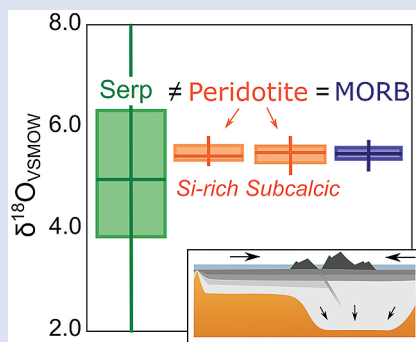# An oxygen isotope test for the origin of Archean mantle roots

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Abstract

The origin of the peridotites that form cratonic mantle roots is a central issue in understanding the history and survival of Earth's oldest continents. A long-standing hypothesis holds that the unusual bulk compositions of some cratonic peridotites stem from their origin as subducted oceanic serpentinite, dehydrated during subduction to form rigid buoyant keels (Schulze, 1986; Canil and Lee, 2009). We present oxygen isotope data from 93 mantle peridotites from five different Archean cratons to evaluate their possible origin as serpentinites. Cratonic mantle peridotite shows remarkably uniform $\delta^{18}O$ values, identical to modern MORB-source mantle, that do not vary with bulk rock Si-enrichment or Ca-depletion. These data clearly conflict with any model for cratonic lithosphere that invokes serpentinite as a protolith for cratonic peridotite, and place additional constraints on cratonic mantle origins. We posit that the uniform $\delta^{18}O$ was produced by sub-arc and/or MOR depletion processes and that the Si-enriched nature of some samples is unlikely to be related to slab melt infiltration. Instead, we suggest a peridotitic source of Si-enrichment, derived from ascending mantle melts, or a water-fluxed depleted mantle. These variably Si-enriched, cratonic mantle protoliths were then collisionally compressed into the thick cratonic roots that have protected Earth's oldest continental crust for over 2.5 Gyr.

Models of Craton Formation

An essential element to the study of the growth and longevity of Earth's continental crust is the origin of the chemically buoyant and rigid lithospheric mantle that underpins ancient continental cratons. The vast majority of geochemical evidence for the origin of cratonic peridotites supports initial melt extraction at pressures ≤5 GPa, with most melting occurring in the spinel stability field. This depletion in a shallow, spinel-bearing environment is indicated by low concentrations of mildly incompatible elements and the Cr-rich nature of garnet in cratonic peridotites (Stachel *et al.*, 1998; Canil, 2004; Brey and Shu, 2018). If a moderate to low pressure origin is accepted, then two end member models remain. The first model (Fig. 1a) invokes the successive imbrication of subducted oceanic litho-sphere (*e.g.*, Helmstaedt and Schulze, 1989; Pearson and Wittig, 2008). The second model – collisional compression *via* pure shear (Fig. 1b) - proposes that depleted mantle protoliths from Neoarchean sub-arc settings and/or in hot spreading centres are tectonically amalgamated, compressed, and gravitationally thickened during cooling (Jordan, 1978; Lee *et al.*, 2011; Wang *et al.*, 2016). The serpentinite-like major element signatures of

some peridotites (Si-enriched bulk rock and subcalcic garnets) have been used to support the imbrication of hydrated oceanic lithosphere (Schulze, 1986; Canil and Lee, 2009). However, these cratonic peridotites have not been systematically tested for the distinctive oxygen isotopic ratios that are characteristic of serpentinites. Here, we search for these distinctive isotopic signatures in mantle-derived cratonic xenoliths.

Approach and Results

To characterise the oxygen isotopic composition of cratonic mantle peridotites we present ion microprobe analyses (Supplementary Information) of olivines from coarse, "low-temperature" peridotite xenoliths (Table S-1), thought to represent the bulk of the cratonic lithospheric mantle. The sample suite is derived from the Slave, Rae, North Atlantic, Kaapvaal, and Siberian Archean cratons, and excludes cratonic peridotites that were modified after emplacement by high temperature deformation and melt metasomatism. We also report precise laser fluorination and ion probe measurements on cratonic mantle orthopyroxene (Opx) as well as olivine from forearc peridotites.

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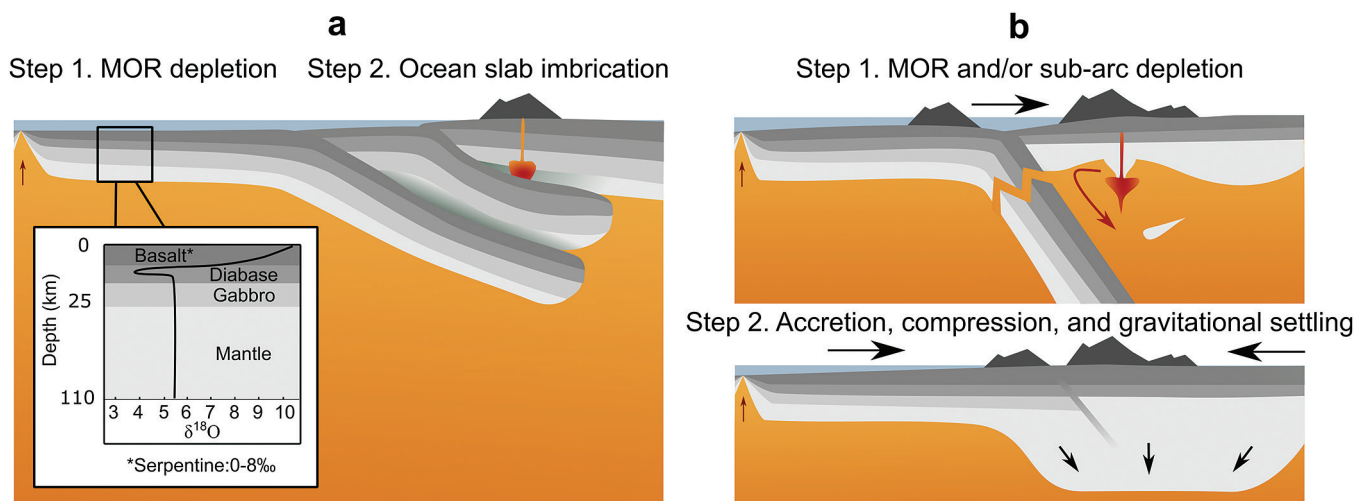* Corresponding author (email: margoregier@gmail.com)

Figure 1 Popular models of cratonic mantle formation. **(a)** Imbrication of MOR sequences to form a thick lithosphere. An estimated oxygen isotope profile through Neoarchean oceanic lithosphere is inset. **(b)** Depleted cratonic mantle protoliths produced at MOR and in sub-arc environments are compressed *via* pure shear into a thick lithospheric root.
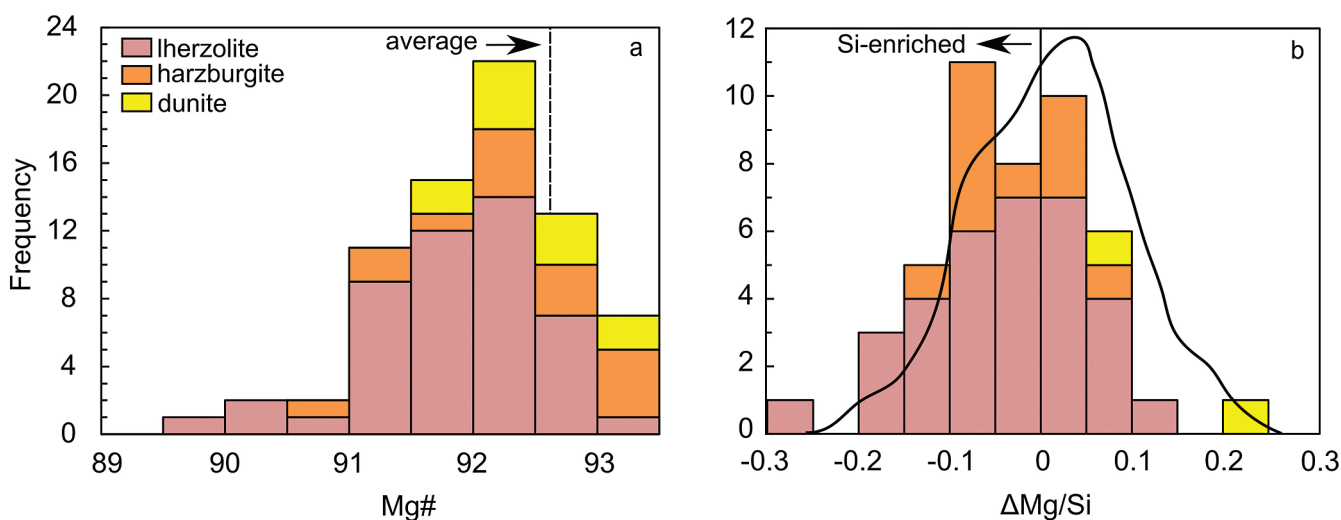

Figure 2 **(a)** Mg# histogram of olivines in this study. Mg#s are both more and less depleted than the worldwide average for olivine in cratonic peridotite, denoted by the dotted line (Pearson and Wittig, 2008). **(b)** ΔMg/Si histogram of samples compared to a vertically unscaled probability density function for worldwide cratonic mantle xenoliths from Canil and Lee (2009). Negative ΔMg/Si designates Si-enriched lithologies.

Our samples span both sides of the average cratonic mantle olivine Mg# (molar Mg/Mg+Fe) of 92.6 (Fig. 2a). A subset of our samples are Si-enriched, manifested as high bulk rock SiO_2 and elevated modal Opx contents. We adopt the ΔMg/Si parameter of Canil and Lee (2009) to quantify Si-enrichment (Fig. 2b), where negative ΔMg/Si denotes Si-enriched, or a lower Mg/Si and Al/Si than can be produced by experimental partial melts of peridotite.

Our measurements reveal that cratonic mantle olivines are normally distributed (Shapiro-Wilk W = 0.99, p = 0.52) over an extremely restricted $\delta^{18}O$ range of +5.01 to +5.53 ‰, with a mean of 5.26 ± 0.22 ‰ (2σ). There are no statistically significant deviations in $\delta^{18}O$ with chemical proxies (Fig. S-1). Additionally, cratonic mantle Opx from variably Si-enriched xenoliths (Table S-2; mean $\delta^{18}O$ of 5.74 ± 0.27 ‰) are in isotopic equilibrium with associated olivine ($\alpha_{enstatite–olivine}$ at 1300 °C = ~0.5 ‰; Rosenbaum *et al.*, 1994).

In order to determine if there are crustal sources of oxygen in the cratonic mantle, we compare our dataset to the well-defined MORB-source mantle (Fig. S-1). We adjust our olivine $\delta^{18}O$ to whole rock peridotite values using a fractionation factor that accounts for the ultramafic composition. Oxygen isotope fractionation between an ultramafic peridotitic mantle source and olivine at high mantle temperatures has been estimated at ~0.2 ‰ (Valley *et al.*, 1998), based on a basalt-olivine fractionation of 0.32 ‰ at 1300 °C (Eiler *et al.*, 2000) and the positive correlation between melt SiO_2 and $D_{melt-olivine}$ (Eiler, 2001). A bootstrapped Kolmogorov-Smirnov (K-S) statistical evaluation of the MORB dataset and the 0.2 ‰ fractionation-corrected cratonic mantle olivines indicates that they are statistically indistinguishable (D = 0.11, p = 0.57), with both populations having analytical uncertainties equal to or larger than the population variance. In contrast, serpentinised peridotite and cratonic mantle olivine have clearly distinct distributions (D = 0.54, p << 0.05; Fig. 3a).

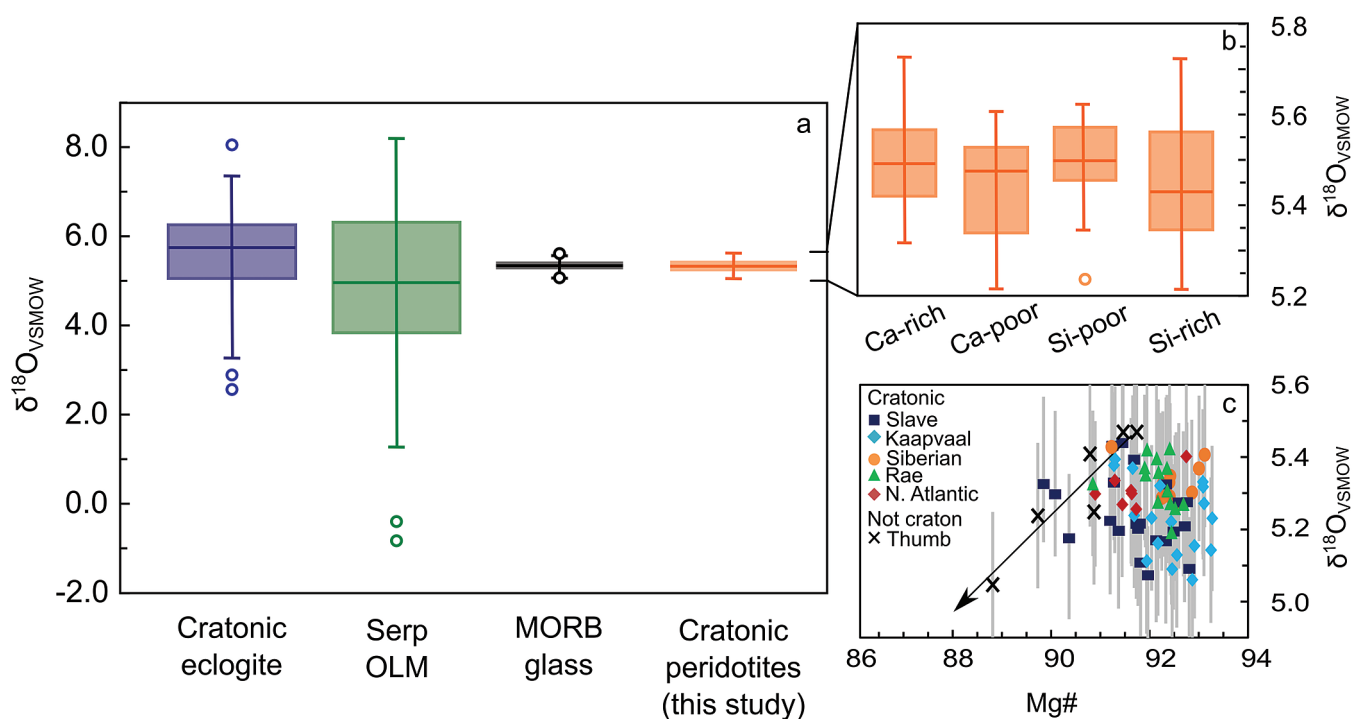**Figure 3**   **(a)** Box-whisker plot of the oxygen isotopic composition of cratonic peridotites, calculated from olivine $\delta^{18}O$, compared to eclogitic xenoliths, serpentinised oceanic lithospheric mantle (OLM), and MORB glass (Supplementary Information). **(b)** A box-whisker plot of peridotite $\delta^{18}O$, divided into statistically insignificant chemical discriminators – Ca-rich (lherzolitic), Ca-poor (harzburgitic/dunitic) and Si-enriched (-ΔMg/Si) and depleted lithologies (+ΔMg/Si), demonstrates that there is no variation in the distribution of oxygen isotopes with bulk rock chemistry. **(c)** Scatter plot of olivine $\delta^{18}O$ and Mg#. The lack of correlation in the cratonic mantle suite contrasts to the trendline of The Thumb xenoliths (r^2 = 0.86).

Implications for Craton Formation

The striking similarity between oxygen isotope compositions of present day MORB and Archean cratonic peridotites documents the stability of the $\delta^{18}O$ of Earth's mantle over a 3 billion year interval. Despite this, the diverse $\delta^{18}O$ values of cratonic eclogite xenoliths demonstrate that $\delta^{18}O$ heterogeneities in the subcontinental lithospheric mantle can persist even at the metre scale, likely due to the slow diffusion of oxygen. Since hydrothermal alteration, or the serpentinisation of ultramafic rocks, is an effective method of producing highly variable $\delta^{18}O$ (Wenner and Taylor, 1971), cratonic mantle olivines derived by prograde metamorphism of serpentinite (Canil and Lee, 2009) should retain both serpentinite-like major element chemistry and distinct oxygen isotopic compositions (Fig 3a).

In contrast to the extreme $\delta^{18}O$ variability of Phanerozoic serpentinite (0 to +8 ‰; Fig. 3a), cratonic peridotitic olivines are strikingly uniform, even over the full compositional range typical for Archean lithospheric mantle. Olivines co-existing with subcalcic garnets and from Si-enriched peridotites - proposed signatures of a serpentinite origin (Schulze, 1986; Canil and Lee, 2009) - have oxygen isotope compositions that are statistically indistinguishable from normal upper mantle (Fig. 3b). A key piece of evidence previously used in support of the meta-serpentinite hypothesis was a reported correlation between $\delta^{18}O$ and Mg/Si from Colorado Plateau peridotitic xenoliths (Canil and Lee, 2009). We note that this Proterozoic terrane is not under-pinned by an Archean cratonic root, and shows clear evidence of hydrous weakening and thinning (Li *et al.*, 2008). Furthermore, our replotting of these data resolves a correlation (r^2 = 0.89) between $\delta^{18}O$ and Mg# (Fig. 3c). This trend is not consistent with a metaserpentinite origin, as serpentine minerals are commonly higher in Mg# than the initial olivine and Opx that they replace (Evans, 2008). Therefore, these samples likely do not represent the products of

seafloor alteration processes (Canil and Lee 2009), but may instead be a consequence of the water-rich metasomatism of the Colorado Plateau lithospheric mantle by Si-enriched fluids or melts from the low-angle subducting Farallon Plate at 80-35 Ma (Li *et al.*, 2008). Finally, as the narrow variance in Archean cratonic mantle peridotite is statistically equivalent to that of MORB, there is no evidence for even small inputs of meta-serpentinite. Hence, meta-serpentinite is an unlikely protolith to the peridotitic root of the Colorado Plateau, and can be rejected as a protolith for Archean cratonic mantle.

While the Colorado Plateau lithosphere is not a good proxy for pristine cratonic mantle, it is a geometric analogue for the Archean slab imbrication model. The low angle subduction that occurred underneath the Colorado Plateau in the Cretaceous to Eocene likely injected slab melts/fluids directly into the overlying lithospheric mantle, offsetting $\delta^{18}O$, ΔMg/Si, and Mg#. The similar geometry required for the Archean slab imbrication model would likely produce the same geochemical traces in cratonic mantle olivine. Since our extensive suite of cratonic mantle olivines does not show "Colorado Plateau-like" systematics (between $\delta^{18}O$ and metasomatic proxies - ΔMg/Si or Mg#; Figs. 3c, S-2), it is unlikely that cratonic mantle thickening occurred by slab imbrication. This lack of a crustal alteration signature would be in line with suggestions of higher pressure melting in plumes, but such a model can be rejected from other considerations that place melt depletion in the spinel stability field (see discussion in Introduction). Instead, we hypothesise that cratonic mantle protoliths were initially depleted at MOR and/or at water fluxed sub-arc mantle wedges, environments that produce material with canonical mantle-like $\delta^{18}O$ (Table S-3). These protoliths were then thickened, without significant isotopic modification, by pure shear compression to form cratonic mantle roots (Jordan, 1978; McKenzie and Priestley, 2016; Wang *et al.*, 2016).
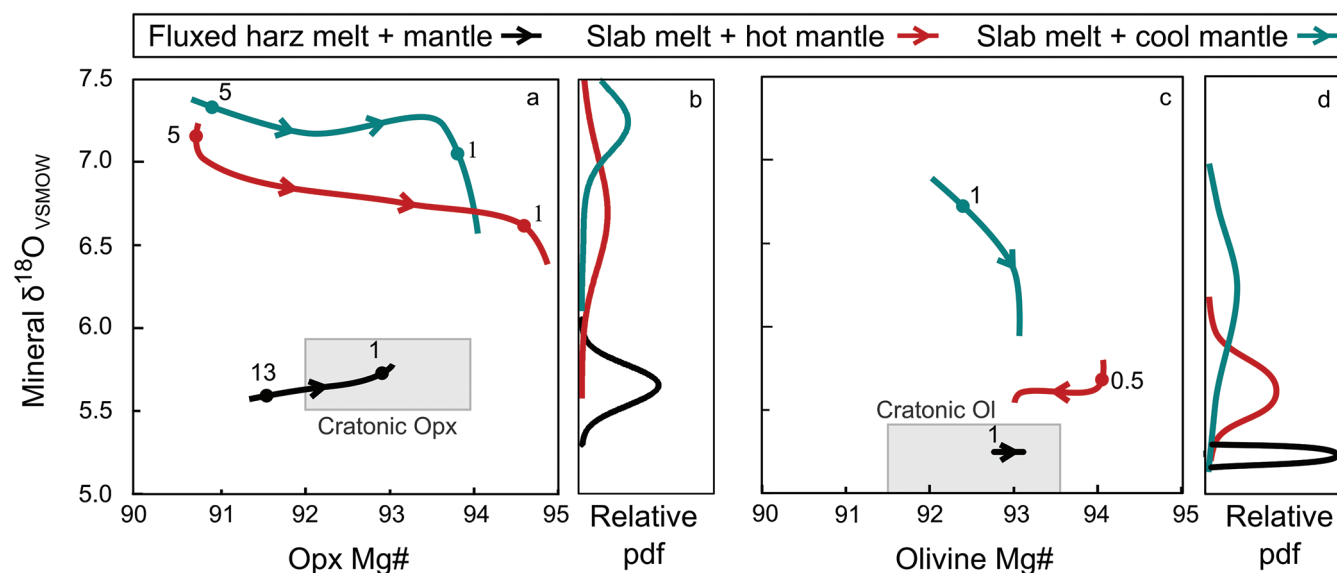
Figure 4   pMELTS modelling of slab melts ($\delta^{18}O$ of +8 ‰) reacting with 900 °C (blue) and 1500 °C (red) harzburgite, as well as a water-fluxed harzburgitic (harz) melt ($\delta^{18}O$ of +5.6 ‰) reacting with 1300 °C harzburgite (black). The major element and isotopic evolution of crystallising Opx **(a)** and olivine **(c)** is indicated by smoothed curves. Numbers indicate the slab melt/assimilated peridotite ratio. Typical cratonic mantle Opx and olivine (Ol) is outlined in gray fields. Relative Kernel estimations of the probability density function (pdf) for Opx **(b)** and olivine **(d)** $\delta^{18}O$ are included.

While our data is consistent with the construction of cratons by collisional compression of un-altered, depleted peridotite protoliths, we still require a means to enrich these regions heterogeneously in high-Si Opx. Many explanations for cratonic mantle Opx enrichment rely on the infiltration of slab derived melts (*e.g.,* Rudnick, 1994; Kelemen *et al.,* 1998). However, lithosphere that has been thinned by crustal melt infiltration is marked by low Mg# and exotic $\delta^{18}O$ (Wang *et al.,* 2018). Using pMELTS isenthalpic modelling (Ghiorso *et al.,* 2002) of assimilation-fractional crystallisation (AFC) for 100 g of slab melt at 3 GPa, we demonstrate that these melts fractionate garnet at slab melt/assimilated rock ratios of >5, followed by Opx (ratios of 1-5), and olivine, once the melt SiO_2 drops to ~50 wt. % (ratios of <1). Given the low MgO and FeO of experimentally-derived slab melts (Table S-4), high Mg# minerals crystallise after minimal assimilation of peridotite. However, producing mantle-like $\delta^{18}O$ is more difficult (Fig. 4). Mass balance calculations that include fractionation factors (Eiler, 2001) and the compositional and mineralogical outputs of pMELTS (Table S-4), indicate that at the required melt/rock ratios, $\delta^{18}O$ of Opx and olivine remains higher than mantle. Even melts with modest initial $\delta^{18}O$ (*e.g.,* $\delta^{18}O$ of +4.0 or +6.5 ‰) cease to crystallise Opx before mantle-like $\delta^{18}O$ is achieved, due to low melt SiO_2 (<50 wt. %). Since the measured $\delta^{18}O$ of olivine and Opx from Si-enriched cratonic peridotites do not reflect those modelled in slab melt AFC models, we do not support the slab melt infiltration hypothesis for Si-enrichment.

Since Si-enrichment cannot be achieved by eclogite-derived melts and, as previously discussed in the Introduction, does not show evidence for a high pressure origin, we instead suggest two possible low pressure origins: 1) asthenospheric melts that have become Si-enriched due to the assimilation of wall rock pyroxene and fractionation of olivine during ascent (Kelemen *et al.,* 1992), or 2) the infiltration of moderately Si-rich melts (~56 wt. %) produced from the melting of a depleted harzburgitic mantle fluxed with ~2.5 wt. % H_2O from a devolatilising slab (Mitchell and Grove, 2015). When 100 g of this +5.6 ‰ harzburgitic melt is input into our AFC model, it crystallises Opx and olivine with cratonic mantle-like Mg# and $\delta^{18}O$ (Fig. 4). The proportion of precipitating Opx, and thus, the Si-enrichment of the surrounding rock, is dependent on the evolving melt-rock ratio. The final stage of thickening, *via* collisional compression of this heterogeneously Si-enriched material, leads to a cratonic mantle root with variable Opx content, but homogeneous oxygen isotopes.

In summary, the $\delta^{18}O$ homogeneity of a wide range of cratonic mantle peridotites demonstrates that their variably Si-enriched, sometimes subcalcic garnet-bearing nature, cannot have been inherited from protoliths that experienced seafloor serpentinisation (*e.g.,* Schulze, 1986; Canil and Lee, 2009). Instead, these peridotites must have 1) lain at depths in the oceanic lithosphere where circulating water was minimal and 2) avoided extensive metasomatism from imbricating oceanic lithosphere. Based on these observations, we suggest that cratonic mantle must have been depleted either in thick Archean MOR sequences (Herzberg and Rudnick, 2012) or in sub-arc fluxed mantle wedges (Parman *et al.,* 2004). The redistribution of Si with mantle-like $\delta^{18}O$ was caused by peridotite-derived melt percolation. Finally, these buoyant, depleted proto-cratonic peridotites were thickened by collisional compression (Wang *et al.,* 2016) into the roots that have protected Earth's >2.5 billion year old crust.

Additional Information

Supplementary Information accompanies this letter at http://www.geochemicalperspectivesletters.org/article1830.

References

Brey, G.P., Shu, Q. (2018) The birth, growth and ageing of the Kaapvaal subcratonic mantle. *Mineralogy and Petrology* 1–19.

Canil, D. (2004) Mildly incompatible elements in peridotites and the origins of mantle lithosphere. *Lithos* 77, 375–393.

Canil, D., Lee, C.-T.A. (2009) Were deep cratonic mantle roots hydrated in Archean oceans? *Geology* 37, 667–670.

Eiler, J.M. (2001) Oxygen Isotope Variations of Basaltic Lavas and Upper Mantle Rocks. *Reviews in Mineralogy and Geochemistry* 43, 319–364.

Eiler, J.M., Crawford, A., Elliott, T., Farley, K.A., Valley, J.W., Stolper, E.M. (2000) Oxygen Isotope Geochemistry of Oceanic-Arc Lavas. *Journal of Petrology* 41, 229–256.

Evans, B.W. (2008) Control of the Products of Serpentinization by the $Fe2+Mg-1$ Exchange Potential of Olivine and Orthopyroxene. *Journal of Petrology* 49, 1873–1887.

Ghiorso, M.S., Hirschmann, M.M. Riners, P.W., Kress, V.C. (2002) The pMELTS: A revision of MELTS for improved calculation of phase relations and major element partitioning related to partial melting of the mantle to 3 GPa. *Geochemistry, Geophysics, Geosystems* 3, 1–36.

Helmstaedt, H., Schulze, D.J. (1989) Southern African kimberlites and their mantle sample: Implications for Archean tectonics and lithosphere evolution. *Kimberlites and Related Rocks* 1, 358–368.

Herzberg, C., Rudnick, R. (2012) Formation of cratonic lithosphere: An integrated thermal and petrological model. *Lithos* 149, 4–15.

Jordan, T.H. (1978) Composition and development of the continental tectosphere. *Nature* 274, 544–548.

Kelemen, P.B., Dick, H.J.B., Quick, J.E. (1992) Formation of harzburgite by pervasive melt/rock reaction in the upper mantle. *Nature* 358, 635–641.

Kelemen, P.B., Hart, S.R., Bernstein, S. (1998) Silica enrichment in the continental upper mantle via melt/rock reaction. *Earth and Planetary Science Letters* 164, 387–406.

Lee, C.-T.A., Luffi, P., Chin, E.J. (2011) Building and Destroying Continental Mantle. *Annual Review of Earth and Planetary Sciences* 39, 59–90.

Li, Z.-X.A., Lee, C.-T.A., Peslier, A.H., Lenardic, A., Mackwell, S.J. (2008) Water contents in mantle xenoliths from the Colorado Plateau and vicinity: Implications for the mantle rheology and hydration-induced thinning of continental lithosphere. *Journal of Geophysical Research* 113, 1–22.

McKenzie, D., Priestley, K. (2016) Speculations on the formation of cratons and cratonic basins. *Earth and Planetary Science Letters* 435, 94–104.

Mitchell, A.L., Grove, T.L. (2015) Melting the hydrous, subarc mantle: the origin of primitive andesites. *Contributions to Mineralogy and Petrology* 170, 13.

Parman, S.W., Grove, T.L., Dann, J.C., de Wit, M.J. (2004) A subduction origin for komatiites and cratonic lithospheric mantle. *South African Journal of Geology* 107, 107–118.

Pearson, D.G., Wittig, N. (2008) Formation of Archaean continental lithosphere and its diamonds: the root of the problem. *Journal of the Geological Society* 165, 895–914.

Rosenbaum, J.M., Kyser, T.K., Walker, D. (1994) High temperature oxygen isotope fractionation in the enstatite-olivine-BaCO3 system. *Geochimica et Cosmochimica Acta* 58, 2653–2660.

Rudnick, R.L. (1994) Northern Tanzanian peridotite xenolith: a comparison with Kaapvaal peridotites and evidence for carbonatite interaction with ultra-refractory residues. *Proceedings of the 5th International Kimberlite Conference*, 336–353.

Schulze, D.J. (1986) Calcium anomalies in the mantle and a subducted meta-serpentinite origin for diamonds. *Nature* 319, 483–485.

Stachel, T., Viljoen, K.S., Brey, G., Harris, J.W. (1998) Metasomatic processes in lherzolitic and harzburgitic domains of diamondiferous lithospheric mantle: REE in garnets from xenoliths and inclusions in diamonds. *Earth and Planetary Science Letters* 159, 1–12.

Valley, J.W., Kinny, P.D., Schulze, D.J., Spicuzza, M.J. (1998) Zircon megacrysts from kimberlite: oxygen isotope variability among mantle melts. *Contributions to Mineralogy and Petrology* 133, 1–11.

Wang, C.-G., Xu, W.-L., Yang, D.-B., Liu, Y.-S., Pei, F.-P., Li, Q.-L., Zhou, Q.-J. (2018) Olivine Oxygen Isotope Evidence for Intracontinental Recycling of Delaminated Continental Crust. *Geochemistry, Geophysics, Geosystems* 19, 1–12.

Wang, H., van Hunen, J., Pearson, D.G. (2016) Making Archean cratonic roots by lateral compression: A two-stage thickening and stabilization model. *Tectonophysics,* doi: 10.1016/j.tecto.2016.12.001.

Wenner, D.B., Taylor, H.P. (1971) Temperatures of serpentinization of ultramafic rocks based on O18/O16 fractionation between coexisting serpentine and magnetite. *Contributions to Mineralogy and Petrology* 32, 165–185.