12TH INTERNATIONAL KIMBERLITE CONFERENCE
30 YEARS OF DIAMONDS IN CANADA
8-12 July 2024 • Yellowknife

12th International Kimberlite Conference Extended Abstract No. 12IKC-44, 2024

Geodynamic Modelling of Cratonic Basins – Hosts for Diamonds and Gold

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Introduction

Earth's dynamic tectonics are constantly recycling crust, but thick continental lithospheric keels that define cratons provide the long-term stability that have allowed some crust to survive for billions of years (Jordan, 1988; Pearson et al., 2021). Sedimentary basins begin forming on cratonic nuclei at various stages of their history. The Archean and Paleoproterozoic basins preserved within cratonic nuclei are not only the erosional archives of early topographic development but often contain valuable deposits of precious metals and gemstones. Despite their economic appeal, currently there is no working model to explain how these early cratonic basins formed in regions of thick cratonic lithosphere. Sedimentological models that classify these basins as rifts, passive margins, or foreland basins are at a crustal scale and do not consider mantle lithosphere geodynamic processes. Likewise, geodynamic models of craton formation usually focus on stabilizing thick cratonic lithosphere while ignoring the implications for the surface topography. Here we explore the topographic consequences of an intrinsic part of craton development – lateral compression.

Methodology

We present a new study of the evolution of surface topography during craton accretion and stabilization using 2D thermal-mechanical models (Fullsack, 1995) of the crust and upper mantle. The models use a stress-free upper boundary, corresponding to the Earth's surface, where topography can develop self-consistently and where surface processes (i.e., sedimentation and erosion) can be applied (Fig. 1). In the first phase, a block of lithospheric material representing depleted peridotite, three times stronger and 2% less dense than the surrounding mantle lithosphere, is thickened by horizontal compression over 50 Myr to simulate craton formation. The model then continues to run for 2000 Myr without any externally applied tectonic forces. Throughout the model run, we monitor the lithosphere thickness of the cratonic nucleus – relevant for Archean diamond growth – and the rate of basin subsidence at the surface. We systematically explore models that use rates of sedimentation and erosion between 0 and 40 mm/year and different values of crustal radiogenic heat production (Fig. 1c).

Results

After 50 Myr of horizontal compression, the modeled surface topography generally has higher elevation in the mobile belts compared to the cratonic nucleus. The topographic relief is greater and the wavelength is shorter at lower levels of crustal heat production, as expected from results presented in Kublik et al. (in press). In our models, the extent of cratonic lithosphere thickening is related to the width of the nucleus after 50 Myr of tectonic shortening, and models with narrower nuclei tend to have thicker lithospheres (Fig. 2). Of the parameters tested here, nucleus thickening and shortening is primarily controlled by crustal heat production, accounting for 20-30 km of the variation in lithosphere thickness. Increasing the rate of sedimentation and erosion during the compression phase is a secondary control and only decreases lithosphere thickness at 50 Myr by 7-16 km.

Subsequent basin subsidence is directly dependent on the volume of sediments filling the accommodation space. In models with medium levels of crustal heat production (Fig. 3), at least 10-40 mm/year sedimentation rates in the post-compression phase are needed to form 7-9 km thick basins within 300 Myr – comparable to the Witwatersrand Basin in the Kaapvaal Craton (Robb and Meyer, 1995). In these models, the thickness of the basin may be up to 4 km less if sedimentation and erosion and erosion occurred during the compression phase (Fig. 3b).

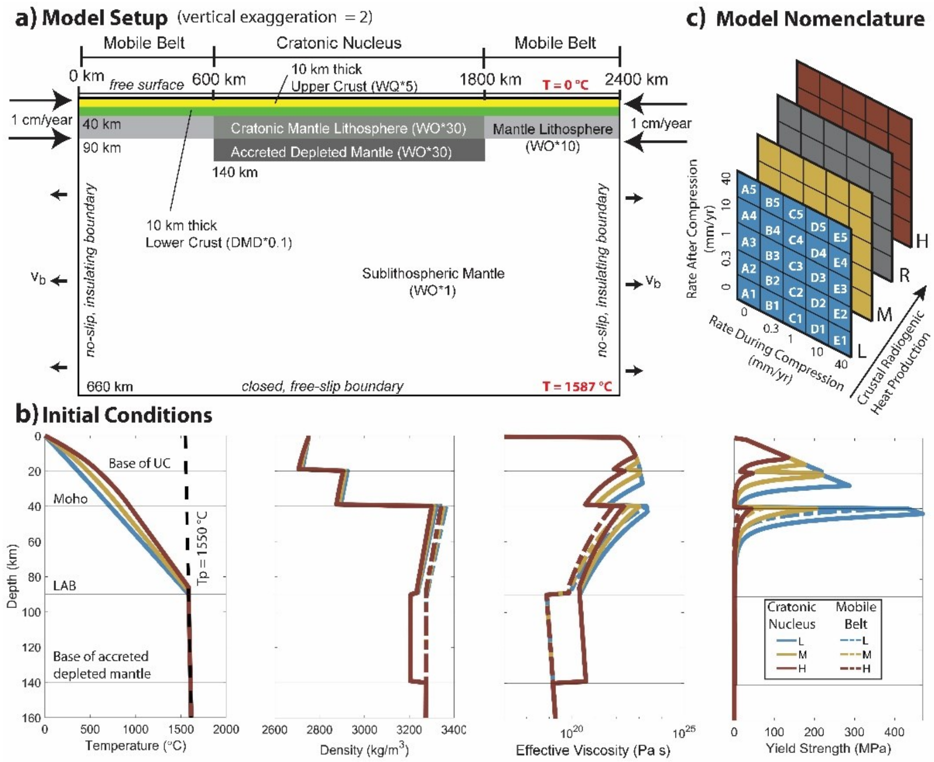

Figure 1: Model setup. **a)** Initial model geometry and boundary conditions. The backflow velocity, v_b, of sublithospheric mantle material counteracts lithospheric material inflow to maintain mass balance within the model domain. WQ is wet quartzite (Gleason and Tullis, 1995), DMD is dry Maryland diabase (Mackwell et al., 1998), and WO is wet olivine (Karato and Wu, 1993). **b)** Initial temperature, density, effective viscosity, and yield strength, of the cratonic nucleus and mobile belts, for different levels of crustal heat production: low (L; $A_{UC} = 0.06\ \mu W/m^3$; $A_{LC} = 0.06\ \mu W/m^3$), medium (M; $A_{UC} = 1.00\ \mu W/m^3$; $A_{LC} = 0.4\ \mu W/m^3$), and high (H; $A_{UC} = 2.00\ \mu W/m^3$; $A_{LC} = 0.8\ \mu W/m^3$). Models where crustal heat production reduces over time through radioactive decay (R) have the same initial conditions as H. Yield strength and effective viscosity are calculated using a strain rate of $10^{-15}\ s^{-1}$. **c)** Nomenclature to identify models based on the level of crustal heat production and rate of surface processes during and after the compression phase. For example, Model L-A5 has low crustal heat production, with zero sedimentation or erosion during the compression phase, and 40 mm/year surface process rates after compression. Model R-C3 initially had high crustal heat production that decreases through radioactive decay; surface process rates are 1 mm/year during and after compression.

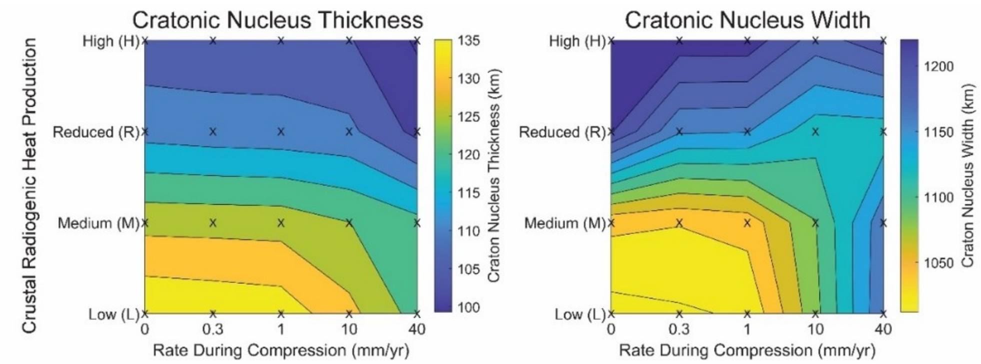

Figure 2: Lithospheric thickness and width of the cratonic nucleus at 50 Myr for different levels of crustal heat production and rates of sedimentation and erosion during the compression phase. The 20 models from the compression phase are indicated by an ‘X’ on the contour map.

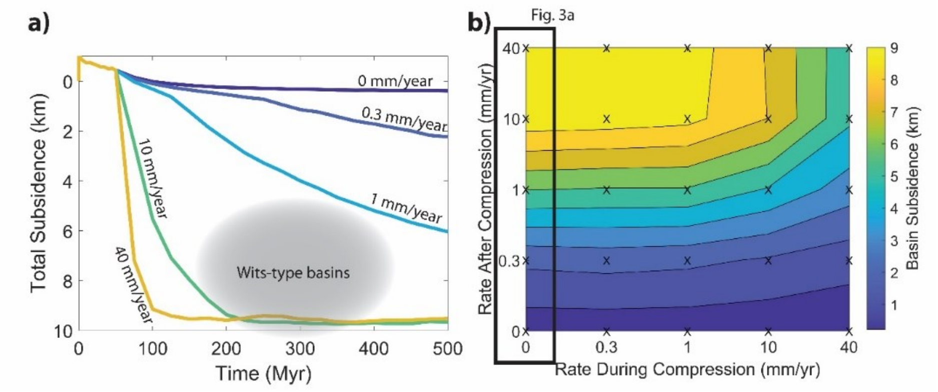

Figure 3: Subsidence of the cratonic nucleus for models with medium (M) levels of crustal heat production. **a)** Basin subsidence for models M-A1 (0 mm/year) to M-A5 (40 mm/year). See Figure 1c for model nomenclature. Subsidence curves passing through the gray-shaded region represent basins comparable in size to the Witwatersrand Basin (approximately 7 km thick sedimentary package deposited episodically over 350 Myr). **b)** Thickness of the basin at 500 Myr for all models with medium (M) levels of crustal heat production. Models M-A1 to M-A5, shown in Figure 3a, are outlined in black on the contour map.

Conclusions

In the context of our models, crustal heat production is the key factor controlling i) surface topography development, ii) cratonic lithosphere thickening, and iii) cratonic basin subsidence.

Active erosion and sedimentation can alter the model outcome, but their potential for influence is dictated by the slope of the surface topography. Model outcomes are more (less) sensitive to the rate of surface processes when the slope of the topography is steeper (less steep), and topography is steeper (less steep) in models with lower (higher) levels of crustal heat production.

Cratonic basin subsidence increases with increasing rates of sedimentation in the post-compression phase, and Wits-type basins can be generated if rates are around 10 mm/year in models with low and medium crustal heat production.

References

Fullsack, P. (1995). An arbitrary Lagrangian-Eulerian formulation for creeping flows and its application in tectonic models. Geophysical Journal International, 120(1), 1–23.

Gleason, G. C., & Tullis, J. (1995). A flow law for dislocation creep of quartz aggregates determined with the molten salt cell. Tectonophysics, 247(1–4), 1–23.

Jordan, T. H. (1988). Structure and Formation of the Continental Tectosphere. Journal of Petrology, Special Volume (1), 11–37.

Karato, S. I., & Wu, P. (1993). Rheology of the upper mantle: A synthesis. Science, 260, 771–778.

Kublik, K., Currie, C. & Pearson, D.G. (2024 – in press). Evaluating the Rheological Controls on Topography Development During Craton Stabilization: Objective Approaches to Comparing Geodynamic Models. Journal of Geophysical Research: Solid Earth

Mackwell, S. J., Zimmerman, M. E., & Kohlstedt, D. L. (1998). High-temperature deformation of dry diabase with application to tectonics on Venus. Journal of Geophysical Research: Solid Earth, 103(B1), 975–984.

Pearson, D.G., Scott, J., Liu, J., Schaeffer, A.J., Wang, L. H., van Hunen, J. Szilas, K., Chacko, T., Kelemen, P. (2021) Deep continental roots and cratons. Nature. 592, 199-210

Robb, L. J., & Meyer, F. M. (1995). The Witwatersrand Basin, South Africa: Geological framework and mineralization processes. Ore Geology Reviews, 10(2), 67–94.