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# Long-lasting viscous drainage of eclogites from the cratonic lithospheric mantle after Archean subduction stacking

Zhensheng Wang[1]*, Timothy M. Kusky[1,2]* and Lu Wang[1]

[1]State Key Laboratory of Geological Processes and Mineral Resources, and Center for Global Tectonics, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China

[2]Three Gorges Research Center for Geohazards, China University of Geosciences, Wuhan 430074, China

## ABSTRACT

**The origin of early continental lithosphere is enigmatic. Characteristics of eclogitic components in the cratonic lithospheric mantle (CLM) indicate that some CLM was likely constructed by stacking of subducted oceanic lithosphere in the Archean. However, the dynamic process of converting high-density, eclogite-bearing subducted oceanic lithosphere to buoyant CLM remains unclear. We investigate this process through numerical modeling and show that some subducted and stacked eclogites can be segregated into the asthenosphere through an episodic viscous drainage process lasting billions of years. This process increases the chemical buoyancy of the CLM, stabilizes the CLM, and promotes the preservation and redistribution of the eclogites in the CLM, explaining the current status of early subduction relicts in the CLM revealed by geophysical and petrological studies. Our results also demonstrate that the subduction stacking hypothesis does not conflict with the longevity of CLM.**

## INTRODUCTION

The origin of cratonic lithospheric mantle (CLM) remains controversial (Lee et al., 2011; Herzberg and Rudnick, 2012). Cratonization and craton growth by subduction stacking in Archean suture zones (Fig. 1), where oceanic mantle and crust are stacked beneath growing lithosphere (Helmstaedt and Schulze, 1989; Kusky, 1993), is suggested by petrological and geochemical observations (Lee et al., 2011; Herzberg and Rudnick, 2012). This hypothesis is also supported by geophysically detected subduction-related dipping structures in many continental regions of Archean to Phanerozoic age (Calvert et al., 1995; Bostock, 1998; Humphreys et al., 2015) and is further confirmed by some deep-seated eclogites, transformed from oceanic crust at depths $>\sim 45$ km (1.2 GPa), showing subduction-related low-pressure origins and/or geochemical features of seawater alteration (Jacob, 2004). With the addition of new evidence from geophysics, petrology, and geochemistry (e.g., Kopylova et al., 2016; Aulbach et al., 2020; Smart et al., 2021), the subduction stacking hypothesis has become increasingly the most reasonable model for craton growth, as supported by multi- and cross-disciplinary data sets.

However, this hypothesis only describes the initial static status of slab stacking, in which large volumes of oceanic crust are transformed to high-density eclogites (Helmstaedt and Schulze, 1989) in dipping layers and are distributed from the top to the base of the CLM with approximately equal abundance (Fig. 1). This limits the acceptability of the hypothesis because these predictions are not in all cases consistent with the presently observed abundance and distribution of CLM eclogites (Kopylova et al., 2016; Aulbach et al., 2020), which represent products of the initial stacking plus the results of billions of years of geodynamic evolution. For instance, eclogites in some cratons are estimated to be mainly concentrated at specific depths (Kopylova et al., 2016; Aulbach et al., 2020) and are not all correlated with detected dipping geophysical anomalies (Kopylova et al., 2016). Thus, if the CLM was constructed by subduction stacking, the billions of years of dynamic evolution after CLM formation is non-negligible and may have changed the initial geometry of slab stacking, removing or redistributing the eclogites in the CLM.

Previous research has been mainly on eclogites in the lower crust, which sink rapidly through the more buoyant mantle peridotites by virtue of their negative buoyancy (e.g., van Thienen et al., 2004; Percival and Pysklywec, 2007; Johnson et al., 2013; Sizova et al., 2015; Fischer and Gerya, 2016; Piccolo et al., 2019). Eclogites subducted to CLM depths are speculated to have similar potential to generate lithospheric sinking and removal (Lee et al., 2011; Herzberg and Rudnick, 2012), thus preserving few eclogites, in contrast with their common occurrence in CLM xenoliths (Kopylova et al., 2016; Aulbach et al., 2020). Recent studies have started to specifically focus on the sinking of eclogite and its preservation in the CLM via simple dynamic modeling but with very limited temporal and spatial resolution (Luo and Korenaga, 2020). Thus, the continuous evolution of eclogite removal and redistribution and their influences on CLM thickness and stability are actually not modeled (Luo and Korenaga, 2020) yet are the most problematic issues with the slab-stacking hypothesis (Lee et al., 2011; Herzberg and Rudnick, 2012). We use two-dimensional geodynamic numerical modeling via the Underworld2 finite-element code (Moresi et al., 2003; https://underworld2.readthedocs.io/en/latest/) to investigate these fundamental questions, combining different geological and physical conditions in the Archean. This allows us to reproduce Archean slab-stacking behaviors revealed by previous studies (Kusky, 1993; Calvert et al., 1995) and quantitively assess the evolution of eclogites and lithospheric thickness for billions of years to compare with geological and geophysical observations.

## NUMERICAL MODELS AND RESULTS

All our models contain two convergent plates (Fig. 2) overlying an Archean ambient mantle with different mantle potential temperatures ($T_p$) higher than at present ($\Delta T_p = 135$–$250$ K in different models) (Herzberg et al., 2010; Ganne and

*E-mails: jasonwang@cug.edu.cn; tkusky@gmail.com

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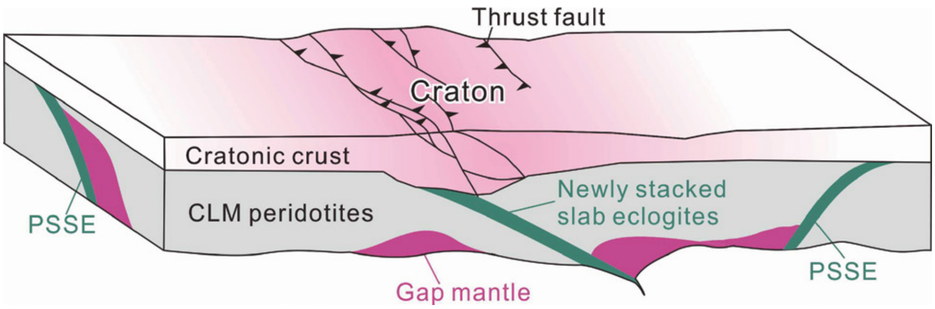


**Figure 1. Conceptual model for construction of cratonic lithosphere via Archean subduction stacking (Helmstaedt and Schulze, 1989; Kusky, 1993). Domains with dark green color are newly or previously stacked slab eclogites (PSSE); those with light gray color are cratonic lithospheric mantle (CLM) peridotites. Gap mantle is made up of asthenospheric, mantle wedge, or arc materials.**

Feng, 2017) under secular cooling (Wang et al., 2018). The pro-plate contains a leading oceanic slab and a trailing cratonic block, whereas the retro-plate contains a cratonic block. The two cratonic blocks are composed of upper crust, lower crust, and CLM, whereas the oceanic slab contains a crustal layer and a chemically buoyant peridotite layer. The thickness of the oceanic crust and depletion of mantle peridotites are functions of melt extraction along different mantle adiabats, while their density and rheology are experiment-based functions, considering influences of eclogitization and depletion (see the Supplemental Material[1]) (Jin et al., 2002; Capitanio et al., 2020). Additionally, we adopted different convergence rates (1–10 cm/yr), stacking dip angles (15°–45°), and thermal slab thicknesses (50–150 km) in different models so as to obtain different slab thermal structures and thus different density and rheology structures (Perchuk et al., 2020). Considering water- or strain-related weakening and episodic modification events, we also tested different weakening effects (strength factor $f = 0.01–1.0$) of the eclogitic ($f_{eclogite}$) and peridotitic ($f_{peridotite}$) layers (Herzberg and Rudnick, 2012; Wang et al., 2018) (see the Supplemental Material and Tables S1 and S2 therein for model parameters). After collision, the convergence rate is set to 0, then the evolution of the eclogitic crust is driven by its negative buoyancy and resistance from the adjacent peridotite.

[1]Supplemental Material. Supplemental text, Figures. S1–S8, Tables S1 and S2, and Movies S0–S13. Please visit https://doi.org/10.1130/GEOL.S.18823967 to access the supplemental material, and contact editing@geosociety.org with any questions.

### Viscous Drainage

In the first 100 m.y. of the models, the geotherm of the convergent zone is gradually changed from a subduction-stacking type (Fig. 2B) to a cratonic type (Fig. 2D). Thus, the eclogites in the stacked slab become heated up, thermally weaker, and more removable. As a consequence, some unstable eclogites near the newly formed lithospheric base gradually move downward due to their negative buoyancy, which makes them and their adjacent peridotites drain into the asthenosphere (Fig. 2C). This process is named viscous drainage (Lee et al., 2011), which initializes and reaches its peak approximately tens to hundreds of millions of years after stacking and episodically lasts billions of years (Fig. 3; Figs. S3–S8, Movies S0–S13 [model runs 0 through 13]). Our results show that faster viscous drainage can be caused by hotter mantle temperatures, younger slab ages, larger stacking dip angles, and weaker slab peridotites (Fig. 3).

### Lithospheric Thinning and Craton Longevity

The drainage of eclogites in the lower CLM can entrain some adjacent peridotites into the asthenosphere (Fig. 2C). This can lead to thinning of the chemical (eclogites and lithospheric peridotites hereby) and thermal (<1350 °C) CLM (Fig. 2C), which has been suggested as one of the important mechanisms for cratonic lithosphere thinning (Lee et al., 2011). However, we find that the entrainment and thinning processes are strongly influenced by the CLM peridotite strength factor, whereas other parameters tested here are not so influential (Fig. 3).

In most of our models with strong slab peridotites (Figs. 3A–3J, 3M–3N), the lithospheric thinning is very limited; only <20 km after ~2500 m.y. of model evolution. This is because dense eclogites under these conditions separate efficiently from strong buoyant CLM peridotites

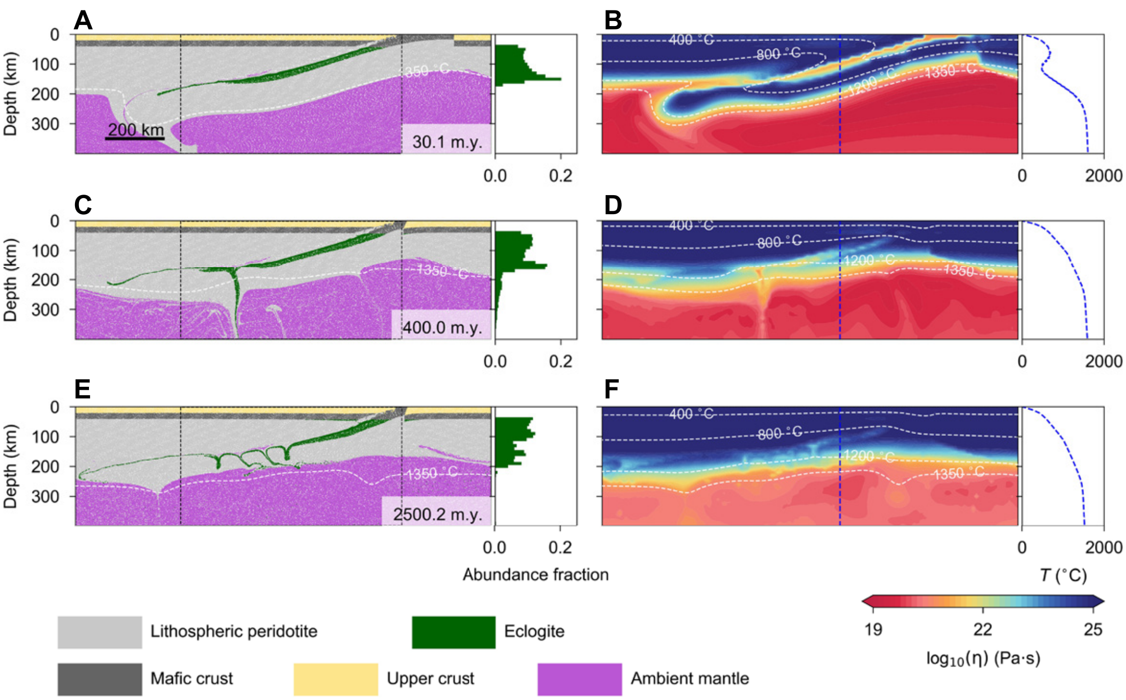


**Figure 2. Snapshots for material and viscosity (η) fields of the reference model, with mantle potential temperatures ($T_p$) higher than at present ($\Delta T_p$ = 135 K), stacking dip angle = 15°, slab thermal thickness = 100 km, strength factor of eclogite, $f_{eclogite}$, = 1.0, and peridotites, $f_{peridotite}$, = 1.0. (A,B) Subduction stacking and formation of stacking-type geotherm. (C,D) Viscous drainage during formation of cratonic geotherm. (E,F) Relicts of viscous drainage after ~2500 m.y. of evolution. Histograms are the volume fraction of eclogites versus depth. Contour lines in B, D, and F are isotherms; plot diagrams on rightmost are geotherms along profiles in B, D, and F.**

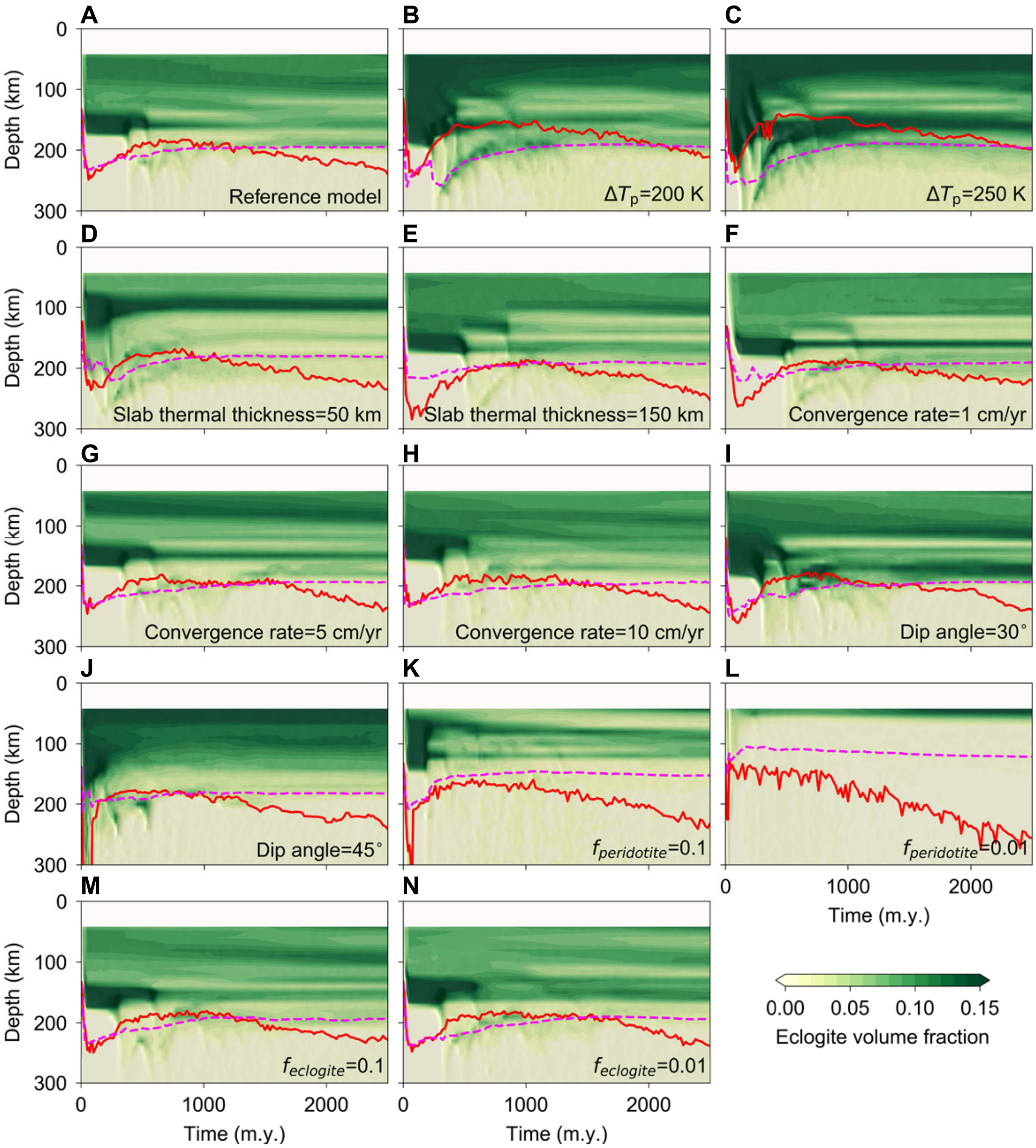


**Figure 3. Evolution of different model runs. Only one parameter is changed in each run (changed parameter is given in each diagram); the other five parameters are consistent with those used in reference model in Figure 2. $\Delta T_p$—change in mantle potential temperature from the present; $f_{eclogite}$—strength factor of eclogite. Green field denotes the distribution of eclogite abundance at different depths through time. Red solid and pink dashed lines denote the temporal variation of the average bottom depths of thermal and chemical cratonic lithospheric mantle (CLM), respectively.**

(Fig. 2D), mainly making eclogites eventually foundered into the asthenosphere.

In contrast, in several of our models with weak slab peridotites (Figs. 3K–3L), strong thinning (50–100 km) of the chemical CLM can be achieved by efficient removal of eclogites and their adjacent buoyant CLM peridotites, which is accompanied or followed by cooling of the ambient and/or mixed mantle below the thinned chemical CLM and reestablishment of a thick thermal CLM (Figs. 3K–3L).

### Eclogite Preservation and Redistribution

After billions of years of gravitational effects, via viscous drainage, some eclogites can still be preserved in the CLM (Figs. 2 and 3). The eclogite's preservation is sensitive to mantle potential temperature ($T_p$) and CLM peridotite strength factor. Higher mantle $T_p$ values can result in larger melting degrees and thicker oceanic crust (Herzberg and Rudnick, 2012) and thus larger residual eclogite volume fraction (Figs. 3A–3C). Weaker CLM peridotites can result in easier viscous drainage of the denser eclogites and thus a smaller residual eclogite volume fraction (Figs. 3A, 3K–3L). According to our models, the residual eclogite volume fraction in the CLM would be ~0.02–0.12 after ~2500 m.y. of viscous drainage.

The eclogites are sensitive to all the parameters tested during their redistribution (Fig. 3) and can be mostly divided into two parts according to their morphological features and depths (Figs. 2 and 3). One main part consists of eclogites below Moho depths, retaining the original dipping structure of subduction stacking to a depth of 50–120 km in the upper CLM after ~2500 m.y. of viscous drainage. The second part consists of eclogites dispersed below the first part (Figs. 2 and 3), with single or multiple concentration depths in the lower chemical CLM, influenced by most tested parameters. These dispersed deeper eclogites show very weak spatial or geometric correlations with the shallowly dipping structure.

## DISCUSSION

Eclogites in the CLM have negative buoyancy similar to that of eclogites in the lower crust. However, their effects on CLM evolution are different, given that the latter tend to trigger rapid delamination (van Thienen et al., 2004; Percival and Pysklywec, 2007; Johnson et al., 2013; Fischer and Gerya, 2016), whereas CLM eclogites formed during subduction stacking are shown here to trigger long-lasting viscous drainage (Lee et al., 2011), which is verifiable

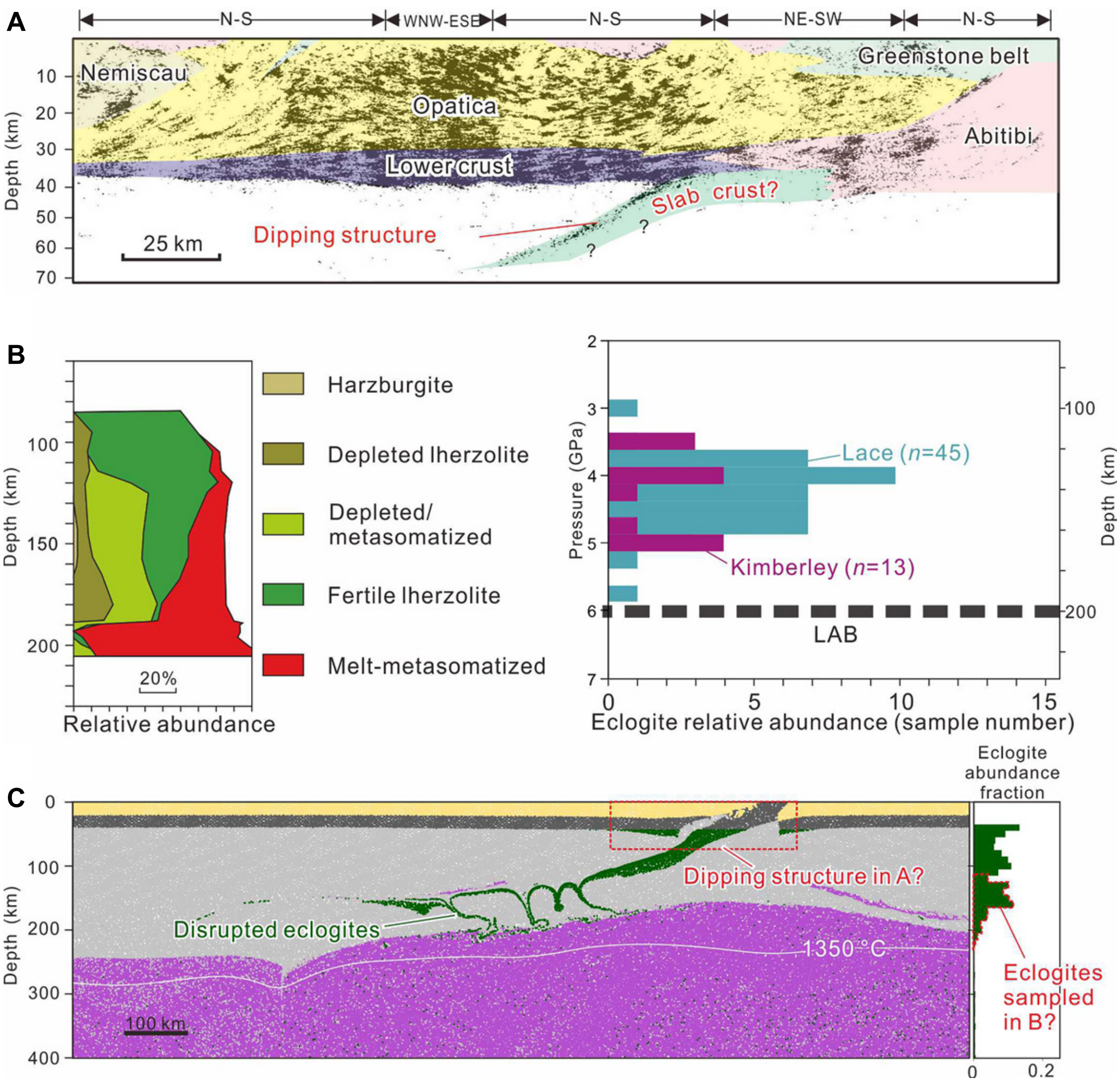


**Figure 4. Distribution of eclogites revealed from geophysical and geological observations and numerical models. (A) Dipping structure in the Superior craton (Canada) shown by seismic reflection data and interpretations after Calvert et al. (1995). Nemiscau, Opatica, and Abitibi are subprovinces of the Superior craton. (B) Lithosphere composition (after Griffin and O'Reilly, 2007) and relative abundance distribution of eclogites in the Kaapvaal craton (southern Africa) (Aulbach et al., 2020). Lace and Kimberley are kimberlites in the Kaapval craton. LAB—lithosphere-asthenosphere boundary. (C) Dipping structure and eclogite distribution in our models after ~2500 m.y. of evolution. See Figure 2 for legend.**

according to its unique relicts (dipping structure, eclogite abundance and distribution). The modeled dipping structure is consistent with the geophysical observations in the Archean Superior craton (Canada), in which dipping structures are shallower than 120 km (Figs. 4A and 4C) (Calvert et al., 1995), compatible with subduction-related eclogites (Smit et al., 2014) but different from the early conceptual model of subduction stacking in which stacked eclogitic crust can be preserved to much greater depths (Helmstaedt and Schulze, 1989). The predicted residual eclogite volume fraction in the CLM (0.02–0.12) is close to recently estimated values ($\leq$0.2) based on geophysical and xenolith studies (Garber et al., 2018), which may be method dependent. The modeled concentration of scattered eclogites in the lower CLM is roughly consistent with recognized concentrations of subduction-related Archean eclogites at intermediate depths ($\sim$3–6 GPa) of some Archean cratons (Fig. 4B) (Aulbach et al., 2020; Smart et al., 2021), although with slight differences resulting from sampling bias and uncertainties in depth estimation of xenoliths (Lee et al., 2011). Interestingly, eclogites in the geophysically revealed dipping structure are rarely sampled by deep xenoliths, likely also indicating some sampling bias or influences of other parameters. For instance, the untested mid-lithosphere discontinuity and entrained buoyant sediments may also influence the redistribution of subducted eclogites (Aulbach et al., 2020).

The thinning and longevity of CLM are influenced by both its intrinsic properties and adjacent geological events (Lee et al., 2011). Eclogites addressed here mainly influence the intrinsic properties of the CLM, including its buoyancy and rheology. However, the eclogite-peridotite separation process modeled here can reduce the influence of eclogites (Herzberg and Rudnick, 2012) and make cratons in some cases achieve similar stability as those of previous studies without such eclogites (e.g., Lenardic et al., 2003; Wang et al., 2018). This answers queries about the longevity of subduction stacking–related lithosphere (Lee et al., 2011; Herzberg and Rudnick, 2012). Later episodic plume and plate-tectonic processes and their related heating and melt and fluid infiltration can weaken the CLM (Lee et al., 2011; Liu et al., 2021). Weakening of CLM peridotites is here shown to result in rapid enhancement of viscous drainage and thinning of the chemical CLM, whereas the thermal CLM can be thickened again during secular cooling (Figs. 3K and 3L). This is consistent with the observed stratification phenomenon in which the chemical CLM is in some cases thinner than its thermal CLM (Eaton et al., 2009; King, 2005). The influence of different adjacent events on the evolution of CLM with such preserved eclogites still needs extensive analysis. For example, plume activities have been shown to have significant influence on the stability of cratons with high-density CLM eclogites, potentially changing their thickness and topography (Hu et al., 2018).

Our results show that viscous drainage is feasible for a broad range of mantle potential temperature ($T_p$), covering reasonable values from 4 Ga to present (Herzberg et al., 2010). According to the limited data available, eclogite-bearing kimberlitic diamonds have first been recognized in samples younger than 3 Ga (Shirey and Richardson, 2011), and the oldest known dipping structure in the Superior CLM formed at ca. 2.7 Ga (Fig. 4A) (Calvert et al., 1995); however, other indicators of subduction are known to have formed much earlier (e.g., Windley et al., 2021). Thus, this slab stacking and eclogite viscous drainage model, with Archean mantle temperatures, is suitable to explain some CLM formation processes at least between 3 and 2.5 Ga. Actually, similar processes are suggested to have taken place in the Slave craton (Canada) and Wyoming craton (U.S. and Canada) during the Proterozoic and Mesozoic, respectively, where newly subducted slabs stacked below thick cratons and then released some eclogites to greater depths (Bostock, 1998; Humphreys et al., 2015; Kopylova et al., 2016) to form deeper layers of concentrated eclogite (Kopylova et al., 2016). Thus, slab stacking and the eclogite viscous drainage model, complimenting the shallow breakoff and viscous underplating models (Perchuk et al., 2020), is likely a more common case for both cratonization (Herzberg and Rudnick, 2012) and recratonization (Liu et al., 2021) from 3 Ga to present. If slab subduction and stacking are also valid before 3 Ga (Windley et al., 2021), our viscous drainage model suggests that some eclogites or their metamorphic analogues may be still preserved as undetected dipping layers or scattered relicts in the CLM.


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## REFERENCES CITED


Aulbach, S., Massuyeau, M., Garber, J.M., Gerdes, A., Heaman, L.M., and Viljoen, K.S., 2020, Ultramafic carbonated melt- and auto-metasomatism in mantle eclogites: Compositional effects and geophysical consequences: Geochemistry Geophysics Geosystems, v. 21, e2019GC008774, https://doi.org/10.1029/2019GC008774.

Bostock, M.G., 1998, Mantle stratigraphy and evolution of the Slave province: Journal of Geophysical Research, v. 103, p. 21,183–21,200, https://doi.org/10.1029/98JB01069.

Calvert, A.J., Sawyer, E.W., Davis, W.J., and Ludden, J.N., 1995, Archaean subduction inferred from seismic images of a mantle suture in the Superior Province: Nature, v. 375, p. 670–674, https://doi.org/10.1038/375670a0.

Capitanio, F.A., Nebel, O., and Cawood, P.A., 2020, Thermochemical lithosphere differentiation and the origin of cratonic mantle: Nature, v. 588, p. 89–94, https://doi.org/10.1038/s41586-020-2976-3.

Eaton, D.W., Darbyshire, F., Evans, R.L., Grütter, H., Jones, A.G., and Yuan, X.H., 2009, The elusive lithosphere-asthenosphere boundary (LAB) beneath cratons: Lithos, v. 109, p. 1–22, https://doi.org/10.1016/j.lithos.2008.05.009.

Fischer, R., and Gerya, T., 2016, Early Earth plume-lid tectonics: A high-resolution 3D numerical modelling approach: Journal of Geodynamics, v. 100, p. 198–214, https://doi.org/10.1016/j.jog.2016.03.004.

Ganne, J., and Feng, X.J., 2017, Primary magmas and mantle temperatures through time: Geochemistry Geophysics Geosystems, v. 18, p. 872–888, https://doi.org/10.1002/2016GC006787.

Garber, J.M., et al., 2018, Multidisciplinary constraints on the abundance of diamond and eclogite in the cratonic lithosphere: Geochemistry Geophysics Geosystems, v. 19, p. 2062–2086, https://doi.org/10.1029/2018GC007534.

Griffin, W.L., and O'Reilly, S.Y., 2007, Cratonic lithospheric mantle: Is anything subducted?: Episodes, v. 30, p. 43–53, https://doi.org/10.18814/epiiugs/2007/v30i1/006.

Helmstaedt, H., and Schulze, D.J., 1989, Southern African kimberlites and their mantle sample: Implications for Archean tectonics and lithosphere evolution, *in* Ross, J., ed., Kimberlites and Related Rocks: Proceedings of the 4th International Kimberlite Conference, Perth, 1986: Geological Society of Australia Special Publication 14, p. 358–368.

Herzberg, C., and Rudnick, R., 2012, Formation of cratonic lithosphere: An integrated thermal and petrological model: Lithos, v. 149, p. 4–15, https://doi.org/10.1016/j.lithos.2012.01.010.

Herzberg, C., Condie, K., and Korenaga, J., 2010, Thermal history of the Earth and its petrological expression: Earth and Planetary Science Letters, v. 292, p. 79–88, https://doi.org/10.1016/j.epsl.2010.01.022.

Hu, J.S., Liu, L.J., Faccenda, M., Zhou, Q., Fischer, K.M., Marshak, S., and Lundstrom, C., 2018, Modification of the Western Gondwana craton by plume-lithosphere interaction: Nature Geoscience, v. 11, p. 203–210, https://doi.org/10.1038/s41561-018-0064-1.

Humphreys, E.D., Schmandt, B., Bezada, M.J., and Perry-Houts, J., 2015, Recent craton growth by slab stacking beneath Wyoming: Earth and Planetary Science Letters, v. 429, p. 170–180, https://doi.org/10.1016/j.epsl.2015.07.066.

Jacob, D.E., 2004, Nature and origin of eclogite xenoliths from kimberlites: Lithos, v. 77, p. 295–316, https://doi.org/10.1016/j.lithos.2004.03.038.

Jin, Z.M., Zhang, J., Green, H.W., II, and Jin, S., 2002, Eclogite rheology: Implications for subducted lithosphere: Geology, v. 29, p. 667–670, https://doi.org/10.1130/0091-7613(2001)029<0667:ERIFSL>2.0.CO;2.

Johnson, T.E., Brown, M., Kaus, B.J.P., and VanTongeren, J.A., 2013, Delamination and recycling of Archaean crust caused by gravitational instabilities: Nature Geoscience, v. 7, p. 47–52, https://doi.org/10.1038/ngeo2019.

King, S.D., 2005, Archean cratons and mantle dynamics: Earth and Planetary Science Letters, v. 234, p. 1–14, https://doi.org/10.1016/j.epsl.2005.03.007.

Kopylova, M.G., Beausoleil, Y., Goncharov, A., Burgess, J., and Strand, P., 2016, Spatial distribution of eclogite in the Slave cratonic mantle: The role of subduction: Tectonophysics, v. 672–673, p. 87–103, https://doi.org/10.1016/j.tecto.2016.01.034.

Kusky, T.M., 1993, Collapse of Archean orogens and the generation of late- to post-kinematic granitoids: Geology, v. 21, p. 925–928, https://doi.org/10.1130/0091-7613(1993)021<0925:COAOAT>2.3.CO;2.

Lee, C.-T..A., Luffi, P., and Chin, E.J., 2011, Building and destroying continental mantle: Annual Review of Earth and Planetary Sciences, v. 39, p. 59–90, https://doi.org/10.1146/annurev-earth-040610-133505.

Lenardic, A., Moresi, L.-N., and Mühlhaus, H., 2003, Longevity and stability of cratonic lithosphere: Insights from numerical simulations of coupled mantle convection and continental tectonics: Journal of Geophysical Research, v. 108, 2303, https://doi.org/10.1029/2002JB001859.

Liu, J.G., Pearson, D.G., Wang, L.H., Mather, K.A., Kjarsgaard, B.A., Schaeffer, A.J., Irvine, G.J., Kopylova, M.G., and Armstrong, J.P., 2021, Plume-driven recratonization of deep continental lithospheric mantle: Nature, v. 592, p. 732–736, https://doi.org/10.1038/s41586-021-03395-5.

Luo, Y.T., and Korenaga, J., 2020, Efficiency of eclogite removal from continental lithosphere and its implications for cratonic diamonds: Geology, v. 49, p. 438–441, https://doi.org/10.1130/G48204.1.

Moresi, L., Dufour, F., and Mühlhaus, H.-B., 2003, A Lagrangian integration point finite element method for large deformation modeling of viscoelastic geomaterials: Journal of Computational Physics, v. 184, p. 476–497, https://doi.org/10.1016/S0021-9991(02)00031-1.

Perchuk, A.L., Gerya, T.V., Zakharov, V.S., and Griffin, W.L., 2020, Building cratonic keels in Precambrian plate tectonics: Nature, v. 586, p. 395–401, https://doi.org/10.1038/s41586-020-2806-7.

Percival, J.A., and Pysklywec, R.N., 2007, Are Archean lithospheric keels inverted?: Earth and Planetary Science Letters, v. 254, p. 393–403, https://doi.org/10.1016/j.epsl.2006.11.047.

Piccolo, A., Palin, R.M., Kaus, B.J.P., and White, R.W., 2019, Generation of Earth's early continents from a relatively cool Archean mantle: Geochemistry Geophysics Geosystems, v. 20, p. 1679–1697, https://doi.org/10.1029/2018GC008079.

Shirey, S.B., and Richardson, S.H., 2011, Start of the Wilson cycle at 3 Ga shown by diamonds from subcontinental mantle: Science, v. 333, p. 434–436, https://doi.org/10.1126/science.1206275.

Sizova, E., Gerya, T., Stüwe, K., and Brown, M., 2015, Generation of felsic crust in the Archean: A geodynamic modeling perspective: Precambrian Research, v. 271, p. 198–224, https://doi.org/10.1016/j.precamres.2015.10.005.

Smart, K.A., Tappe, S., Woodland, A.B., Greyling, D.R., Harris, C., and Gussone, N., 2021, Constraints on Archean crust recycling and the origin of mantle redox variability from the $\delta^{44/40}$Ca–$\delta^{18}$O–$f_{O_2}$ signatures of cratonic eclogites: Earth and Planetary Science Letters, v. 556, 116720, https://doi.org/10.1016/j.epsl.2020.116720.

Smit, K.V., Stachel, T., Creaser, R.A., Ickert, R.B., DuFrane, S.A., Stern, R.A., and Seller, M., 2014, Origin of eclogite and pyroxenite xenoliths from the Victor kimberlite, Canada, and implications for Superior craton formation: Geochimica et Cosmochimica Acta, v. 125, p. 308–337, https://doi.org/10.1016/j.gca.2013.10.019.

van Thienen, P., van den Berg, A.P., and Vlaar, N.J., 2004, Production and recycling of oceanic crust in the early Earth: Tectonophysics, v. 386, p. 41–65, https://doi.org/10.1016/j.tecto.2004.04.027.

Wang, H.L., van Hunen, J., and Pearson, D.G., 2018, Making Archean cratonic roots by lateral compression: A two-stage thickening and stabilization model: Tectonophysics, v. 746, p. 562–571, https://doi.org/10.1016/j.tecto.2016.12.001.

Windley, B.F., Kusky, T., and Polat, A., 2021, Onset of plate tectonics by the Eoarchean: Precambrian Research, v. 352, 105980, https://doi.org/10.1016/j.precamres.2020.105980.


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