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## Strain and retrogression partitioning explain long-term stability of crustal roots in stable continents

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1 <sup>1</sup>GSA Data Repository item 2020xxx, Table DR1 (thermal and mechanical parameters),  
2 Figure DR1 (slow modeling results), Figure DR2 (fast modeling results), and the Python  
3 input file (Script-G47301\_285-Cenki-Tok-et.al.ipynb), is available online at  
4 <http://www.geosociety.org/datarepository/2020/>, or on request from  
5 [editing@geosociety.org](mailto:editing@geosociety.org).

6

7 **Strain and retrogression partitioning explain long-term**  
8 **stability of crustal roots in stable continents**

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15 **ABSTRACT**

16 Away from tectonically active regions, the continental crust has an average  
17 thickness of  $40 \pm 1$  km. Yet, it shows a remarkable variability from 25 to 65 km,  
18 comparable to that of the most tectonically active regions. Here, we consider the problem  
19 of the formation and preservation of anomalous deep crustal roots in stable  
20 intracontinental regions. Using two-dimensional thermomechanical experiments, we  
21 show that the interplay between partial melting, the formation of garnet-pyroxene-bearing  
22 rocks, and their strain rate-dependent retrogression result in the preservation of thick and  
23 strong crustal roots. We argue that it is the partitioning into narrow regions of strain,  
24 retrogression, and weakening coupled into a positive feedback loop that explains why

25 strong high-grade crustal roots remain largely immune to gravitational stresses and are  
26 able to persist over hundreds of millions of years.

## 27 **INTRODUCTION**

28         The crust-mantle transition is generally well-defined on geophysical images,  
29 enabling detailed knowledge of crustal thickness at global and regional scales (Prodehl et  
30 al., 2013). Discarding tectonically active regions, the thickness of the stable continental  
31 crust has a global average of ~40 km ( $\pm 1$  km error on the calculated average crustal  
32 thickness) (Christensen and Mooney, 1995; Fig. 1A). Yet, crustal root anomalies as much  
33 as 65 km deep exist in all stable continents (e.g., Szwillus et al., 2019) from cratonic  
34 regions such as the Baltic and Canadian Shields (Cook et al. 2010; Artemieva and Thybo,  
35 2013; Fig. 1B) to Proterozoic and Paleozoic terranes such as Antarctica and Australia  
36 (Salmon et al., 2012; An et al., 2015; Ebbing et al., 2018; Fig. 1C). Some of these crustal  
37 roots have been interpreted as inherited regions of thick orogenic crust (e.g., Fischer,  
38 2002; Studinger et al., 2004), others as mantle-derived mafic roots accreted below a  
39 continental crust of normal thickness (e.g., Thybo and Artemieva, 2013). In both cases,  
40 we expect that the enhanced heat flow would thermally weaken the deep crust, enabling  
41 efficient viscous flow to relax gradients of crustal thickness and to flatten the Moho on a  
42 regional scale (Clark and Royden, 2000; Beaumont et al., 2001; Nábělek et al., 2009; Rey  
43 et al., 2010). Hence, the persistence over hundreds of millions of years of thick crustal  
44 roots poses an intriguing problem. Although high heat flow produces migmatites and  
45 granites that contribute to the transient weakening of the deep continental crust, it also  
46 produces drier and stronger garnet-pyroxene rocks such as granulites (e.g., Jackson et al.,  
47 2004). Upon cooling, hydration, and deformation, these stronger rocks may be

48 retromorphosed into weaker amphibolitic gneisses. Here, we explore through two-  
49 dimensional (2-D) thermomechanical experiments how the interplay between mechanical  
50 weakening due to partial melting, strengthening and density increase due to the  
51 crystallization of garnet-pyroxene assemblages, and post-orogenic weakening due to  
52 retrogression may impact the long-term crustal thickness. Our results suggest that thick  
53 crustal root anomalies could be the remnants of dry garnet-pyroxene-bearing rocks that  
54 survived post-orogenic extension and retrogression. These garnet-pyroxene-bearing  
55 crustal-scale boudins strengthen the lower crust and reduce its capacity to flow. Our  
56 experiments are a first step toward explaining why relaxed orogenic crust may maintain  
57 heterogeneities in crustal thickness hundreds of millions of years after orogeny has  
58 ceased.

## 59 **NUMERICAL EXPERIMENTS, CODE, AND MODEL SETUP**

60 Our 2-D thermomechanical experiments consider a 360-km-wide orogenic plateau  
61 with a 70-km-thick crust (i.e., the thickness of the Tibetan Plateau; Nábělek et al., 2009)  
62 above 40 km of mantle (Fig. 2). A layer of air-like material with low viscosity and low  
63 density is imposed on top of the crust to accommodate the development of surface  
64 topography. The plateau experiences extensional deformation as the crust returns to a  
65 normal thermomechanical state. Extensional-velocity boundary conditions are imposed  
66 on both vertical walls of the model. We have tested slow ( $0.18 \text{ cm yr}^{-1}$ ) and fast ( $1.8 \text{ cm}$   
67  $\text{yr}^{-1}$ ) velocities, delivering a strain rate averaged over the length of the model of  $3 \times 10^{-16}$   
68  $\text{s}^{-1}$  and  $3 \times 10^{-15} \text{ s}^{-1}$  respectively. Horizontal boundaries of the model are free slips. The  
69 thermal properties of the material combined with constant basal heat flow and constant  
70 top temperature deliver an initial steady-state geotherm leading to a Moho temperature of

71 ~900 °C (Fig. 2). We select from the literature plausible visco-plastic parameters (see the  
72 GSA Data [Repository](#)<sup>1</sup>) so the mechanical behavior of the modeled lithosphere depends  
73 on temperature, strain rate, deviatoric stress, and accumulated strain. Details of modeling  
74 procedures, rheological and thermal parameters, as well as the input Python script are  
75 available in the Data Repository.

76 In order to explore the interplay between partial melting, the formation of stronger  
77 garnet-pyroxene-bearing rocks, and their retrogression into weaker amphibolite facies  
78 rocks, we parameterize three first-order metamorphic phase transitions. The first phase  
79 change simulates partial melting and its feedback on density, viscosity, and temperature  
80 (Rey et al., 2009; see the Data Repository). A second phase change with feedback on  
81 density and viscosity occurs at temperature  $T = 777$  °C to simulate prograde amphibolite  
82 to garnet-pyroxene rock reaction (Philpotts and Ague, 2009). Finally, a third phase  
83 change with feedback on density and viscosity accounts for the retrogression of garnet-  
84 pyroxene-bearing rocks back into amphibolite facies rocks. This third phase change  
85 occurs at  $T = 777$  °C as well and for a strain rate  $\geq 10^{-14}$  s<sup>-1</sup>. Our model implicitly  
86 assumes that water is available. Therefore, retrogression is contingent upon strain rate,  
87 which simulates the metastability of dry high-grade rocks during exhumation. This strain-  
88 rate threshold is in the range of expected strain rates measured in orogenic shear zones  
89 (Sassier et al., 2009; Boutonnet et al., 2013; Fagereng and Biggs, 2019). Rock solidus  
90 depends on rock fertility and availability of fluid. Hence, we have tested different solidii  
91 for the continental crust and the garnet-pyroxene-bearing rocks (Data Repository) in the  
92 range commonly accepted for these rock types. For the continental crust, we have tested a  
93 solidus representative of fertile metapelites with a melting temperature at room pressure

94 of 650 °C (Figs. 3A and 3B; White et al., 2001), and a solidus representative of less-  
95 fertile rocks with a melting temperature at room pressure of 720 °C (Fig. 3C; Rey and  
96 Müller, 2010). For the dry garnet-pyroxene-bearing crust, we use a melting temperature  
97 at room pressure of 790 °C representative of refractory granulites (Cenki-Tok et al.,  
98 2016). We use *Underworld*, a well-tested open-source finite-element code  
99 (<https://underworld2.readthedocs.io/>), to solve the equations of conservation of  
100 momentum, mass, and energy for an incompressible fluid on a Cartesian Eulerian mesh  
101 (Moresi et al., 2007; Beucher et al., 2019).

## 102 **RESULTS**

103       When a slow divergent velocity is imposed ( $0.18 \text{ cm yr}^{-1}$ ), the crust thins  
104 homogeneously, the Moho remains flat, and deformation is dominated by pure shear  
105 strain whether melt and/or garnet-pyroxene rocks are present or not (Fig. DR1 in the Data  
106 Repository). In contrast, under faster extensional velocities ( $1.8 \text{ cm yr}^{-1}$ ), the  
107 experimental outcome depends on phase changes. When the formation of strong garnet-  
108 pyroxene rocks is not allowed, partial melting makes the deep crust hot and mobile,  
109 which allows the formation of a migmatitic dome (Fig. 3A). In the partially molten dome,  
110 finite strain ellipses are strongly flattened, with a vertical long axis indicating the  
111 presence of a vertical high-strain zone separating two sub-domes. This double-dome  
112 geometry has been well documented (Rey et al., 2011, 2017; Korchinski et al., 2018).  
113 Figures 3B and 3C show a different result when prograde garnet-pyroxene rock formation  
114 and retrogression into amphibolite are allowed. In the case where retrogression does not  
115 occur (Fig. DR2A), the crust thins homogeneously. As the formation of garnet-pyroxene  
116 rocks strengthens the deep crust, its capacity to flow is much reduced and the upper crust

117 remains mechanically coupled to the mantle. Extensional deformation is more distributed  
118 and heterogeneous as documented by the crustal-scale pinch-and-swell strain pattern, as  
119 well as the finite strain field imaged by the finite strain ellipses (Fig. 3B). As strain rate  
120 controls the retrogression of garnet-pyroxene rocks (Figs. DR2B and DR2C), we observe  
121 that retrogression is partitioned into the pinch regions where strain rate is higher, whereas  
122 garnet-pyroxene pods are preferentially preserved in the swell regions where strain rate is  
123 lower and below the threshold required to activate retrogression. Because retrogression  
124 leads to weakening, favoring strain localization and therefore higher strain rates, there is  
125 a positive feedback loop between strain rate, retrogression, and weakening. When the  
126 crustal solidus is that of a fertile metapelite, portions of the lower crust are partially  
127 molten and able to flow under gravitational stresses, whereas flow is inhibited in the  
128 strong garnet-pyroxene rock pods (Fig. 3D). Raising the solidus temperature of the  
129 continental crust by 70 °C results in a similar outcome except that there are no more  
130 partially molten domains within the continental crust (Fig. 3C). Because of the formation  
131 of garnet-pyroxene rock pods, the Moho presents a winding geometry with crustal  
132 thickness variations of as much as 50%, from 35 to 53 km. After 25% of extension and  
133 thinning, we have left these experiments to thermally and mechanically relax over 180  
134 m.y. under fixed boundary conditions (i.e., setting the kinematic boundary condition to 0  
135  $\text{cm yr}^{-1}$ ). We observe that the heterogeneity of crustal thickness persists throughout this  
136 long cooling history.

## 137 **DISCUSSION**

138 Our numerical experiments suggest that strain rate-dependent retrogression that  
139 typically localizes along ductile shear zones cutting through high-grade rocks may

140 explain how remnants of thick and strong orogenic crust can survive orogenic collapse.  
141 These regions can be ~50% thicker than the adjacent crust and as narrow as a few tens of  
142 kilometers across, and survive for hundreds of millions of years. Anomalous deep crustal  
143 roots have been imaged in stable intracontinental regions all around the globe. In the  
144 eastern Canadian Shield, for example, the Lithoprobe project  
145 (<https://lithoprobe.eos.ubc.ca/>) has documented several crustal roots (Cook et al., 2010).  
146 Below the Torngat orogen along the eastern Canadian Shield, a Paleoproterozoic crustal  
147 root as much as 50 km deep, 15 km deeper than the average adjacent crust, and ~80 km  
148 wide and >200 km long has been imaged on seismic profiles (Fig. 1B; Funck and  
149 Louden, 1999). It is interesting to note that this Paleoproterozoic crustal root is bounded  
150 to the north and east by major shear zones (Cook et al., 2010). In the Baltic Shield, along  
151 an Archean–Paleoproterozoic suture, the Moho reaches a depth of ~60 km over a region  
152 centered on southern Finland (Artemieva and Thybo, 2013). In central Australia, even  
153 though this continent has been tectonically relatively stable for the past 300 m.y., crustal  
154 roots reaching 65 km depth have been imaged as deep regions of diffuse reflectivity over  
155 circular domains a few hundred kilometers in diameter (Fig. 1C; Kennett et al., 2011;  
156 Salmon et al., 2012). In Antarctica, a series of crustal roots as much as 60 km deep have  
157 been documented between Dronning Maud Land and Gamburtsev Subglacial Mountains  
158 (An et al., 2015; Ebbing et al., 2018). In peninsular India, made up of Archean to  
159 Paleozoic terranes, the Moho depth varies from ~38 km below the southernmost tip of  
160 India’s Proterozoic Southern Granulite terrane, to 50 km below the Archean Dharwar  
161 craton in semicircular regions ~250 km in diameter (Reddy and Vijaya Rao, 2013; Das et  
162 al., 2019). The structure and nature of the lower crust below the Southern Granulite



163 terrane is heterogeneous, but because the middle and upper crust shows a constant  
164 thickness of 20–25 km, this variability must be accommodated by variation in thickness  
165 of the lower crust (18–32 km; Das et al., 2019).

166         The gravimetric and seismic characteristics of these crustal roots suggest the  
167 presence of garnet-pyroxene-bearing rocks. For example, in Canada, crustal roots  
168 showing P-wave velocities  $>7 \text{ km s}^{-1}$  led Cook et al. (2010) to propose that in the  
169 absence of later tectonic reworking, the variations in Moho depth originate solely from  
170 rheological variations. In southern India, crustal roots display compressional-wave  
171 velocities that are systematically  $>7 \text{ km s}^{-1}$  (Reddy and Vijaya Rao, 2013), and shear-  
172 wave velocities between 4 and  $4.2 \text{ km s}^{-1}$  (Das et al., 2019). The contrasting density and  
173 seismic characteristics between granitic rocks and/or amphibolite facies gneisses ( $<2700$   
174  $\text{kg m}^{-3}$  and  $<6.4 \text{ km s}^{-1}$ ) and higher-grade garnet-pyroxene-bearing rocks ( $>2800 \text{ kg m}^{-3}$   
175 and  $>6.6 \text{ km s}^{-1}$ ; Christensen and Mooney, 1995; Artemieva and Thybo, 2013) suggest  
176 that deep crustal roots are made of the latter (Williams et al., 2014). This proposition is  
177 compatible with the seismically diffuse boundary that is commonly observed between the  
178 lower crust and the mantle (O'Reilly and Griffin, 2013). Because the petrophysical  
179 properties of garnet-pyroxene-bearing rocks are intermediate between the ones of the  
180 crust and the mantle, a garnet-pyroxene-rich lower crust would explain the seismic  
181 properties of the transition between the crust and the mantle observed in Peninsular India  
182 for example (Reddy and Vijaya Rao, 2013).

183         Importantly, in all of these examples, crustal roots are interpreted as inherited  
184 remnants of ancient orogenic crust that have survived gravitational collapse and the  
185 flattening of the Moho. We propose that these strong orogenic crustal roots owe their

186 survival to the presence of retrogressed and therefore weaker adjacent crusts in which  
187 deformation is strongly partitioned. The positive feedback loop between strain,  
188 retrogression, and weakening insures that deformation remains localized into retrogressed  
189 domains, isolating and protecting garnet-pyroxene-bearing pods that remain largely  
190 immune to deformation.

## 191 **CONCLUSIONS**

192 In this study, we have explored through 2-D thermomechanical modeling how the  
193 interplay between partial melting, the formation of garnet-pyroxene high-grade rocks, and  
194 strain rate-dependent retrogression could explain the long-term preservation of deep  
195 crustal roots in stable continents. Though 2-D experiments are sufficient to illustrate how  
196 strain rate, retrogression, and weakening can explain the preservation of thick roots,  
197 future work involving 3-D experiments will allow investigation of triclinic boundary  
198 conditions. Our experiments show that following the formation of high-grade rocks in  
199 deep orogenic crusts, extension is partitioned into regions where strain, retrogression, and  
200 weakening are coupled into a positive feedback loop. This results in the preservation of  
201 thick, dense, and strong garnet-pyroxene-rich pods, separated by retrogressed and  
202 attenuated pinched regions. The strong high-grade pods form crustal-scale boudins that  
203 are able to survive through the orogenic relaxation phase and over a duration of >100  
204 m.y. As a result, the equilibrated orogenic crust preserves deep crustal roots similar to  
205 those documented in all stable continents. These results are first steps toward  
206 understanding of the feedback between metamorphic reactions and deformation. In the  
207 future, 3-D models involving porous flow and surface processes will allow a more  
208 detailed understanding of these systems.

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336 **FIGURE CAPTIONS**

337 Figure 1. (A) Crustal thickness histogram for world shields extracted from CRUST 5.1  
338 model (modified from <https://earthquake.usgs.gov/data/crust/crust.php>). (B) Interpolated  
339 compressional-wave velocities across the Torngat orogen, northeastern Canada (modified  
340 from Funck and Loudon, 1999). (C) Interpolated Moho surfaces for Australia constructed  
341 by interpolating weighted averages for each  $0.5^\circ \times 0.5^\circ$  pixel (modified from Kennett et  
342 al., 2011).

343



344 Figure 2. Model geometry and initial conditions, as well as geotherm, viscosity, and  
345 density profiles. Weak prismatic region dipping  $45^\circ$  simulates detachment fault in upper  
346 crust. Circles pattern superimposed on continental crust represents finite-strain ellipses.

347

348 Figure 3. Fast-velocity modeling results ( $1.8 \text{ cm yr}^{-1}$  extension speed) at average strain  
349 rate of  $3 \times 10^{-15} \text{ s}^{-1}$  and 25% extension. Colors are the same as in Figure 2. (Model A)

350 Only partial melting is allowed (garnet-pyroxene isograd and retrogression into  
351 amphibolite are removed). (Model B) Partial melting, crystallization of garnet-pyroxene  
352 assemblages, and retrogression are allowed. Temperature for transformation of  
353 continental crust into garnet-pyroxene-rich rocks is  $777^\circ\text{C}$  (see text for explanation).

354 Reference temperatures for solidus of continental crust and garnet-pyroxene-rich crust are  
355  $650^\circ\text{C}$  and  $790^\circ\text{C}$ , respectively. (Model C) Same as model B but temperature for  
356 continental crust solidus is increased to  $720^\circ\text{C}$ . (Model D) Zoom on model B illustrating  
357 velocity field (black arrows) when boundary condition mimicking extension is removed  
358 (after 2 m.y. of gravity forces operating), showing that partially molten crust flows while  
359 garnet-pyroxene-rich rocks do not.

360