The Relation Between Tractions and Strain Rate at the Base of the Lithosphere: Key to Understanding Cratonic Stability

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1. INTRODUCTION

Cratons are the oldest parts of the lithosphere, some of them surviving since Archean. Their long-term stability has sometimes been attributed to high viscosity and low density. In this study, we use numerical models of global mantle flow to understand the nature of shear tractions at the base of the lithosphere. We relate these tractions to strain rates, which indicate how cratons are deforming uniquely due to the convective shear within the mantle. Cooper & Conrad (2009), using a rigid boundary condition in their analytical model, showed that these tractions exponentially increase sub-lithospheric strain-rates. In our study, we use instantaneous 3-D global mantle convection models to examine how cratonic viscosity structure and thickness relate to strain rates beneath the cratons.

2. MANTLE FLOW MODELLING

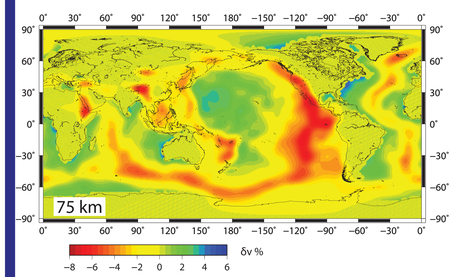

Fig 1: Velocity anomaly from SMEAN2

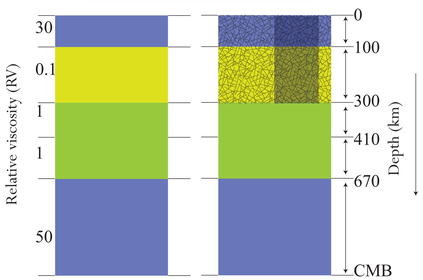

Fig 2: Schematic digram of mantle viscosity

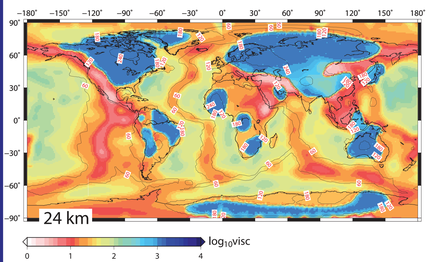

Fig 3: Net lateral viscosity variation in the input model with cratons of 100 times viscosity contrast. Numbers on the contour lines indicate lithosphere thickness.

Mantle convection solver: **CitcomS**

Model input:

1. Density anomaly from SMEAN2 tomography (following Becker and Boschi, 2002), with high velocity regions removed under continents up to 300 km.

2. Radial visosity variation.

3. Lateral viscosity variation.

Reference Model (left panel fig 2): 5 layers of different viscosities. Reference viscosity of the upper mantle (10^{21} Pa-s) is multiplied by relative viscosities in each of these layers, which are 30, 0.1, 1, 1, and 50 respectively.

Laterally varying viscosity (LVV) models (right panel fig 2 & fig 3): Lithosphere thicknesses of more than 180 km based on the lithosphere thickness model of Conrad and Lithgow-Bertelloni (2006) are considered as cratons. Craton viscosity varies between 10 to 1000 times the relative viscosities of each layer. Temperature dependence of viscosity is introduced till 300 km. Asthenosphere viscosity varies between 10^{19} Pa-s and 10^{21} Pa-s.

Model output:

1. Shear tractions ($\tau_{r\phi}$, $\tau_{r\theta}$).

2. Velocities from which strain rates are calculated.

3. SHEARING AT THE BASE OF THE LITHOSPHERE

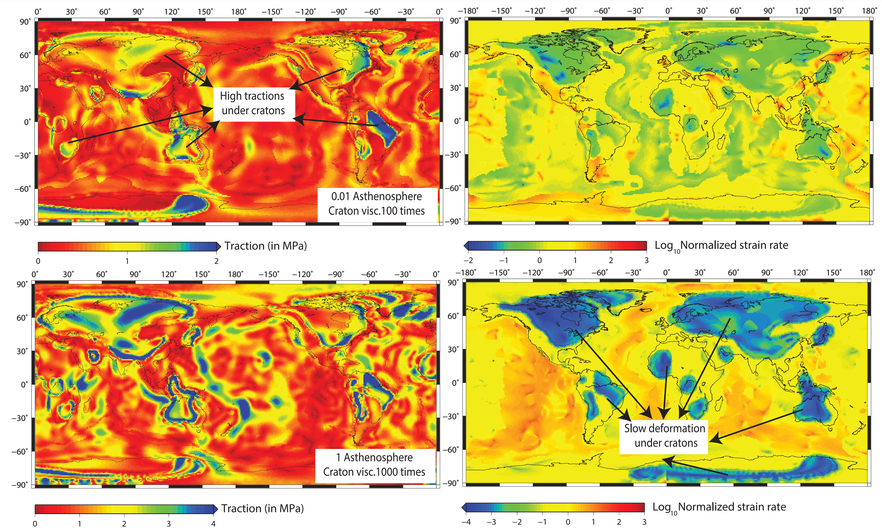

Fig 4: Tractions (left) and their corresponding normalized strain rates (right) (ratio of strain rates in LVV model to the strain rates in the reference radial model) at the variable base of the lithosphere. Viscosity combination of models are mentioned in the bottom right corner of figures. Asthenospheric viscosity is w.r.t 10^{21} Pas. Craton viscosities are w.r.t ambient layer viscosity.

4. STRESS STRAIN RELATION

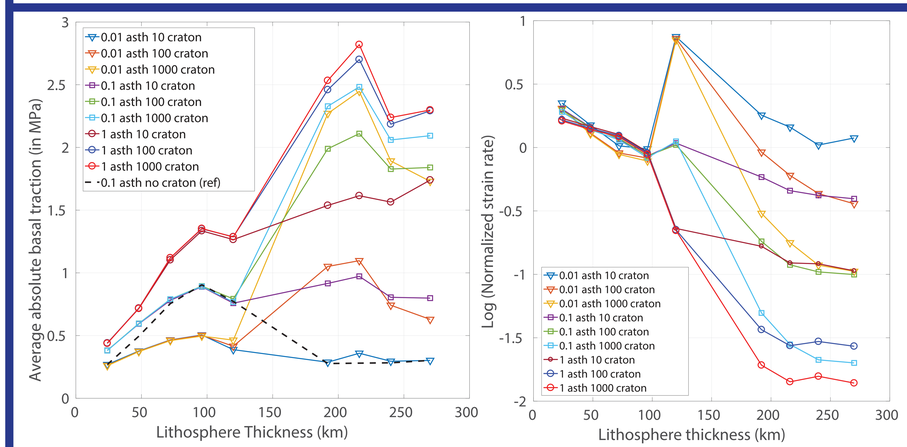

Fig 5: Traction vs. lithospheric thickness (left) and normalized strain rate vs. lithospheric thickness (right)

Traction magnitudes increase with increasing lithospheric thickness, asthenospheric viscosity and craton viscosity. Normalized strain rates decrease with lithospheric thickness, asthenospheric viscosity and craton viscosity.

5. EFFECT OF FREE SLIP CONDITION

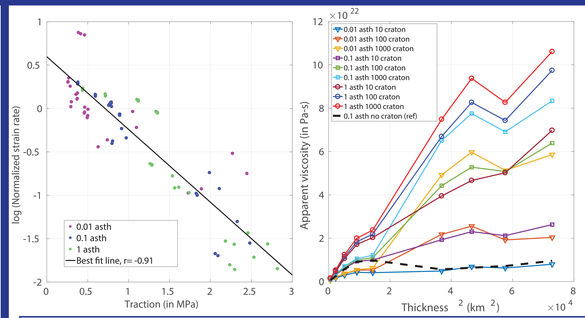

Fig 6: Relationship between traction and strain rates (left). Apparent viscosity vs. square of lithosphere thickness (right). In the equation of V_{ap}, T= magnitude of absolute traction, h = thickness of lithosphere, dv = average velocity drop across the lithosphere.

The apparent viscosity (v_{ap} = T * h/ dv) of the lithosphere roughly increases with the square of the lithosphere thickness, resulting in an inverse relation between traction and strain rate.

Such a relation between apparent viscosity and thickness likely results from the free-slip boundary conditions at the surface.

6. SURVIVAL OF CRATONS OVER AGES

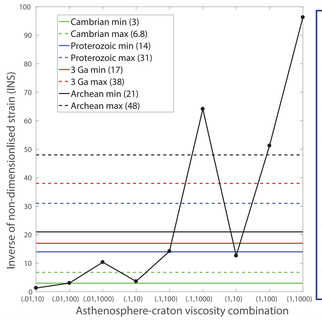

Fig 7: If a craton has to survive n times the age of an oceanic lithosphere, it must experience strain rates that are at least 1/n times those appropriate for the oceanic lithosphere.

To test this hypothesis, we calculate an inverse of non-dimensional strain rate (INS = E_o/E_c). E_o and E_c are the average strain rate underneath oceanic and cratonic lithosphere respectively.

If the INS of a craton is greater than the ratio of survival time of craton to ocean (eg. for Cambrian, 540/180=3; marked as straight lines in the figure) of a particular age, then that craton can potentially survive longer than that age.

7. CONCLUSIONS

1. Tractions at the base of the lithosphere increase with increasing lithosphere thickness and craton viscosity.

2. Normalized strain rates decrease with increasing lithosphere thickness and craton viscosity. Slow strain rates at the base of the cratons, which are associated with their high viscosity and thickness, are potentially one of the main reasons for their long-term stability.

3. The analytical study of Cooper and Conrad (2009), using a rigid boundary condition, showed that strains rates increased with increasing lithosphere thickness. Using a free-slip boundary condition we find that strain rates decrease with lithospheric thickness.

4. In addition to craton thickness and viscosity, we find that asthenosphere viscosity also affects the strain rates underneath the cratons. Stronger asthenosphere slows down the strain rates underneath the cratons.

5. We have also estimated the asthenosphere- craton viscosity combinations that would allow the craton to survive for a certain period of time. For example, a craton can survive for at least 3 Ga if its viscosity is 100 times the ambient layer and the asthenosphere viscosity is at least 10^{20} Pas.

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