An Investigation of Continental Rift-Parallel Deformation

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In the East African Rift (EAR), an archetype continental rift system and "focus-site" for GeoPRISMS, large-scale plate motions can be described by traditional rifting models (*e.g.* McKenzie, 1978; Wernicke 1981; Buck, 1991; Calais et al., 2006; Stamps et al., 2008) that predict rift-perpendicular extension (Figure 1A). Interestingly, 9 new GPS-derived velocities show a pattern of rift-parallel deformation along the Rukwa Rift, Western Branch, and Main Ethiopian Rift (Figure 1B). Rift-parallel GPS velocities presented here are poorly constrained due to short observation periods, as shown by the large confidence ellipses. Verifying the existence of rift-parallel deformation within the EAR and determining the responsible mechanism would provide a more complete understanding of continental rifting processes.

Rift-parallel deformation may be ubiquitous across all rifts in the EAR, which would challenge our current understanding of continental rifting mechanisms. Although the number and quality of GPS observations along the East African Rift has increased significantly over the past decade (*e.g.* Sella 2002; Fernandes et al., 2004; Bendick et al., 2006; Stamps et al., 2008; Kogan et al., 2012) many of the EGPS observations are unreliable due to short observation periods. The timespan of all CGPS velocities shown in Figure 1B (yellow vectors) is greater than 2.5 years and considered reliable within 3 sigma as shown by Blewitt and Lavalleé (2002). The EGPS sites shown in Figure 1B were installed in 2006 and 2007 with the most recent occupations made in 2010, hence the time-span of EGPS velocities shown in Figure 1B (red vectors) is 3-4 years. Currently, 3-sigma uncertainties are larger than the velocity magnitudes on EGPS data that indicate rift-parallel plate motions (Figure 1B.). We propose making additional observations at these sites to decrease the level of uncertainty on EGPS velocities such that we can determine the extent of rift-parallel deformation along the Western Branch and Rukwa Rift of the EAR.

The pattern of rift-parallel motions observed in East Africa conflict with traditional continental rifting models and may indicate additional processes influence rift initiation and evolution. The current end-member models of rifting that have replaced "passive" and "active" rifting models are classified as (1) tectonic stretching, far-field tectonic forces break strong continental lithosphere, and (2) magma-assisted rifting, magmatic intrusions weaken the lithosphere and reduce the amount of force required for continental rupture (Buck, 2004). In each end-member case, predicted surface motions that result from rift initiation are perpendicular to the rift axis. If GPS observations confirm rift-parallel motions across multiple rift segments, a new model of continental rifting is needed.

Plate motions driven by upper mantle flow through mechanical coupling has long been a proposed mechanism for surface deformation (*e.g.* Morgan, 1972; Forsyth and Uyeda,1975; Richardson et al., 1979; Kusznir and Park, 1984; Lithgow-Bertelloni and Guynn, 2004; Bird et al., 2008; Forte et al., 2010, Ghosh and Holt, 2012). In Africa, a recent study by Stamps et al. (submitted) using a "top-down" approach (forces are derived from lithospheric observations) suggests tractions from mantle flow contribute up to 30% of the total force budget sustaining present-day rifting across the East African Rift. Using a "bottom-up" approach (forces are derived from mantle constraints), Forte et al. (2010) suggest asthenospheric flow contributes to the force balance driving rifting in East Africa, however the degree of coupling at the scale of rift segments ($\sim$800$\times$200 km) is undetermined because the number of surface deformation observations and the resolution of seismic tomography were limited.

In the East African Rift, geophysical observations of crust/mantle composition and the timing of volcanism from petrology studies can be explained by along-axis, channelled asthenospheric flow (*e.g.* Ebinger and Sleep, 1998; Walker et al., 2004; Chang and Van der Lee, 2011). If coupling is high, hypothesized rift-parallel asthenospheric flow may drive rift-parallel surface deformation within and around rift-segments, a hypothesis that can be tested with new GPS observations, detailed fault-derived strain rate maps, and geodynamic modeling. Alternative hypotheses for rift-parallel deformation include shearing along existing transform faults due to rift-propagation (*e.g.* Hey et al., 1980), strain accumulation within the elastic crust over multiple rifting episodes (Hetland and Hager, 2004), and rotation of blocks within rifts at overstepping rift segments.

Imperative for testing hypotheses about localized rift-parallel deformation within the East African Rift are (1) new GPS observations along rift-parallel transects that are currently not addressed with GeoPRISMS's aim to density rift-perpendicular GPS observations (cf. Reilinger et al. White Paper), (2) a detailed understanding of the role of vertical and lateral variations in viscosity within the lithosphere and upper mantle at the scale of individual rift segments (∼800×200 km), and (3) integrated geodynamic models that explain geophysical observations. Therefore, we plan to:

- remeasure key geodetic markers along rift-parallel transects (Rukwa Rift, Western Branch)
- construct viscosity models that satisfy the latest geophysical constraints (Main Ethiopian Rift, Western Branch, and Rukwa Rift)
- developed geodynamic models to test the influence of hypothesized asthenospheric flow on rift-parallel surface deformation (Main Ethiopian Rift, Western Branch, and Rukwa Rift)

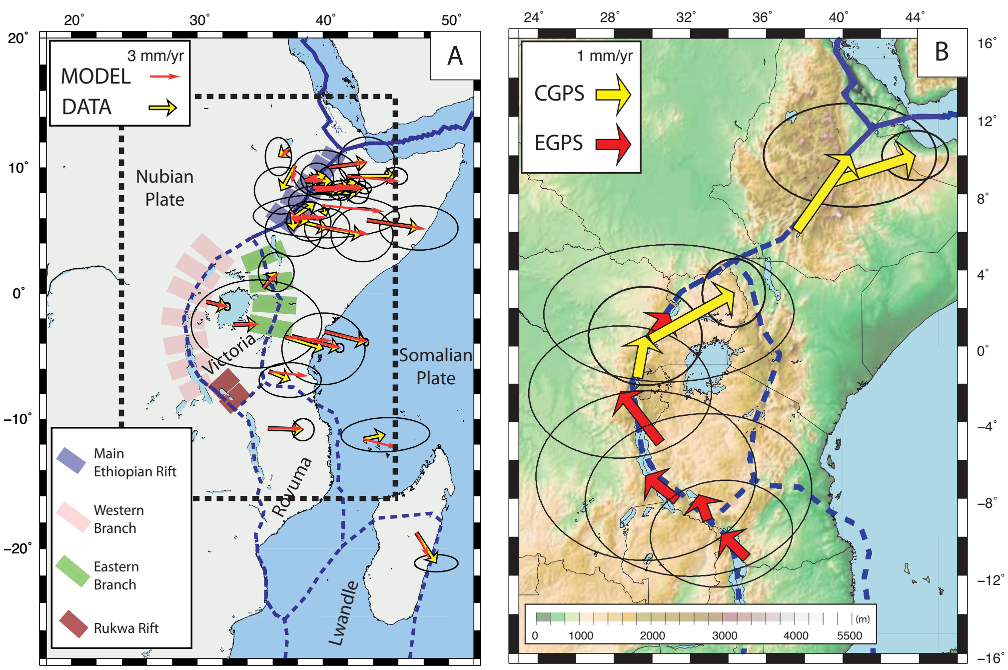

Figure 1: A. A kinematic model of the East African Rift (Stamps et al., submitted). B. New GPS data along the Rukwa Rift, Western Branch, and Main Ethiopian Rift that does not conform to predicted plate motions. Red vectors are episodic GPS (EGPS) velocities from sites installed in 2006 and 2007. Yellow vectors are continuous GPS (CGPS) velocities from sites installed in 2007 or later. All data and predicted velocities are in a Nubia-fixed reference frame. Confidence ellipses are 3-sigma, 95%. Blue dashed lines represent approximate plate boundaries based on seismicity distribution (Stamps et al., 2008).

Bendick, R., S. McClusky, R. Bilham, L. Asfaw, and S. Klemperer, Distributed Nubia-Somalia relative motion and dike intrusion in the Main Ethiopian Rift. Geophys. J. Int. doi:10.1111/j.1365-246X.2006.02904.x, 2006

Bird P., Z. Liu , W.K. Rucker, Stresses that drive the plates from below: Definitions, computational path, model optimization, and error analysis, *J. Geophys. Res., 113*, B11406, .doi:10.1029/2007JB005460, 2008.

Blewitt, G. and D. Lavallée, Effect of annual signals on geodetic velocity, *J. Geophys. Res., 107(B7)*, 10.1029/2001JB 000570, 2002.

Buck, W.R., Modes of continental lithospheric extension, *J. Geophys. Res., 96*, 20,161-20,178, 1991.

Buck, W.R., Consequences of athenospheric variability on continental rifting, in Rheology and Deformation of the Lithosphere at Continental Margins, G. D. Karner, B. Taylor, N. Driscoll, and D. Kohlstedt, Columbia University Press, New York, 1-30, 2004.

Calais E., C. J. Ebinger, C. Hartnady, and J.-M. Nocquet, Kinematics of the East African Rift from GPS and earthquake slip vector data, in *The Afar Volcanic Province Within the East African Rift System,* vol. 259, edited by G. Yirgu et al, pp. 9-22, Gel. Soc. of Lond. Spec. Pub.

Ebinger, C.J., and N.H. Sleep, Cenozoic magmatism in central and east Africa resulting from impact of one large plume, *Nature, 395*, 788-791, 1998.

Fernandes R.M.S, B.A.C. Ambrosius, R. Noomen, L. Bastos, L. Combrinck, J.M. Miranda, W. Spakman, Angular velocities of Nubia and Somalia from continuous GPS data: implications on present-day relative kinematics, *Earth and Planetary Science Letters, 222*, 197-208, 2004.

Forsyth D. and S. Uyeda, On the relative importance of the driving forces of plate motion, *Geophys. J. R. Astr. Soc., 43*, 163-200, 1975.

Forte A.M., S. Quéré, R. Moucha, N.A. Simmons, S.P. Grand, J.X. Mitrovica, and D.B. Rowley, Joint seismic geodynamic-mineral physical modeling of African geodynamics: A reconciliation of deep-mantle convection with surface geophysical constraints, *Earth Planet. Sci. Lett., 295*, 329-341, doi:10.1016/j.epsl.2010.03.017, 2010.

Ghosh A. and W. Holt, Plate motions and stresses from global dynamic models, *Science*, 335(838), dot: 10.1126/science.1214209, 2012.

Hetland E. A. and B. H. Hager, Relationship of geodetic velocities to velocities in the mantle, *Geophys. Res. Ltts., 31*, 10.1029/2004GL020691, 2004.

Hey R., F. Duennebier, and W. J. Morgan, Propagating rifts on midocean ridges, *J. Geophys. Res.,* 85 (B7), 3647-3658, 1980.

Kogan, L., S. Fisseha, R. Bendick, R. E. Reilinger, S. McClusky, B. King, and T. Soloman, Lithospheric strength and strain localization in continental extension from observations of the East African Rift, *J. Geophys. Res.,* doi:10.1029/2011JB008516, 2012.

Kusznir, N.J., and Park, R.G., The extensional strength of the continental lithosphere: its dependence on geothermal gradient, and crustal composition and thickness. In Continental Extensional Tectonics (ed. M. P. Coward, J. F. Dewey, and P. L. Hancock), *Geol. Soc. Lond. (Spec. Publ.) 28*, 35-52, 1987.

Lithgow-Bertelloni, C., and J.H. Guynn, Origin of the lithospheric stress field, *J. Geophys. Res., 109*, B01408, doi:10.1029/2003JB002467, 2004.

McKenzie, D.P., Some remarks on the development of sedimentary basins, *Earth Planet. Sci. Lett. 40*, 25-32, 1978.

Morgan, W.J., Deep mantle convection plumes and plate motions, *The Amer. Assoc. Petro. Geol. Bull., 56(2)*, p. 203-213, 1972.

Richardson, R. M., S. C. Soloman, and N.H. Sleep, Tectonic stress in the plates, *Rev. Geophys. Space. Phys., 17(5)*, 981-1019, 1979.

Sella, G. F., T.H. Dixon and A. Mao, REVEL : A model for recent plate velocities from Space Geodesy, *J. Geophys. Res., 107*, 10.1029/2000JB00033, 2002.

Stamps D.S., E. Calais, E. Saria, C. Hartnady, J.-M. Nocquet, C.J. Ebinger, and R.M. Fernandes, A kinematic model for the East African Rift, *Geophys. Res. Lett., 35*, L05304, doi:10.1029/2007GL03278, 2008.

Stamps D.S., L. M. Flesch, E. Calais, Current kinematics and dynamics of Africa and the East African Rift *J. Geophys. Res.*, submitted.

Walker, K., Nyblade, A.A., Klemperer, S.L., Bokelmann, G.H.R., and Owens, T.J., On the relationship between extension and anisotropy: Constraints from shear wave splitting across the East Africa Plateau, *J. Geophys. Res., 109*, doi:10,1029/2003JB002866, 2004.

Wernicke, B., Low-angle normal faults in the basin and range province: nappe tectonics in an extending orogen, *Nature, 291*, 645-647, 1981.