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1	Non-uniform splitting of a single mantle plume by double cratonic roots:
2	Insight into the origin of the central and southern East African Rift System
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15	

16 Abstract

17 Using numerical thermo-mechanical experiments we analyze the role of active mantle plume and pre-existing lithospheric thickness differences in the structural development of the 18 central and southern East African Rift system. The plume-lithosphere interaction model setup 19 20 captures the essential features of the studied area: two cratonic bodies embedded into surrounding lithosphere of normal thickness. Results of numerical experiments suggest that localization of rift 21 branches in the crust is mainly defined by the initial position of the mantle plume relative to the 22 cratons. We demonstrate that development of the Eastern branch, the Western branch and the 23 Malawi rift can be the result of non-uniform splitting of the Kenyan plume that has been rising 24 25 underneath the southern part of the Tanzanian craton. Major features associated with Cenozoic rifting can thus be reproduced in a relatively simple context of the interaction between a single 26 mantle plume and pre-stressed continental lithosphere with double cratonic roots. 27

28

29 Introduction

The East African Rift system (EARS) (McConnell, 1972; Chorowicz, 2005; Braile et al., 30 2006; Ring, 2014) has two branches, the Eastern branch and Western branch. The N-S oriented 31 32 Eastern branch (Baker et al., 1972; Williams, 1982; Baker, 1987; Keller et al., 1991; Smith, 1994; 33 Mechie et al., 1997; Ebinger, 2005) extends over 2000 km from the Afar Triple Junction (Mohr, 1970; McClusky et al., 2003) in the north to the North Tanzanian Divergence Zone (Dawson, 34 1992; Le Gall et al., 2004, 2008; Isola et al., 2014) in the south (Figure 1) and consists of the 35 36 relatively narrow Main Ethiopian rift (Keranen et al., 2009), the wide rift in the Turkana depression (Morley et al., 1992) and a narrow rift at the Tanzanian craton margin in the Kenya 37 rift (Zeyen et al., 1997). In the present study, however, we consider only the southern part of the 38 Eastern branch from Northern Kenya to North-Eastern Tanzania. The Western branch (Ebinger, 39

1989; Pasteels et al., 1989; Daly et al., 1989; Morley et al., 1999; Bauer et al., 2013) is composed 40 41 by the Albert-Edward, Kivu and Tanganyika-Rukwa rifts stretched in NE-SW, N-S and NW-SE directions, respectively, depicting an arcuate map-trace along the western side of the Tanzanian 42 craton (Figure 1). The southern prolongation of the Western branch is represented by the Malawi 43 rift (Ring et al., 1992; Laó-Dávila et al., 2015) that is aligned on a N-S trend extending from the 44 Rungwe volcanic province (southern Tanzania) to the Urema graben (Mozambique). Geological 45 46 estimates indicate a higher degree of total lithospheric extension in the Kenya rift as compared to the Western branch and the North Tanzanian Divergence Zone (Ring, 2014 and references 47 therein). 48

The Western and Eastern branches are separated by the Archaean (2500-3000 Ma) 49 50 Tanzanian craton (Bell and Dodson, 1981; Chesley et al., 1999; Manya, 2011) characterized by a 51 strong and cold lithosphere with a 150-300-km-thick keel (Artemieva, 2006; Adams et al., 2012; 52 Mulibo and Nyblade, 2013a,b). The 175-km-thick (Artemieva, 2006) Archaean-Paleoproterozoic Bangweulu block (Andersen and Unrug, 1984; De Waele et al., 2006) that is stable since 1750 53 54 Ma (Lenoir et al., 1994), lies to the south-west of the Tanzanian craton. The Tanzanian and 55 Bangweulu cratons are both surrounded by Proterozoic orogenic belts (Cahen et al., 1984; Begg et al., 2009) with a relatively thin (\leq 150 km) thermal lithosphere (Artemieva, 2006; Koptev and 56 57 Ershov, 2011).

Geophysical (e.g., Ritsema et al., 1998; Nyblade et al, 2000; Nolet et al., 2006) and geochemical (e.g., Rooney et al., 2012; Armitage et al., 2015) observations indicate the presence of mantle plumes under the EARS, possibly rooted into a common deep mantle anomaly (Ritsema et al., 1999) corresponding to the African superplume. However, the actual number of plumes and their relative position within this broad upwelling region remain contentious (e.g., Weeraratne et al., 2003; Chang and Van der Lee, 2011; Chang et al., 2015; Civiero et al., 2016). It is commonly assumed that the Cenozoic rifts have avoided the cratons and follow the mobile belts (McConnell, 1972; Mohr, 1982) which serve as the weakest pathways for rift propagation. Structural control of the pre-existing heterogeneities within the Proterozoic belts at the scale of individual faults or rifts has been demonstrated as well (Versfelt and Rosendahl, 1989; Ring, 1994; Theunissen et al., 1996; Corti et al., 2007; Morley, 2010; Katumwehe et al., 2015; Smets et al., 2016).

However, as shown by Koptev et al. (2015, 2016), the formation of two rift zones on 70 opposite sides of a thick lithosphere segment can be explained without appealing to pre-imposed 71 heterogeneities at the crustal level. These models have provided a unified physical framework to 72 understand simultaneous development of the Western and Eastern branches around a thicker 73 74 Tanzanian craton (Roberts et al., 2012) as a result of the interaction between pre-stressed continental lithosphere and single mantle plume anomaly corresponding to the Kenyan plume 75 76 (George et al., 1998; Pik et al., 2006; Chang and Van der Lee, 2011). Yet, the southern prolongation of the Western rift by the Malawi rift has not been reproduced in any of these "one-77 craton" experiments (Koptev et al., 2015, 2016). In order to overcome this discrepancy, we 78 follow-up on our previous studies with a series of laterally widened thermo-mechanical models 79 characterized by a presence of a second zone of lithospheric thickening that roughly mimics the 80 81 isometric (i.e. having equal horizontal dimensions) Bangweulu block situated south-west of the Tanzanian craton and by a single mantle plume seeded underneath the southern part of the 82 Tanzanian craton (e.g., Hansen et al., 2012; Bagley and Nyblade, 2013). 83

84

85 Model and experiments

Our modeling is based on the thermo-mechanical viscous-plastic 3DELVIS code (Gerya and Yuen, 2007) that combines the finite difference method with a marker-in-cell technique (see Gerya (2010) for more details).

The 3D model box encompasses the entire 650-km-deep upper mantle, with large 89 90 horizontal scales (2000 \times 2000 km) and offers "lithospheric-scale" resolution (~ 5 km \times 5 km \times 5 km per grid cell). The initial model setup corresponds to onset of a stratified three-layer 91 (upper/lower crust and lithospheric mantle) continental lithosphere which is underlain by 92 asthenospheric upper mantle. The initial geotherm is piece-wise linear, with 0°C at the surface, 93 700° C at the Moho, 1300° C at the lithosphere-asthenosphere boundary and 1630° C at the bottom 94 of the model box. The mantle plume is initiated by a temperature anomaly of +370°C at the base 95 of the upper mantle. In all presented experiments we have applied a constant extension in E-W 96 direction with a half rate of 3 mm/year, a typical value for pre-break-up continental rifts 97 98 including the Nubia-Somalia plate system (Stamps et al., 2008; Saria et al., 2014).

The general model series (Table 1; models 1-13) is characterized by lateral homogeneity 99 of the crustal composition and by presence of two zones of 250 km-thick cratons embedded into 100 101 surrounding "normal" (150 km-thick) lithosphere. The first cratonic block is elongated in a N-S direction (horizontal dimensions are 400×800 km) roughly mimicking the configuration of the 102 103 Tanzanian craton whereas the second one is small and isometric (horizontal dimensions are $400 \times$ 400 km) corresponding to the Bangweulu block. The initial plume location represents a key 104 controlling parameter of our study (Figure 2). In all performed experiments (except for "no-105 106 plume" model 1; Figure 3) the mantle plume has been shifted to the south up to 230 km with 107 respect to the center of the Tanzanian craton. We have studied the impact of small lateral variations in its initial position: a southward shift varies from 210 km to 230 km whereas 108 109 latitudinal displacement is from 10 km to the west to 30 km to the east; different configurations of the Tanzanian craton have been tested as well (Table 1; Figures 4-5). In order to investigate the potential role of second-order structural heterogeneities we have performed several complementary experiments (models 14-17, Figure 6) including stronger (plagioclase flow law instead of wet quartzite flow law) lower crust within the cratonic blocks (models 16-17) and/or third zone of lithospheric thickening situated to the west of the Tanzanian craton and roughly mimicking the size and configuration of the Masai block (models 14-15, 17).

116

117 **Results and discussions**

Similarly to previous 3D experiments (Burov and Gerya, 2014; Koptev et al., 2015, 118 119 2016), the models presented here predict a rapid mantle ascent as the mantle plume reaches the lithospheric bottom after 0.5 Myr. The common point of the performed models is a separation of 120 the upwelling plume head into three parts by the lithosphere of the Tanzanian and Bangweulu 121 122 blocks. After being divided, the buoyant plume material ponds at the base of "normal" lithosphere adjacent to the western, eastern and southern sides of the Tanzanian craton (Figure 4). 123 In absence of active mantle upwelling ("no-plume" model 1), ultra-slow tectonic 124 extension can only result in broadly distributed small-offset parallel faults (Figure 3). On the 125 contrary, in most of the other experiments (Figure 4), the continental crust above the hot plume 126 material is subjected to localized brittle deformation forming three linear, 100-500 km-long 127 rifting centers stretched in the direction perpendicular to external E-W extension. As already 128 shown by Burov and Gerya (2014), such large-scale linear normal faults are triggered and 129 130 maintained by mantle flow that impacts the bottom of continental lithosphere.

The degree of development (in terms of modeled strain rates) of each of these branches is directly controlled by the relative amount of hot plume material ponding underneath the corresponding lithosphere segment (Figure 4). In certain cases, however, this amount appears to

be too small to localize any visible deformation in the crust. For example, the plume's eastward 134 135 shift of 10 km in combination with the simplified shape of the Tanzanian craton results in the absence of a discernible western rift (model 4, Figure 4c). Similarly, the eastern branch is not 136 reproduced in the experiments assuming a more realistic Tanzanian craton and the mantle plume 137 138 with initial latitudinal displacement of 0 km or 10 km to the west (models 6 and 5, respectively; Figure 4e and Figure 4d). Only the plume's eastward shift up to 20 km (models 8-10; Figure 4g-i) 139 can provide a symmetrical rifting on both (eastern and western) sides of the Tanzanian craton. 140 Further plume displacement to the east (up to 30 km) leads to a more developed eastern branch 141 comparing to the western one (models 11-13; Figure 4i-l). The southern rift zone situated east of 142 the Bangweulu block is expressed clearly in all models. Note, however, that it becomes less 143 pronounced when the plume's southward shift decreases from 230 km to 210 km (compare 144 models 8 (Figure 4g) and 10 (Figure 4i) or models 11 (Figure 4j) and 13 (Figure 4l)). The 145 146 asymmetrical distribution of hot mantle material on the opposite sides of the craton (e.g., models 11-12) can provoke contrasted magmatic activity as observed in the central EARS, explaining a 147 magma-rich Eastern branch and magma-poor Western branch (e.g., Chorowicz et al., 2005; Ring, 148 149 2014).

We have identified model 9 (Figure 4h; Figure 5) as the "best-fit" experiment of the 150 general model series (models 1-13) because it reproduces all three rift zones that are clearly 151 reflected not only in strain rate field but also in the surface topography (Figure 5c). Several other 152 models (such as models 3 or 8), however, could also be considered as the "best-fit" (Figure 4b,g) 153 154 because they are able to reproduce a synchronous growth of the Eastern branch, the Western 155 branch and the Malawi rift as well. Note that modeled accumulated deformation in the localized rift basins amounts to several tens km of total extension, that is in accord with geological 156 estimates for the central part of the EARS (e.g., Ring, 2014 and references therein). A striking 157

158 feature is the consistency between modeled and observed rift distribution in case of the Kenyan159 plume seeded underneath the southern part of the Tanzanian craton.

A principal shortcoming of this "best-fit" experiment (model 9; Figure 5) is that it does 160 not reproduce the NW-SE oriented Rukwa rift segment of the Western branch (Figure 1). 161 162 Similarly to most of the other models, the southern end of the western branch penetrates into the area underlain by the Bangweulu block. In this case, thick lithosphere appears to be not resistant 163 to lateral propagation of localized deformation given homogenous crustal composition adopted in 164 the general model series when crustal rheology of the cratonic blocks does not differ from 165 surrounding "normal" lithosphere. The situation changes completely when not only thicker 166 167 lithospheric mantle but also stronger rheology of the lower crust is considered for the cratonic areas (complementary model series: models 16-17, Figure 6c,d): in this case, localized strain 168 tends to avoid the strong cratons keeping them almost undeformed. In particular, this leads to the 169 170 change of orientation from N-S to NW-SE for the southernmost segment of the western branch (corresponding to the Rukwa rift) thus providing a framework much more consistent with the 171 observed data. Introduction of the Masai block, for its part, improves the relative location of 172 widening of the rift zone in the southern segment of the eastern branch (models 15, 17; Figure 173 6b,d) that would correspond to the observed transition between the narrow Kenya rift to a 174 175 considerably wider zone (300-400 km) of block faulting in northern Tanzania (Dawson, 1992; Ebinger et al., 1997; Foster et al., 1997; Le Gall, 2008; Corti et al., 2013). 176

177 It should be noted that given the better fit with the observed data in case of 178 complementary models containing more predefined complexities (see Figure 6d), the analyzed 179 plume-induced multi-branch continental rifting dynamics need further numerical investigation 180 and quantitative analysis of the controlling factors including complex 3D structure of the central

181 EARS in terms of inherited compositional and rheological heterogeneities of the crust and182 lithospheric mantle (e.g., Sippel et al., 2017).

183

184 Conclusions

The fully-coupled thermo-mechanical models presented here start from relatively simple 185 initial conditions: a single mantle plume anomaly seeded underneath the continental lithosphere 186 embedding two cratonic blocks. These experiments evolve over time to create a complex system 187 characterized by asymmetrical splitting of the plume head into three parts. The resulting relative 188 distribution of hot plume material ponding below "normal" lithosphere is a controlling parameter 189 for deformation localization at the crustal level. Very small variations in initial plume position 190 with respect to cratonic bodies (up to several tens km only) appear to be able to change the 191 relation between these three segments of separated plume head that, in turn, alters the degree of 192 193 development of corresponding rift branches. We argue, thus, that the resulting rifting pattern is largely controlled by relative position of the initial mantle plume anomaly with respect to first-194 order lithospheric thickness differences rather than by second-order crustal and/or lithospheric 195 196 compositional heterogeneities as commonly assumed before (Theunissen et al., 1996; Corti et al., 197 2007; Katumwehe et al., 2015; Smets et al., 2016).

The performed analysis permits to identify an initial model configuration that results in a strain distribution that bears strong similarities with the central and southern EARS showing simultaneous development of the Eastern branch, the Western branch and its southern prolongation by the Malawi rift. The number and relative positions of rift branches with respect to the cratons within the studied area can be explained by an impact of single mantle anomaly on pre-stressed continental lithosphere that does not contain any pre-defined heterogeneities other than the well-known cratonic blocks.

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214 **References**

- Adams, A., Nyblade, A. and Weeraratne, D., 2012. Upper mantle shear wave velocity structure
 beneath the East African plateau: evidence for a deep, plateauwide low velocity anomaly.
 Geophysical Journal International, 189, 123-142.
- Albaric, J., Déverchère, J., Petit, C., Perrot, J. and Le Gall B., 2009. Crustal rheology and depth
 distribution of earthquakes: insights from the central and southern East African Rift
 System. *Tectonophysics*, 468, 28-41.
- Andersen, L.S. and Unrug, R., 1984. Geodynamic evolution of the Bangweulu Block, northern
 Zambia. *Precambrian Research*, 25, 187-212.
- Armitage, J.J., Ferguson, D.J., Goes, S., Hammond, J.O.S., Calais, E., Rychert, C.A. and
 Harmon, N., 2015. Upper mantle temperature and the onset of extension and break-up in
 Afar, Africa. *Earth and Planetary Science Letters*, **418**, 78-90.
- 226Artemieva, I.M., 2006. Global 1×1 thermal model TC1 for the continental lithosphere:227implications for lithosphere secular evolution. *Tectonophysics*, **416**, 245-277.

- Bagley, B. and Nyblade, A.A., 2013. Seismic anisotropy in eastern Africa, mantle flow, and the
 African superplume. *Geophysical Research Letters*, 40, 1500-1505.
- Baker, B.H., Mohr, P.A. and Williams, L.A.J., 1972. Geology of the eastern rift system of Africa.
 Geological Society of America Special Papers, 136, 1-68.
- Baker, B.H., 1987. Outline of the petrology of the Kenya rift alkaline province. *Geological Society, London, Special Publications*, **30**, 293-311.
- Bauer, F.U., Glasmacher, U.A., Ring, U., Karl, M., Schumann, A. and Nagudi, B., 2013. Tracing
 the exhumation history of the Rwenzori Mountains, Albertine Rift, Uganda, using low
 temperature thermochronology. *Tectonophysics*, **599**, 8-28.
- Begg, G.C. et al., 2009. The lithospheric architecture of Africa: Seismic tomography, mantle
 petrology, and tectonic evolution. *Geosphere*, 5, 23-50.
- Bell, K. and Dodson, M.H., 1981. The geochronology of the Tanzanian Shield. *The Journal of Geology*, **89**, 109-128.
- Beniest, A., Koptev, A. and Burov, E., 2017a. Numerical models for continental break-up:
 Implications for the South Atlantic. *Earth and Planetary Science Letters*, 461, 176-189.
- Beniest, A., Koptev, A., Leroy, S., Sassi, W. and Guichet, X., 2017b. Two- branch break- up
 systems by a single mantle plume: Insights from numerical modeling. *Geophysical Research Letters*, 44.
- Braile, L.W., Keller, G.R., Wendlandt, R.F., Morgan, P. and Khan, M.A., 2006. The East African
 rift system. *Developments in Geotectonics*, 25, 213-III.
- Burov, E., 2011. Rheology and strength of the lithosphere. *Marine and Petroleum Geology*, 28, 1402-1443.
- Burov, E. and Cloetingh, S., 2010. Plume-like upper mantle instabilities drive subduction
 initiation. *Geophysical Research Letters*, 37.

- Burov, E. and Gerya, T., 2014. Asymmetric three-dimensional topography over mantle plumes.
 Nature, **513**, 85-89.
- Burov, E. and Guillou-Frottier, L., 2005. The plume head–continental lithosphere interaction using a tectonically realistic formulation for the lithosphere. *Geophysical Journal International*, **161**, 469-490.
- Burov, E., Guillou-Frottier, L., d'Acremont, E., Le Pourhiet, L. and Cloetingh, S., 2007. Plume
 head-lithosphere interactions near intra-continental plate boundaries. *Tectonophysics*,
 434, 15-38.
- Cahen, L., Snelling, N., Delhal, J. and Vail, J., 1984. *The Geochronology and Evolution of Africa*. Oxford Univ. Press, New York.
- Chang, S.J. and Van der Lee, S., 2011. Mantle plumes and associated flow beneath Arabia and
 East Africa. *Earth and Planetary Science Letters*, **302**, 448-454.
- Chang, S.J., Ferreira, A.M.G., Ritsema, J., van Heijst, H.J. and Woodhouse, J.H., 2015. Joint
 inversion for global isotropic and radially anisotropic mantle structure including crustal
 thickness perturbations. *Journal of Geophysical Research: Solid Earth*, 120, 4278-4300.
- Chesley, J.T., Rudnick, R.L. and Lee, C.T., 1999. Re-Os systematics of mantle xenoliths from the
 East African Rift: Age, structure, and history of the Tanzanian craton. *Geochimica et Cosmochimica Acta*, 63, 1203-1217.
- Chorowicz, J., 2005. The east African rift system. *Journal of African Earth Sciences*, 43, 379410.
- Civiero, C.et al., 2016. Small-scale thermal upwellings under the northern East African Rift from
 S travel time tomography. *Journal of Geophysical Research: Solid Earth*, **121**, 73957408.

- Corti, G., Iandelli, I. and Cerca, M., 2013. Experimental modeling of rifting at craton margins.
 Geosphere, 9, 138-154.
- Corti, G., van Wijk, J., Cloetingh, S. and Morley, C.K., 2007. Tectonic inheritance and
 continental rift architecture: Numerical and analogue models of the East African Rift
 system. *Tectonics*, 26.
- Daly, M.C., Chorowicz, J. and Fairhead, J.D., 1989. Rift basin evolution in Africa: the influence
 of reactivated steep basement shear zones. *Geological Society, London, Special Publications*, 44, 309-334.
- Dawson, J., 1992. Neogene tectonics and volcanicity in the North Tanzania Sector of the Gregory
 Rift Valley: Contrasts with the Kenya sector. *Tectonophysics*, 204, 81-92.
- De Waele, B., Liégeois, J.P., Nemchin, A.A. and Tembo, F., 2006. Isotopic and geochemical
 evidence of Proterozoic episodic crustal reworking within the Irumide Belt of south central Africa, the southern metacratonic boundary of an Archaean Bangweulu Craton.
 Precambrian Research, 148, 225-256.
- Ebinger, C., 2005. Continental break-up: the East African perspective. *Astronomy & Geophysics*,
 46, 2-16.
- Ebinger, C.J., 1989. Tectonic development of the western branch of the East African rift system.
 Geological Society of America Bulletin, 101, 885-903.
- Ebinger, C., Poudjom, Y., Mbede, E., Foster, F. and Dawson, J., 1997. Rifting Archean
 lithosphere: The Eyasi-Manyara-Natron rifts, East Africa. *Journal of the Geological Society London*, **154**, 947-960.
- Fishwick, S. and Bastow I.D., 2011. Towards a better understanding of African topography: a
 review of passive-source seismic studies of the African crust and upper mantle.
 Geological Society, London, Special Publications, 357, 343-371.

- Foster, A., Ebinger, C., Mbede, E. and Rex, D., 1997. Tectonic development of the northern
 Tanzanian sector of the East African Rift System. *Journal of the Geological Society London*, 154, 689-700.
- George, R., Rogers, N. and Kelley, S., 1998. Earliest magmatism in Ethiopia: evidence for two
 mantle plumes in one flood basalt province. *Geology*, 26, 923-926.
- Gerya, T.V., 2010. Introduction to Numerical Geodynamic Modelling. Cambridge University
 Press, 358 pp.
- Gerya, T.V. and Yuen, D.A., 2007. Robust characteristics method for modelling multiphase
 visco-elasto-plastic thermo-mechanical problems. *Physics of the Earth and Planetary Interiors*, 163, 83-105.
- Hansen, S.E., Nyblade, A.A. and Benoit, M.H., 2012. Mantle structure beneath Africa and Arabia
 from adaptively parameterized P-wave tomography: Implications for the origin of
 Cenozoic Afro-Arabian tectonism. *Earth and Planetary Science Letters*, 319, 23-34.
- Huismans, R.S. and Beaumont, C., 2007. Roles of lithospheric strain softening and heterogeneity
 in determining the geometry of rifts and continental margins. In: *Imaging, Mapping and*
- 314 Modelling Continental Lithosphere Extension and Breakup (Karner, G.D., Manatschal,
- G.D., Pinheiro, L.M., eds). *Geological Society, London, Special Publications*, 282, 111138.
- Isola, I., Mazzarini, F., Bonini, M. and Corti, G., 2014. Spatial variability of volcanic features in
 early-stage rift settings: the case of the Tanzania Divergence, East African rift system.
 Terra Nova, 26, 461-468.
- Katumwehe, A.B, Abdelsalam, M.G. and Atekwana, E.A., 2015. The role of pre-existing
 Precambrian structures in rift evolution: The Albertine and Rhino grabens, Uganda.
 Tectonophysics, 646, 117-129.

323	Keller, G.R., Khan, M.A., Morganc, P., Wendlandt, R.F., Baldridge, W.S., Olsen, K.H., Prodehl,
324	C. and Braile, L.W., 1991. A comparative study of the Rio Grande and Kenya rifts.
325	<i>Tectonophysics</i> , 197 , 355-371.
326	Keranen, K.M., Klemperer, S.L., Julia, J., Lawrence, J.F. and Nyblade, A.A., 2009. Low lower
327	crustal velocity across Ethiopia: Is the Main Ethiopian Rift a narrow rift in a hot craton?
328	Geochemistry Geophysics Geosystems, 10, Q0AB01.
329	Koptev, A., Burov, E., Calais, E., Leroy, S., Gerya, T., Guillou-Frottier, L. and Cloetingh, S.,
330	2016. Contrasted continental rifting via plume-craton interaction: Applications to Central
331	East African Rift. Geoscience Frontiers, 7, 221-236.
332	Koptev, A., Burov, E., Gerya, T., Le Pourhiet, L., Leroy, S., Calais, E. and Jolivet, L., 2017a.
333	Plume-induced continental rifting and break-up in ultra-slow extension context: Insights
334	from 3D numerical modeling. <i>Tectonophysics</i> , doi.org/10.1016/j.tecto.2017.03.025.
335	Koptev, A., Calais, E., Burov, E., Leroy, S. and Gerya, T., 2015. Dual continental rift systems
336	generated by plume-lithosphere interaction. Nature Geoscience, 8, 388-392.
337	Koptev, A., Cloetingh, S., Burov, E., François, T. and Gerya, T., 2017b. Long-distance impact of
338	Iceland plume on Norway's rifted margin. Scientific Reports, 7.
339	Koptev A.I. and Ershov A.V., 2011. Thermal thickness of the Earth's lithosphere: a numerical
340	model. Moscow University Geology Bulletin, 66, 323-330.
341	Laó-Dávila, D.A., Al-Salmi, H.S., Abdelsalam, M.G. and Atekwana, E.A., 2015. Hierarchical
342	segmentation of the Malawi Rift: The influence of inherited lithospheric heterogeneity
343	and kinematics in the evolution of continental rifts. <i>Tectonics</i> , 34 , 2399-2417.
344	Le Gall, B., Gernigon, L., Rolet, J., Ebinger, C., Gloaguen, R., Nilsen, O., Dypvik, H.,
345	Deffontaines, B. and Mruma, A., 2004. Neogene-Holocene rift propagation in central

Tanzania: Morphostructural and aeromagnetic evidence from the Kilombero area. 346 347 Geological Society of America Bulletin, 116, 490-510. Le Gall, B., Nonnotte, P., Rolet, J., Benoit, M., Guillou, H., Mousseau-Nonnotte, M., Albaric, J. 348 and Deverchère, J., 2008. Rift propagation at craton margin: Distribution of faulting and 349 volcanism in the North Tanzanian Divergence (East Africa) during Neogene times. 350 Tectonophysics, 448, 1-19. 351 Lenoir, J.L., Liégeois, J.P., Theunissen, K. and Klerkx, J., 1994. The Palaeoproterozoic Ubendian 352 shear belt in Tanzania: geochronology and structure. Journal of African Earth Sciences, 353 **19**, 169-184. 354 Manya, S., 2011. Nd-isotopic mapping of the Archaean–Proterozoic boundary in southwestern 355 Tanzania: Implication for the size of the Archaean Tanzania Craton. Gondwana 356 Research, 20, 325-334. 357 358 McClusky, S., Reilinger, R., Mahmoud, S., Sari, D.B. and Tealeb, A., 2003. GPS constraints on Africa (Nubia) and Arabia plate motions. Geophysical Journal International, 155, 126-359 138. 360 361 McConnell, R.B., 1972. Geological development of the rift system of eastern Africa. *Geological* Society of America Bulletin, 83, 2549-2572. 362 Mechie, J., Keller, G.R., Prodehl, C., Khan, M.A. and Gaciri, S.J., 1997. A model for the 363 structure, composition and evolution of the Kenya rift. *Tectonophysics*, 278, 95-119. 364 Mohr, P., 1982. Musings on continental rifts. In: Continental and oceanic rifts (G. Palmason, ed). 365 366 American Geophysical Union Geodynamics Series, 8, 293-309. Mohr, P.A., 1970. The Afar Triple Junction and sea-floor spreading. Journal of Geophysical 367 Research, 75, 7340-7352. 368

- Morley, C.K., 2010. Stress re-orientation along zones of weak fabrics in rifts: An explanation for
 pure extension in 'oblique' rift segments? *Earth and Planetary Science Letters*, 297, 667 673.
- Morley, C.K., Cunningam, S.M., Wescott, W.A. and Harper, R.M., 1999. Geology and geophysics of the Rukwa rift. In: *Geoscience of Rift Systems - Evolution of East Africa* (C.K. Morley, ed). *AAPG Studies in Geology*, **44**, 91-110.
- Mulibo, G.D. and Nyblade, A.A., 2013a. The P and S wave velocity structure of the mantle
 beneath eastern Africa and the African superplume anomaly. *Geochemistry, Geophysics, Geosystems*, 14, 2696-2715.
- Mulibo, G.D. and Nyblade, A.A., 2013b. Mantle transition zone thinning beneath eastern Africa:
 Evidence for a whole-mantle superplume structure. *Geophysical Research Letters*, 40, 3562-3566.
- Nolet, G., Karato, S.I. and Montelli, R., 2006. Plume fluxes from seismic tomography. *Earth and Planetary Science Letters*, 248, 685-699.
- Nyblade, A.A., Owens, T.J., Gurrola, H., Ritsema, J. and Langston, C.A., 2000. Seismic evidence
 for a deep upper mantle thermal anomaly beneath east Africa. *Geology*, 28, 599-602.
- Pasteels, P., Villeneuve, M., De Paepe, P. and Klerkx, J., 1989. Timing of the volcanism of the
 southern Kivu province: implications for the evolution of the western branch of the East
 African Rift system. *Earth and Planetary Science Letters*, 94, 353-363.
- 388 Pérez-Gussinyé, M., Metois, M., Fernández, M., Vergés, J., Fullea, J., and Lowry A.R., 2009.
- Effective elastic thickness of Africa and its relationship to other proxies for lithospheric
 structure and surface tectonics. *Earth and Planetary Science Letters*, 287, 152–167.
- Pik, R., Marty, B. and Hilton, D.R., 2006. How many mantle plumes in Africa? The geochemical
 point of view. *Chemical Geology*, 226, 100-114.

- Ring, U., 1994. The influence of preexisting structure on the evolution of the Cenozoic Malawi
 Rift (East African Rift system). *Tectonics*, 13, 313-326.
- Ring, U., 2014. The East African Rift System. *Austrian Journal Earth Sciences*, **107**, 132-146.
- Ring, U., Betzler, C. and Delvaux, D., 1992. Normal vs. strike-slip faulting during rift
 development in East Africa: the Malawi rift. *Geology*, 20, 1015-1018.
- Ritsema, J., Nyblade, A.A., Owens, T.J. and Langston, C.A., 1998. Upper mantle seismic
 velocity structure beneath Tanzania, East Africa: Implications for the stability of cratonic
 lithosphere. *Journal of Geophysical Research*, 103, 21201-21213.
- 401 Ritsema, J., van Heijst, H.J. and Woodhouse, J.H., 1999. Complex shear wave velocity structure
 402 imaged beneath Africa and Iceland. *Science*, 286, 1925-1928.
- 403 Roberts, E.M., Stevens, N.J., O'Connor, P.M., Dirks, P.H.G.M., Gottfried, M.D., Clyde, W.C.,
- Armstrong, R.A., Kemp, A.I.S. and Hemming, S., 2012. Initiation of the western branch
 of the East African Rift coeval with the eastern branch. *Nature Geoscience*, 5, 289-294.
- 406 Saria, E., Calais, E., Stamps, D.S., Delvaux, D. and Hartnady, C.J.H., 2014. Present-day
 407 kinematics of the East African Rift. *Journal of Geophysical Research*, **119**, 3584-3600.
- 408 Rooney, T.O., Herzberg, C. and Bastow, I.D., 2012. Elevated mantle temperature beneath East
 409 Africa. *Geology*, 40, 27-30.
- Sippel, J. et al., 2017. The Kenya rift revisited: insights into lithospheric strength through datadriven 3-D gravity and thermal modelling. *Solid Earth*, 8, 45.
- 412 Smets, B., Delvaux, D., Ross, K. A., Poppe, S., Kervyn, M., d'Oreye, N. and Kervyn, F., 2016.
- The role of inherited crustal structures and magmatism in the development of rift
 segments: Insights from the Kivu basin, western branch of the East African Rift. *Tectonophysics*, 683, 62-76.

- Smith, M., 1994. Stratigraphic and structural constraints on mechanisms of active rifting in the
 Gregory Rift, Kenya. *Tectonophysics*, 236, 3-22.
- Stamps, D.S., Calais, E., Saria, E., Hartnady, C., Nocquet, J.M., Ebinger, C.J. and Fernandes,
 R.M., 2008. A kinematic model for the East African Rift. *Geophysical Research Letters*,
 35.
- Theunissen, K., Klerkx, J., Melnikov, A. and Mruma, A., 1996. Mechanisms of inheritance of rift
 faulting in the western branch of the East African Rift, Tanzania. *Tectonics*, 15, 776-790.
- Versfelt, J. and Rosendahl, B.R., 1989. Relationships between pre-rift structure and rift
 architecture in Lakes Tanganyika and Malawi, East Africa. *Nature*, **337**, 354-357.
- Weeraratne, D.S., Forsyth, D.W., Fischer, K.M. and Nyblade, A.A., 2003. Evidence for an upper
 mantle plume beneath the Tanzanian craton from Rayleigh wave tomography. *Journal of Geophysical Research: Solid Earth*, 108.
- Wenker, S. and Beaumont, C., 2016. Effects of lateral strength contrasts and inherited
 heterogeneities on necking and rifting of continents. *Tectonophysics*,
 http://dx.doi.org/10.1016/j.tecto.2016.10.011.
- Williams, L.A.J., 1982. Physical aspects of magmatism in continental rifts. *Continental and oceanic rifts*, 193-222.
- Zeyen, H., Volker, F., Wehrle, V., Fuchs, K., Sobolev, S.V. and Altherr, R., 1997. Styles of
 continental rifting: crust-mantle detachment and mantle plumes. *Tectonophysics*, 278,
 329-352.

437 **Figure captions**



Figure 1. Topographic map showing the tectonic setting of the central and southern EARS (after Mulibo and Nyblade (2013b) and Corti et al. (2013)) that comprises the Tanzanian craton that likely includes the Uganda Basement Complex (UgB), the Bangweulu block, the Masai block and several Proterozoic orogenic belts: Rwenzori (RwB), Kibaran (KiB), Ubendian (UbB), Usagaran (UsB), Mozambique (MoB), Iruminde (IrB), Southern Iruminde (SIrB), Lufilian (LuB). Black lines show major faults (Corti et al., 2013). The inset indicates the location of the studied area.



Figure 2. Model setups for the general model series shown on Figure 4: a) the models 2-4, 446 characterized by a simple quasi-rectangular shape of the Tanzanian craton as in previously 447 published experiments (Koptev et al., 2015, 2016); b) the models 5-13, with a more complex 448 asymmetrical configuration of the Tanzanian block (based on its present-day surface outline). 449 Initial plume positions are shown by red circles within tested areas (shaded green) with respect to 450 cratonic blocks (gray ellipses). "No-plume" model 1 (see Figure 3) is characterized by simple 451 symmetrical configuration of the Tanzanian craton and by absence of pre-imposed mantle plume 452 anomaly. The initial model setup and geotherm have been adopted with respect to observation-453 454 based models of regional thermal and rheological structure of the continental lithosphere in East Africa (Artemieva et al., 2006; Albaric et al., 2009; Pérez-Gussinyé et al., 2009; Fishwick and 455 456 Bastow, 2011). Rheological parameters have been chosen in consideration of extensive and successful experience obtained from heterogeneous continental rifting (e.g., Huismans and 457 Beaumont, 2007; Wenker and Beaumont, 2016 and references therein) and plume-lithosphere 458 459 interaction modelling (e.g., Burov and Guillou-Frottier, 2005; Burov et al., 2007; Burov and Cloetingh, 2010; Burov, 2011; Burov and Gerya, 2014; Koptev et al., 2017a,b; Beniest et al., 460 461 2017a,b) including our previous Africa-oriented experiments (Koptev et al., 2015, 2016) that have permitted to reproduce a number of key features of the central EARS as timing, surface 462 velocity distribution, and large-scale topography. 463



Figure 3. "No-plume" model 1 at 5 Myr. Blue to red colors indicate crustal strain rate. The 465 cratons are the dark gray volumes. Unidirectional tectonic stretching of the continental 466 lithosphere in the absence of active mantle upwelling results in distributed closely spaced small-467 468 offset parallel faults, which are not localized within any particular zone. Upper crustal distributed deformation covers all model domains uniformly (including the cratonic areas) because of lateral 469 homogeneity of the crustal composition adopted in the general model series. Note that 470 progressive focusing and amplification of localized non-axisymmetric deformation is generated 471 only by simultaneous presence of the hot plume material underneath the lithosphere basement 472 and passive horizontal extension while mantle plume impingement on non-pre-stressed 473 lithosphere can only result in axisymmetric domal-shaped features with multiple radiating rifts 474 (see Burov and Gerya, 2014 for more detail). 475



Figure 4. Top view of the results of 3D experiments 2-13 at 5-10 Myr. The plume material is
shown in dark red. Left top insets schematically illustrate initial position of the mantle plume.
Note that relative position of lithospheric heterogeneities and initial mantle plume anomaly
appears to be the crucial factor for resulting rifting pattern.



Figure 5. The "best-fit" experiment 9 (*Asym.E/20,S/220*) of the general model series: a) 3D view;
b) top view; c) corresponding surface topography; d) bottom view. Note that strain distribution
bears strong similarities with the central and southern EARS showing the "three-branches"
pattern with simultaneous development of the Eastern branch, the Western branch and the
Malawi rift.



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Figure 6. Top view of the complementary models **14-17** at 5-10 Myr. Complementary models differ from the general model series (models **1-13**; Figure 4-5) by: a-b, d) the presence of third area of lithospheric thickening corresponding to the Masai block (models **14-15**, **17**) and/or by cd) a stronger rheology for the lower crust within cratonic areas (models **16-17**). Note that these experiments containing more predefined complexities provide better fitting with the observed data than in case of the general model series. In particular, the model **17** reproduces not only

494 three first-order rift structures corresponding to the Eastern branch, the Western branch and the 495 Malawi rift but also such second-order features as NW-SE oriented Rukwa rift and along-axis 496 transition observed between the narrow Kenya rift and the broader Turkana depression to the 497 north and the multi-basin North Tanzania Divergence Zone to the south (compare Figure 1 and 498 Figure 6d).

Table 1. Controlling parameters of the models.

Model	Model	Model title	Controlling parameters				Figure
number	series		Tanzanian	Plume	Presence of	Stronger	1
			craton shape	position	the Masai	lower crust	
				(az/shift, km)	block	for cratons	
1	General	Sym.No plume	Symmetrical	-	No	No	Fig.3
2	General	Sym.W/10,S/230	Symmetrical	W/10, S/230	No	No	Fig4a
3	General	Sym.S/230	Symmetrical	E/0, S/230	No	No	Fig4b
4	General	Sym.E/10,S/230	Symmetrical	E/10, S/230	No	No	Fig4c
5	General	Asym.W/10,S/230	Asymmetrical	W/10, S/230	No	No	Fig4d
6	General	Asym.S/230	Asymmetrical	E/0, S/230	No	No	Fig4e
7	General	Asym.E/10,S/230	Asymmetrical	E/10, S/230	No	No	Fig4f
8	General	Asym.E/20,S/230	Asymmetrical	E/20, S/230	No	No	Fig4g
9	General	Asym.E/20,S/220	Asymmetrical	E/20, S/220	No	No	Fig4h;
							Fig.5
10	General	Asym.E/20,S/210	Asymmetrical	E/20, S/210	No	No	Fig4i
11	General	Asym.E/30,S/230	Asymmetrical	E/30, S/230	No	No	Fig4j
12	General	Asym.E/30,S/220	Asymmetrical	E/30, S/220	No	No	Fig4k
13	General	Asym.E/30,S/210	Asymmetrical	E/30, S/210	No	No	Fig41
14	Complementary	Asym.E/20,S/220;	Asymmetrical	E/20, S/220	Yes	No	Fig6a
		with Masai					
15	Complementary	Asym.E/30,S/210;	Asymmetrical	E/30, S/210	Yes	No	Fig6b
		with Masai					
16	Complementary	Asym.E/20,S/220;	Asymmetrical	E/20, S/220	No	Yes	Fig6c
		with diff.crust					
17	Complementary	Asym.E/30,S/210;	Asymmetrical	E/30, S/210	Yes	Yes	Fig6d
		with Masai+diff.crust					