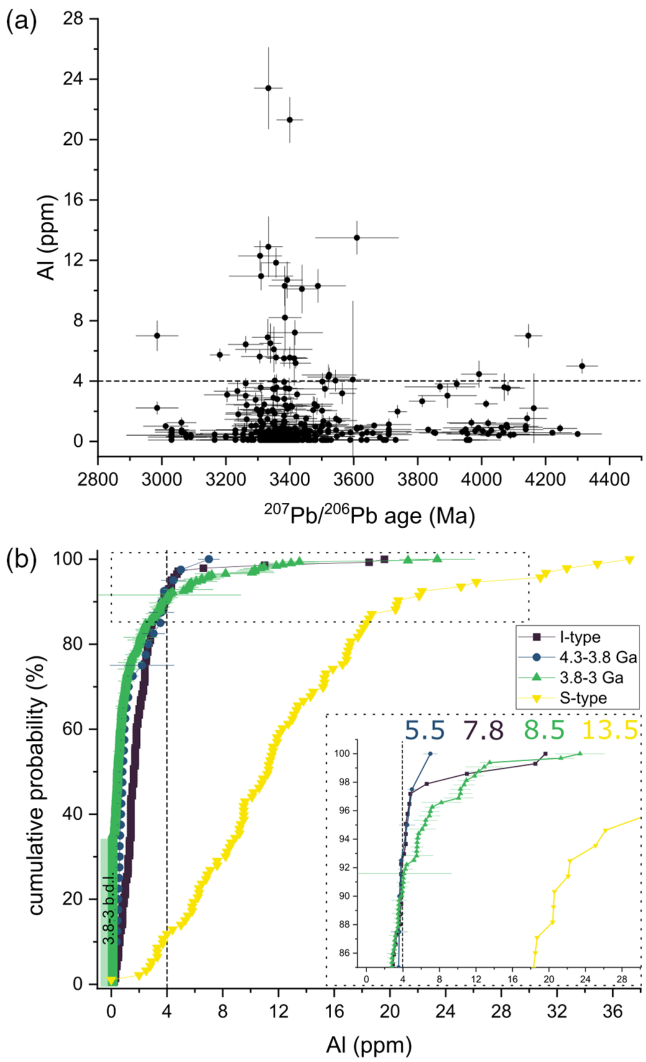

Figure 2 **(a)** Age *versus* Al concentration for JH zircons, error bars are 2σ. Zircons with X_{Al}^{Zrc} below detection limit (b.d.l.) are indicated at base of the diagram. Horizontal dashed line at 4 ppm Al defines zircons that likely formed from peraluminous melts. **(b)** Cumulative probability diagram of I- and S-type LFB (Trail *et al.*, 2017) and age binned JH zircons. Numbers in inset are average X_{Al}^{Zrc} for $X_{Al}^{Zrc} >$ 4 ppm zircon populations from each group.

tectonic shifts on the early Earth. Experiments and investigations of modern magmatic systems have demonstrated multiple mechanisms to produce peraluminous magmas, including: (1) late stage differentiation of silicic "I-type" granitic magmas, (2) melting and incorporation of metasedimentary material, and (3) partial melting or fractionation of hydrous mafic parent material at >7 kbar.

Late stage differentiation of metaluminous I-type bulk compositions can produce weakly peraluminous melts. However, this peraluminosity yields a negligible amount of zircon (Trail *et al.*, 2017). Similarly, I-type systems can also evolve toward weakly peraluminous bulk compositions (Chappell, 1999 and sources therein), but peraluminous I-type zircons have similar compositions to their metaluminous counterparts (Fig. 3).

On Earth today, the most volumetrically significant way to produce strongly peraluminous melts is through melting of weathered sediments (*e.g.*, psammites, metapelites) (Patiño Douce and Johnston, 1991). Based on a P *versus* REE (or Dy) discrimination diagram that records the increase in P content of apatite saturated peraluminous melts, zircons from the Jack Hills have been dismissed as being derived from peraluminous melts (Burnham and Berry, 2017). However, there is significant overlap at low P content between peraluminous S-type and metaluminous and weakly peraluminous I-type granitoids (Fig. 3). Although the JH zircons do not exhibit high P-Dy signals, the overlap at low P content between S-type and I-type zircons makes it difficult to rule out metasediments as a source of some JH zircons, and does not discount previous work suggesting a potential sedimentary source for some JH zircons (Bell *et al.*, 2015).

In lieu of metasediment melting, moderate pressure fractionation of hydrous mafic material could produce peraluminous zircons in excess of those found in modern I-type granitoids. At pressures greater than ~7 kbar, hydrous mafic magmas can produce alumina-rich melts *via* crystallisation of Ca-rich pyroxene and suppression of plagioclase crystallisation (Müntener and Ulmer, 2006; Blatter *et al.*, 2013), and at pressures within the garnet stability field (≥10 kbar), incongruent melting of amphibole and biotite in metaluminous bulk compositions can produce alumina-rich melts and pyroxene (Chappell *et al.*, 2012). These moderate pressure processes lead to the generation of peraluminous melts at lower bulk SiO_2 (~60 wt. % SiO_2 *versus* ~70 wt. % SiO_2) than modern arcs magmas (Fig. 4), which in turn could yield a higher proportion of peraluminous zircons than modern arcs.

Implications for early Earth geodynamics. The distribution of X_{Al}^{Zrc} of JH zircons >3.8 Ga is similar to modern I-type magmas (Fig. 2), whose intermediate compositions overlap in SiO_2-ASI space with >4 Ga granitoids from the Acasta Gneiss Complex (AGC) that have been interpreted as crystallising from an environment akin to modern oceanic plateaus (Reimink *et al.*, 2014) at 3–4 kbar (Fig. 4). On the ancient Earth, this is consistent with crystallisation in a vertical tectonic regime prior to 3.8 Ga, and is further supported by other chemical similarities between pre-4 Ga AGC and JH zircons (Reimink *et al.*, 2019a).

Pre- and post-3.8 Ga JH and I-type populations cross the 4 ppm Al threshold at roughly the same cumulative probability (~90 %). However, the average Al content of the likely peraluminous post-3.8 Ga zircons is greater than either the pre-3.8 or I-type populations. This potentially indicates a different and strongly peraluminous source to the 3.8–3 Ga group. Regardless of whether the peraluminous zircons are derived from metasedimentary sources or moderate high pressure fractionation processes, both scenarios likely require a geodynamic shift toward horizontal tectonics. For sediment melting, weathered continental material is required to be brought to depths great enough to be melted. For deep mafic melting, hydrated near surface mafic material needs to be brought to moderate pressures (≥7 kbar) in order to melt and fractionate. Although it is possible for hydrated mafic material to be brought to depths through vertical tectonic processes, the relative short timescales invoked to account for the shift in ε^{176}Hf observed from JH and other ancient zircons (Bauer *et al.*, 2020), similarities in trace element content between JH and AGC zircons (Reimink *et al.*, 2019a), and the onset of peraluminosity indicate a shift toward a horizontal tectonic regime.

Whereas peraluminous granitic rocks dominate the bedrock geology in the AGC at ~3.6 Ga (Reimink *et al.*, 2019b), the peraluminous zircons that emerge in the JH record at ~3.6 Ga are only a fraction of the total zircon population (~10 %). This could indicate preservation bias of the peraluminous rocks of the AGC, preservation of more diverse protoliths in the detrital JH zircons, or a globally heterogeneous distribution of crust-forming processes *ca.* 3–3.6 Ga. Regardless, the emergence of significant peraluminous zircons in the JH conforms with observations from other ancient crustal systems (*e.g.*,

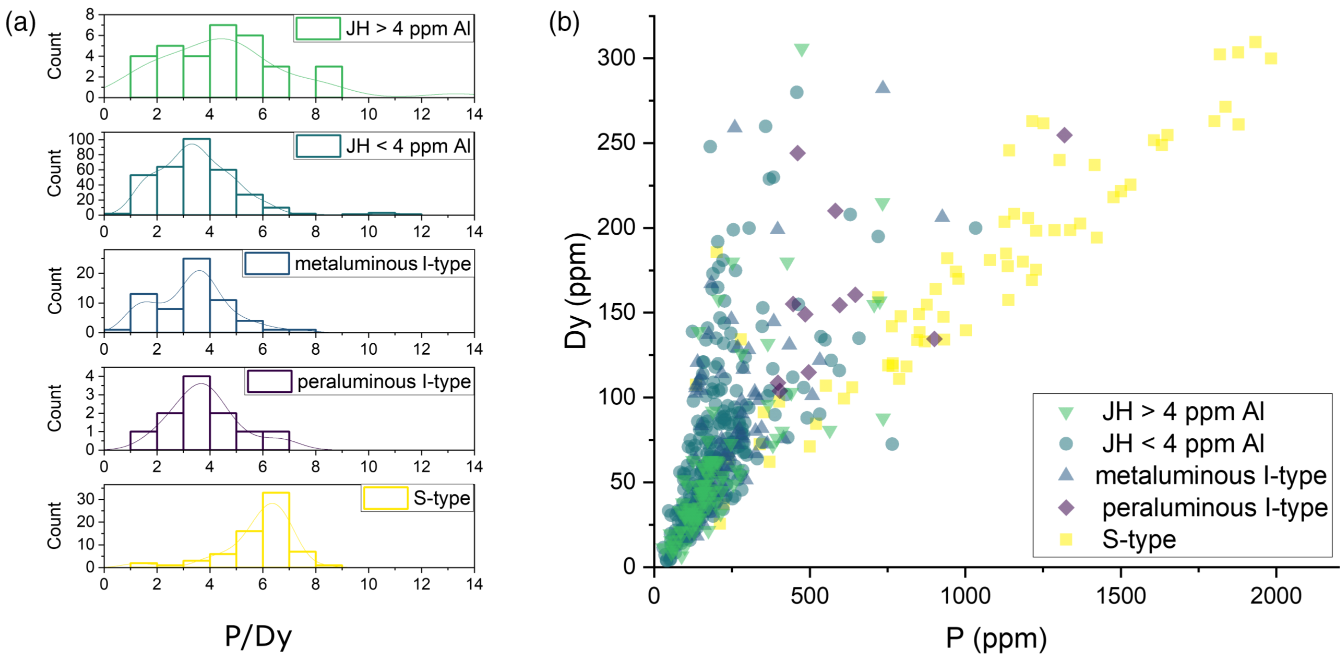

Figure 3 **(a)** Histograms of P/Dy ratios and **(b)** scatterplot of P and Dy concentrations in zircons from I-type and S-type LFB granitoids compared with likely peraluminous ($X_{Al}^{Zrc} > 4$ ppm) and non-peraluminous JH zircons. On the whole, peraluminous zircons from the JH have higher P/Dy ratios than non-peraluminous JH, and their median value of P/Dy is higher than that of peraluminous I-types. LFB data from (Burnham and Berry, 2017).

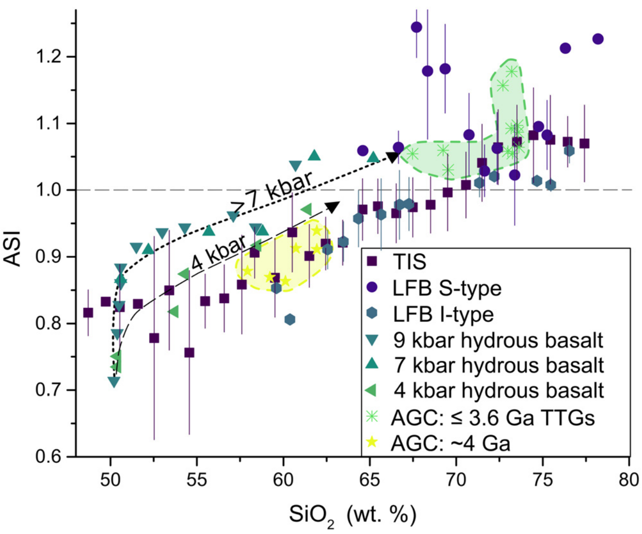

Figure 4 SiO_2 *versus* ASI for common magmatic rocks and melts. LFB and Tuolumne Intrusive Suite (TIS) intrusive rocks binned in 1 wt. % SiO_2 increments, error bars are 1σ. I-type granitic rocks from the LFB (Griffin *et al.*, 1978; Chappell and White, 1992) and intrusive rocks from the TIS (Bateman *et al.*, 1984; Ratajeski *et al.*, 2001) become peraluminous at ~70 wt. % SiO_2, whereas hydrous basalts fractionated at depths ≥7 kbar can produce melts that become peraluminous at ~60 wt. % SiO_2, unlike those fractionated at lower pressures (Blatter *et al.*, 2013).

AGC, Pilbara Craton; Bauer *et al.*, 2020) of a geodynamic shift toward horizontal tectonics by at least ~3.6 Ga.

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Additional Information

Supplementary Information accompanies this letter at https://www.geochemicalperspectivesletters.org/article2114.

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