Supporting Information for
Accretion of the cratonic mantle lithosphere via massive regional relamination
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1. Numerical method and constitutive laws

The conservation of mass is described as:
\[ \nabla \cdot \mathbf{u} = 0 \]  \hspace{1cm} (1)
where \( \mathbf{u} \) is the velocity vector, the conservation of momentum is:
\[ \nabla \cdot [ -P \mathbf{I} + \eta(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) ] = -\Delta \rho g \]  \hspace{1cm} (2)
where \( P \) is the pressure, \( \eta \) the effective viscosity, \( \mathbf{I} \) the identity tensor, \( \Delta \rho \) the density contrast relative to the ambient mantle, \( g \) the gravitational acceleration vector.

The conservation of energy is under the extended Boussinesq approximation, which is frequently adopted in geodynamic numerical modeling:
\[ \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \kappa \nabla^2 T - \frac{\alpha u_y g T}{C_p} \]  \hspace{1cm} (3)
where \( T \) is the temperature, \( t \) the time, \( \kappa \) the thermal diffusivity, \( \alpha \) the thermal expansivity, \( u_y \) the vertical component of velocity, \( C_p \) the specific heat. Both \( \kappa \) and \( \alpha \) are functions of \( T \) and \( P \) (1).

1.1 Density

The density of mantle materials is a function of \( T \), \( P \), and reference density \( \rho_{\text{stp}(CCLM)} \):
\[ \rho(T, P) = \rho_{\text{stp}(CCLM)}(1 - \alpha(T, P)(T - T_0) + \beta(P - P_0)) + \Delta \rho_{\text{phase}} \]  \hspace{1cm} (4)
where \( \alpha \) is the thermal expansivity mentioned above, \( \beta \) the compressibility coefficient. \( \Delta \rho_{\text{phase}} \) is density contrast at 410 and 660 km phase boundaries (2), controlled by Clapeyron
slope ($\gamma$) (3). $\rho_{\text{stp}(CCLM)}$ is the density measured under standard temperature ($T_0$) and pressure ($P_0$) (STP) condition and is a function of concentration of CLM ($c_{\text{CLM}}$), density of pure CLM ($\rho_{\text{CLM,stp}}$) and pure primitive mantle ($\rho_{\text{pri,stp}}$) under STP condition:

$$\rho_{\text{stp}}(c_{\text{CLM}}) = c_{\text{CLM}}\rho_{\text{CLM,stp}} + (1 - c_{\text{CLM}})\rho_{\text{pri,stp}}$$  \hspace{1cm} (5)

The $c_{\text{CLM}}$ is the non-dimensionalized concentration of CLM particles per element, which can be calculated via the particle-in-cell method.

The density of mantle peridotites under STP conditions, including $\rho_{\text{stp}}$, $\rho_{\text{CLM,stp}}$, and $\rho_{\text{pri,stp}}$, can be described as a monotonic function of depletion degree (F) (Fig. S1) (4, 5). Thus, $\rho_{\text{pri,stp}}$ corresponds to $F=0$ and $\rho_{\text{CLM,stp}}$ corresponds to $F=0-50\%$, depending on what initial depletion degree is used for the CLM.

![Fig. S1. Relationship of depletion degree (F) and reference density (\(\rho_{\text{stp}}\)) (4, 5).](image)

1.2 Constitutive laws

A non-linear visco-plastic rheology is used through the definition of an effective viscosity ($\eta$), which is equivalent to the harmonic mean of the diffusion creep ($\eta_{\text{diff}}$), dislocation creep ($\eta_{\text{dis}}$), and plastic rheology ($\eta_{\text{plastic}}$). $f_{\text{vis}}$ is the weakening factor (0.1-1.0 tested) caused by melt or fluids (6), to test the influence of regional mantle weakening on CLM recycling:

$$\eta = \left(\frac{1}{\eta_{\text{plastic}}} + \frac{\eta_{\text{diff}} + \eta_{\text{dis}}}{\eta_{\text{diff}} \cdot \eta_{\text{dis}} \cdot f_{\text{vis}}}\right)^{-1}$$  \hspace{1cm} (6)

We used a simplified pressure-dependent Drucker-Prager yield criterion to model the plastic rheology:

$$\eta_{\text{plastic}} = \frac{C_0 + C_1P}{2\dot{\varepsilon}_H}$$  \hspace{1cm} (7)

The diffusion creep and dislocation creep are defined as a function of the pressure ($P$), temperature ($T$), pre-factor ($A$), second invariant of the strain rate tensor ($\dot{\varepsilon}_H$), Power-law exponent ($n$), activation energy ($E$), and activation volume ($V$). $R$ is the gas constant.
\[ \eta_{diff,\,dist} = \frac{1}{A_1} \beta_{11}^{1-n} \exp \left( \frac{E + PV}{nRT} \right) \] (8)

The maximum of the effective viscosity is further constrained via a limiter \( (\eta_{\text{max}}) \) with constant value \( (10^{23} - 10^{24} \text{ Pas tested}) \), to test the influence by lithosphere maximum viscosity:

\[ \eta = \min(\eta, \eta_{\text{max}}) \] (9)

The value of parameters above are given in Table S1.

Table S1. Parameters in numerical models (6-9).

| Symbol | Definition | Upper mantle value | Lower mantle value | Unit |
|--------|------------|--------------------|--------------------|------|
| \( A_{\text{diff}} \) | Pre-exponential parameter of diffusion creep | 2.4*10^{10} | 1*10^{16} | Pa's |
| \( A_{\text{disl}} \) | Pre-exponential parameter of dislocation creep | 10*10^{20} | - | Pa's |
| \( E_{\text{diff}} \) | Activation energy of diffusion creep | 3.0*10^5 | 2*10^5 | J/mol |
| \( E_{\text{disl}} \) | Activation energy of dislocation creep | 5.4*10^5 | - | J/mol |
| \( V_{\text{diff}} \) | Activation volume of diffusion creep | 4.0*10^{-6} | 1.1*10^{-6} | m^3/mol |
| \( V_{\text{disl}} \) | Activation volume of dislocation creep | 10*10^{-6} | - | m^3/mol |
| \( n \) | Power-law exponent | 3.5 | - | - |
| \( C_0 \) | Sine of internal friction angle | 0.6 | - | - |
| \( C_1 \) | Residual rock strength | 10^8 | - | Pa |

\( T \) | Temperature | - | °C |
| \( P \) | Pressure | - | Pa |
| \( g \) | Gravitational acceleration | 9.81 | m/s^2 |
| \( C_P \) | Specific heat | 1200 | J/kg/K |
| \( C_{\text{CLM}} \) | Concentration of CLM | - | |
| \( F \) | Depletion degree | 0-100 | % |
| \( \rho_{\text{st}} \) | Density at STP condition | Function of \( C_{\text{CLM}} \) and \( F \) | kg/m^3 |
| \( \beta \) | Compressibility | 0.5124*10^{-11} Pa^{-1} | Pa^{-1} |
| \( T_0 \) | Reference temperature | 25 | °C |
| \( P_0 \) | Reference pressure | 101325 | Pa |
| \( \gamma_{410} \) | Clapeyron slope (410 km phase transition) | 3*10^6 | Pa/K |
| \( \gamma_{660} \) | Clapeyron slope (660 km phase transition) | -2.5*10^6 | Pa/K |
| \( \Delta \rho_{410} \) | Density contrast (410 km phase transition) | 273 | kg/m^3 |
| \( \Delta \rho_{660} \) | Density contrast (660 km phase transition) | 341 | kg/m^3 |

Thermal diffusivity \(-\alpha(T, P)\) and thermal expansion coefficient \(-\alpha(T, P)\) are functions of \( T \) and \( P \). Heat production \((0 \mu\text{W m}^{-3})\) are set to be fixed for different rocks, \( R \) is the gas constant \((8.314 \text{ J/k/mol})\).

### 1.3 Depletion and age record

The potential partial melting degree \( (\phi) \) of mantle materials is calculated using the methods by Katz et al. (10), whereas the dry solidus is updated to the newly constrained one (11). The age of mantle rocks is set to 0 at the initial step and increases with model time. The updated age is reset to 0 if the temperature of the mantle rock is greater than its solidus temperature.

The depletion degree \( (F) \) of mantle rocks is caused by melt extraction after partial melting.
$F$ is recorded on particles and is assumed to represent the historical maximum partial melting degree of the related particles without refertilization. Thus, $F$ is updated to $\phi$ if the newly calculated $\phi$ is greater than the previously calculated $F$ or greater than the $F$ given as initial values marked on CLM particles. This kind of melt extraction and melt depletion method is similar to those in previous works (12).

2. Model setup

The delamination is a very common process in the Earth’s history, especially in the early time (13-15). It can be compatible with different tectonic regimes, whether subduction occurs or not, and can be induced by different triggers, including subduction, collision, plume, faulting, and rifting (14, 16-23). Thus, we do not investigate here the complex delamination processes, which are also addressed in our previous papers (24, 25). In this work, we mainly focus on the fate of the lithospheric root sinking in the mantle, once it has decoupled and delaminated. Thus, the lithosphere is initially immersed in the mantle and positioned just below a weak layer, assuming the layer with the same viscosity as that of the ambient mantle. Similar setups are adopted in previous works to facilitate the implementation of the control variable method to investigate the sinking and stagnation of subducted slab or foundered lithosphere in the mantle (e.g., 26, 27).

The modeling space extends from the surface to 1200 km depth (Fig. S2 A), where major phase transitions at 410 and 660 km depths are modeled via the Clausius - Clapeyron equation. The mantle flow is initially driven by surface motions imposed on the top boundary ($v=0$-10 cm/yr), considering different plate/lid velocities under different spatiotemporal backgrounds. Periodic boundary conditions are imposed on the side walls in the $x$-direction, allowing materials to freely flow laterally.
**Fig. S2. Numerical model setup.** a, Initial conditions for different model setups, the CLM has different depletion degrees ($F=0$-$50\%$) in different models, CLM (solid line) and ambient mantle (dashed line) profiles are shown. b, Geotherm profiles of the CLM and ambient mantle in different models with different mantle potential temperatures ($\Delta T_p =0$, 50, 100, 150, 200, 250, 300 °C for lines from blue to red).

The CLM is modeled as a block extending from 40 to 100-200 km depths with different constant depletion degrees ($F$) ranging from 0-50% to investigate the fate of foundered CLM influenced by different average CLM depletion degrees (5). The initial thermal conditions in the ambient mantle are changed in different models considering different mantle potential temperatures (hereby $\Delta T_p$) and are shown in Fig. S2 B, whereas the temperature in the block is influenced by the block thickness and increases linearly from the Moho depth (400 °C for cratonic Moho) to the bottom of the block (100-200 km depths), where the temperature is equal to the value of the ambient mantle at the same depth.

We design two modeling groups: a sensitivity test group and a main group. The sensitivity test aims to investigate the influence of the different model parameters mentioned in the main text and above, whereas the main group aims to investigate the evolution of the foundered CLM in the ambient mantle. For a common cratonic lithosphere sinking in the dry ambient mantle ($f_{vis}=1.0$), the characteristic size is usually determined by its thickness (rather than its length), which is close to mantle lithosphere thickness (14, 25, 28). Under this condition, the model evolution is mainly controlled by the $F$ and the $\Delta T_p$, which jointly determine CLM buoyancy, and the latter, the viscosity of the mantle. Accordingly, in the main test, we mainly focus on the influences of $\Delta T_p$ and $F$ on the models’ evolution.
3. Sensitivity test

In the sensitivity test, we address the impact of different parameters, such as the block length and thickness, $\Delta T_p$, $V_{surf}$, $F$, $\eta_{max}$ and $f_{vis}$ used in different model setups are given in Table S2.

Table S2. Model setups for sensitivity tests (– denotes values consistent with those in the reference model).

| Length (km) | Thickness (km) | $V_{surf}$ (cm/yr) | $\eta_{max}$ (Pas) | $f_{vis}$ | $F$ (%) | $\Delta T_p$ (°C) |
|-------------|----------------|-------------------|-------------------|-----------|---------|-----------------|
| Reference model | 500 | 160 | 3 | $10^{21}$ | 30 | 150 |
| Group test block | 100, 200, 300, | - | - | - | - | - |
| length | 400 | - | - | - | - | - |
| Group test block thickness | - | 60, 110 | - | - | - | - |
| Group test $V_{surf}$ | - | - | 0, 1, 5, 10 | - | - | - |
| Group test $\eta_{max}$ | - | - | - | $10^{21}$, $10^{24}$ | - | - |
| | | | | $10^{24}$ | - | - |
| Group test $f_{vis}$ | - | - | - | - | 0.1 | - |
| Group test $f_{vis}$ | - | - | - | - | 0.5 | - |
| Group test $F$ | - | - | - | - | 0, 10, 20, 40, | 50 |
| Group test $\Delta T_p$ | - | - | - | - | - | 0, 50, 100, 200, |
| | | | | | | 250, 300 |

The mixing degree of the foundered CLM with the ambient mantle can be quantified by lowering of standard deviation of CLM concentration ($\text{std}_{\text{CLM}}$) in the mantle:

\[
\text{std}_{\text{CLM}} = \sqrt{\frac{\sum_{i=1}^{n}(C_{\text{CLM}} - \bar{C}_{\text{CLM}})^2}{n}}
\]  

(10)

where $C_{\text{CLM}}$ is the concentration of CLM in each mesh element, $\bar{C}_{\text{CLM}}$ the average concentration of CLM in the mantle, $n$ the total number of elements for statistics, $t$ the model time. This $\text{std}_{\text{CLM}}$ value can be normalized according to its initial value $\text{std}_{\text{CLM}} t=0$.

The mixing of the CLM with the ambient mantle can lead to the decrease of $\text{std}_{\text{CLM}}$. Therefore, if the mixing is sensitive to some parameters, the $\text{std}_{\text{CLM}}$ can be also sensitive to this parameter. Fig. S3 shows the sensitivity of $\text{std}_{\text{CLM}}$ to $\Delta T_p$, $V_{surf}$, $F$, $\eta_{max}$, block length, thickness, and $f_{vis}$. It indicates that the surface velocity $V_{surf}$ and maximum CLM viscosity $\eta_{max}$, have negligible influence (Fig. S3).
Fig. S3. Sensitivity test. Chemical heterogeneities influenced by A, different CLM depletion degrees; B, different mantle potential temperatures; C, different maximum viscosity limiters; and D, different surface velocities. E, different block length; F, different block thickness; and G, different viscosity weakening factors.

The test also indicates that the evolution of the chemical anomalies is mainly influenced by the depletion degree ($F$) of the foundered CLM, the $T_p$ of the ambient mantle, the size (thickness and length) of the block, and the weakening factor ($f_{vis}$) of the mantle. In these factors, the $F$ and $\Delta T_p$ influence the whole process of the recycling, including the viability of relamination, whereas the size and $f_{vis}$ mainly influence the sinking depth, CLM segment size, episode number and duration of upwelling and do not change the feasibility of relamination. For instance, Fig. S4 and Fig. S5 show some examples of these model results. They show that the characteristic size (diameter of the maximum inscribed circle, minimum value of length and thickness, usually determined by the thickness rather than length) of the foundered CLM influences the volume of the foundered CLM and thus the model evolution (Fig. S4 and Fig. S5). Small blocks are easier to be heated by the mantle to counteract its negative buoyancy, so upwelling occurs earlier. Smaller initial block sizes usually result in shallower sinking depth, and smaller lithospheric fragments yet fewer upwelling episodes (Fig. S4 and Fig. S5). Thus,
small blocks usually result in small heterogeneities in the relaminated CLM. In models with block length (200-500 km) > block thickness (160 km), the increase of block length does not significantly influence the model evolution (Fig. S3 E and Fig. S4). Thus, the evolution of a relatively short CLM (~500 km long) is likely to be representative. The weakening factor ($f_{vis}$) is also very important. Weaker mantle rheology ($f_{vis} < 1.0$) can also lead to smaller lithospheric fragments, more upwelling episodes and stronger mixing (Fig. S4 and Fig. S5). However, this kind of weakening mainly works in regions with melts or fluids.

Fig. S4. Evolution of CLM influenced by different block length, thickness, and weakening factor. In the reference model, block length=500 km, block thickness=160 km, $f_{vis}=1.0$. In other models, only one parameter is changed relative to the reference model, and the changed parameter is given in the related panel.
**Fig. S5. Snapshots of CLM evolution influenced by different block length, thickness, and weakening factor.** A-F, the reference model, block length=500 km, block thickness=160 km, $f_{vis}=1.0$. In other models, only one parameter is changed relative to the reference model. G-L, block length=100 km. M-R, block thickness=60 km. S-X, weakening factor $f_{vis}=0.1$.

For a common cratonic lithosphere sinking in the dry ambient mantle ($f_{vis}=1.0$), the characteristic size is usually determined by its thickness (rather than its length), which is close to mantle lithosphere thickness. Under this condition, the model evolution is mainly controlled by the $F$ and the $\Delta T_p$, which jointly determine CLM buoyancy, and the latter, the viscosity of the mantle. Accordingly, in the main test, we mainly focus on the influences of $\Delta T_p$ and $F$ on the models’ evolution.

**4. The role of excess mantle temperature $\Delta T_p$ and initial depletion degree $F$**

In the main test, the values of $\Delta T_p$ and $F$ investigated are given in Table S3.
Table S3. Key parameters changed in different model setups for investigation of the fate of CLM.

| Run | ΔT_{p} (ºC) | F (%) |
|-----|-------------|-------|
| 01  | 0           | 0     |
| 02  | 0           | 10    |
| 03  | 0           | 20    |
| 04  | 0           | 30    |
| 05  | 0           | 40    |
| 06  | 0           | 50    |
| 07  | 50          | 0     |
| 08  | 50          | 10    |
| 09  | 50          | 20    |
| 10  | 50          | 30    |
| 11  | 50          | 40    |
| 12  | 50          | 50    |
| 13  | 100         | 0     |
| 14  | 100         | 10    |
| 15  | 100         | 20    |
| 16  | 100         | 30    |
| 17  | 100         | 40    |
| 18  | 100         | 50    |
| 19  | 150         | 0     |
| 20  | 150         | 10    |
| 21  | 150         | 20    |
| 22  | 150         | 30    |
| 23  | 150         | 40    |
| 24  | 150         | 50    |
| 25  | 200         | 0     |
| 26  | 200         | 10    |
| 27  | 200         | 20    |
| 28  | 200         | 30    |
| 29  | 200         | 40    |
| 30  | 200         | 50    |
| 31  | 250         | 0     |
| 32  | 250         | 10    |
| 33  | 250         | 20    |
| 34  | 250         | 30    |
| 35  | 250         | 40    |
| 36  | 250         | 50    |
| 37  | 300         | 0     |
| 38  | 300         | 10    |
| 39  | 300         | 20    |
| 40  | 300         | 30    |
The detailed evolution of the Run01 to Run 42 is shown in Fig. S6 below.
Fig. S6. Evolution of CLM influenced by different F and ΔTp during delamination, relamination, and mantle mixing. F and ΔTp values of each run are given in Table S3. In white to red, the concentration of CLM tracers at a depth relative to their initial concentration at 40-160 km depths, across the model in time. The green dashed line denotes the average depth of the 1350 °C isotherm. This indicates the thickness of the thermal lithosphere, as it grows in the later stages of the simulations, and is less meaningful during the initial stages of the model, sinking, and stagnation.

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