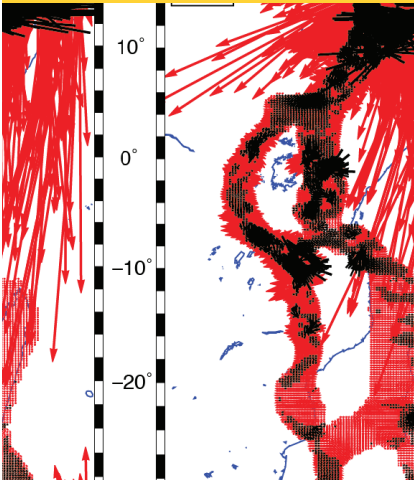


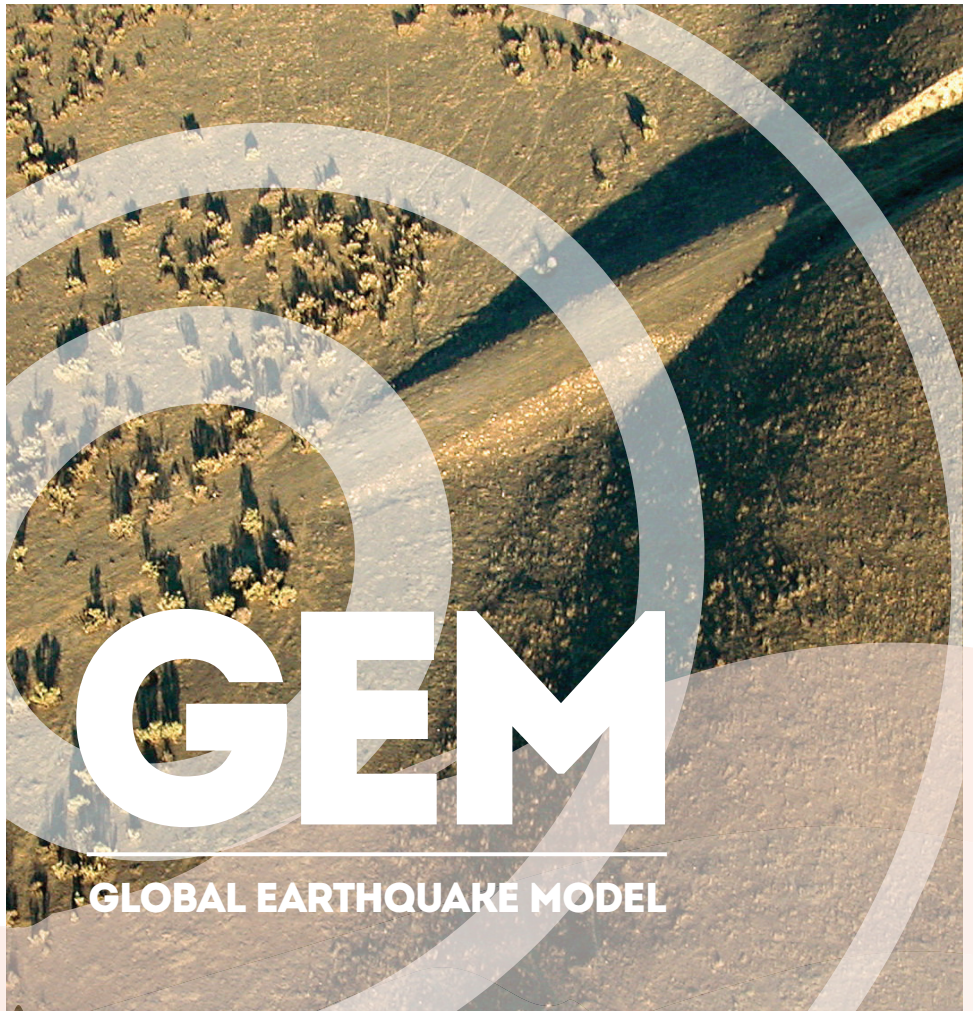
Sub-Saharan Africa Geodetic Strain Rate Model 1.0

GEM PROJECTS REPORT
2015-03 V1.0.0



D.S. Stamps, E. Saria, C. Kreemer

GEOLOGICAL,
EARTHQUAKE AND
GEOPHYSICAL DATA





USAID
FROM THE AMERICAN PEOPLE

This report is made possible by the generous support of the American people through the United States Agency for International Development (USAID). The contents are the responsibility of D.S. Stamps, E. Saria, C. Kreemer and do not necessarily reflect the views of USAID or the United States Government.

SUB-SAHARAN AFRICA GEODETIC STRAIN RATE MODEL 1.0

GEM PROJECTS REPORT 2015-03 V1.0.0



 **GEM**
GLOBAL EARTHQUAKE MODEL
working together to assess risk

Sub-Saharan Africa Geodetic Strain Rate Model 1.0

Strain Rate Model / Sub-Saharan Africa

Deliverable: geodetic strain rate model for Sub-Saharan Africa

Version: 1.0

Author(s): D. S. Stamps, E. Saria, C. Kreemer

Date: September 2015

Copyright © 2015 **[D. S. Stamps, E. Saria, C. Kreemer]** Except where otherwise noted this work is made available under the terms of Creative Commons Attribution-ShareAlike 4.0 ([CC BY-SA 4.0](https://creativecommons.org/licenses/by-sa/4.0/)).

The views and interpretations in this document are those of the individual author(s) and should not be attributed to the GEM Foundation. With them also lies the responsibility for the scientific and technical data presented. The authors do not guarantee that the information in this report is completely accurate. .

GEM.Project.Report.2015-03.V1.0.0,.GEM.Foundation,.Pavia,.Italy,.doi:10.13117/GEM.REG.TR2015.03.

Citation: **Stamps, D.S., E. Saria, C. Kreemer (2015) Sub-Saharan Africa Geodetic Strain Rate Model 1.0, August 2015, Strain Rate Model / Sub-Saharan Africa**, available from <http://www.globalquakemodel.org/what/seismic-hazard/strain-rate-model/>.

ABSTRACT

In this report we describe the Sub-Saharan Africa Geodetic Strain Rate Model 1.0, which is a contribution to the Global Earthquake Model Foundation (GEM) Strain Rate Project. The objective of this work is to improve the latest GEM geodetic strain rate model with an updated strain rate field of sub-Saharan Africa. Sub-Saharan Africa encompasses the East African Rift System (EARS), the active divergent plate boundary between the Nubian and Somalian plates, which accommodates strain along the boundaries of at least 3 microplates. The current version of the GEM geodetic strain rate model is constrained by published geodetic data along the EARS and includes microplates between the Nubian and Somalian plates. In this work we developed an improved strain rate field for sub-Saharan Africa that incorporates 1) an expanded geodetic velocity field within the Nubia-Somalia plate system and along the EARS 2) redefined regions of deforming zones guided by seismicity distribution, and 3) updated constraints on block rotations from the recent publication of Saria et al. (2014). The Sub-Saharan Africa Geodetic Strain Rate Model 1.0 spans longitudes 22 to 55.5 and latitudes -52 to 20 with 0.5° (longitude) by 0.4° (latitude) spacing, which includes part or all of the following plates and/or sub-plates: Somalia, Nubia, Rovuma, Lwandle, Victoria, Antarctica, and Arabia. For these plates/sub-plates we assign rigid block rotations as boundary constraints on the strain rate calculation that is determined using the Haines and Holt method of fitting splines to geodetic data for an interpolated velocity gradient tensor field. We derive strain rates, velocities, and vorticity rates from the velocity gradient tensor field. Following the work of Kreemer et al. 2014 for the GEM geodetic strain rate field we also provide estimates of model uncertainties, velocities, vorticity, and strain rates in a Nubia-fixed reference frame relative to the lower mantle for a $0.1^\circ \times 0.1^\circ$ mesh.

Keywords: strain rate; East African Rift System; Sub-Saharan Africa; geodesy; GPS; Global Earthquake Model

TABLE OF CONTENTS

| | Page |
|---|------|
| ABSTRACT | ii |
| TABLE OF CONTENTS | iii |
| LIST OF FIGURES | iv |
| 1 Acknowledgements | 1 |
| 2 Introduction..... | 2 |
| 3 Methodology | 3 |
| 3.1 Mesh Geometry | 3 |
| 3.2 Geodetic Velocity Solution | 4 |
| 3.3 Geodetic Strain Rate Calculation..... | 6 |
| 4 Results | 7 |
| 5 Final Remarks | 9 |
| REFERENCES..... | 10 |

LIST OF FIGURES

| | Page |
|--|------|
| Figure 3.1 A. Locations of coordinates that define the mesh. B. Seismicity from the International Seismic Catalog. C. Black shows regions we define as deforming relative to areas we consider rigid. | 3 |
| Figure 3.2 GPS velocity field in a Nubia-fixed reference frame (Saria et al. 2013). Red vectors are within the deforming zones as defined in this work. White vectors are positioned in rigid zones constrained by Euler poles. Uncertainty ellipses are 95%..... | 5 |
| Figure 3.3 A. Step one. B. Step two of the methodology used in this work following Kreemer et al. (2014). Red represents extensional strain components and black represents compressional tensor components. | 6 |
| Figure 4.1 A. Input GPS data and modeled velocities. B. Strain rate tensor field. Red = extension, black = compression. C.The second invariant of the strain rate tensor. D. The trace of the strain rate tensor..... | 8 |

1 Acknowledgements

Materials in this work are based on data and equipment services provided by the UNAVCO Facility with support from the National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA) under NSF Cooperative Agreement No. EAR-0735156. We are grateful for the efforts of the International GNSS Service for providing data products and access to publicly accessible GNSS data. GPS data collection by D.S. Stamps was funded by NSF EAR Postdoctoral Fellowship Program #EAR-1249295 and is available through the UNAVCO archive in accordance with data policies. We also thank the institutions and scientists who contribute to the following networks from which we included data in our geodetic analysis: AFREF; AfricaArray; the Institute and Observatory of Antananarivo (IOGA); Ardhi University; TRIGNET, NIGNET, SIO, IGS, and SEGAL. ALL figure were made with GMT5.0.

2 Introduction

The GEM Foundation aims to improve the global GEM strain rate model (Kreemer et al., 2014) by revising regional strain rate estimates. Sub-Saharan Africa (SSA) is one of the GEM Foundation's 8 defined regions. The previous estimates of strain in SSA from the GEM geodetic strain rate model were based largely on published geodetic data and, in the SSA region, block rotations from MORVEL (DeMets et al., 2010). Since the publication of the GEM geodetic strain rate model new observations have been obtained along the East African Rift System and Saria et al. (2014) published new angular velocity vectors for the Somalian, Antarctica, Victoria, Rovuma, and Lwandle plates and sub-plates. Stamps et al. (2014) also published a continuous strain rate field for the region using both geodetic and seismic data. In this work we incorporate only geodetic information from both the new geodetic data and Euler poles to develop a new strain rate model calculated using the methods of Haines and Holt (e.g., Haines and Holt, 1993; Haines et al, 1998; Holt et al., 2000; Beavan and Haines, 2001).

3 Methodology

3.1 Mesh Geometry

Our mesh for SSA includes the region from longitudes 26 to 55.5 and latitude -52 to 20 with grid spacing of 0.5° in longitude and 0.4° in latitude (Figure 1A). We chose these values for grid spacing because they are compatible with the GEM geodetic strain rate field. These choices will allow for integration of the SSA geodetic strain rate field into the next version of the GEM global geodetic strain rate model. We define regions of deformation by evaluating the locations of seismicity data from the International Seismicity Catalog (Figure 1B), the locations of existing GPS observations, and previous studies that indicate rigidity (i.e. Malservisi et al., 2013; Saria et al. 2013). Along the EARS we outline zones of profuse active seismicity and then reduce these zones because there are currently no GPS observations available to constrain the possible deformation or the region is rigid within observational error (Figure 1C). In particular, we note active seismicity in the South Western Branch of the EARS, but remove these predefined deforming zones because GPS data are absent. Similarly seismicity is present in south Africa, but the existing GPS observations indicate rigidity (i.e. Malservisi et al., 2013).

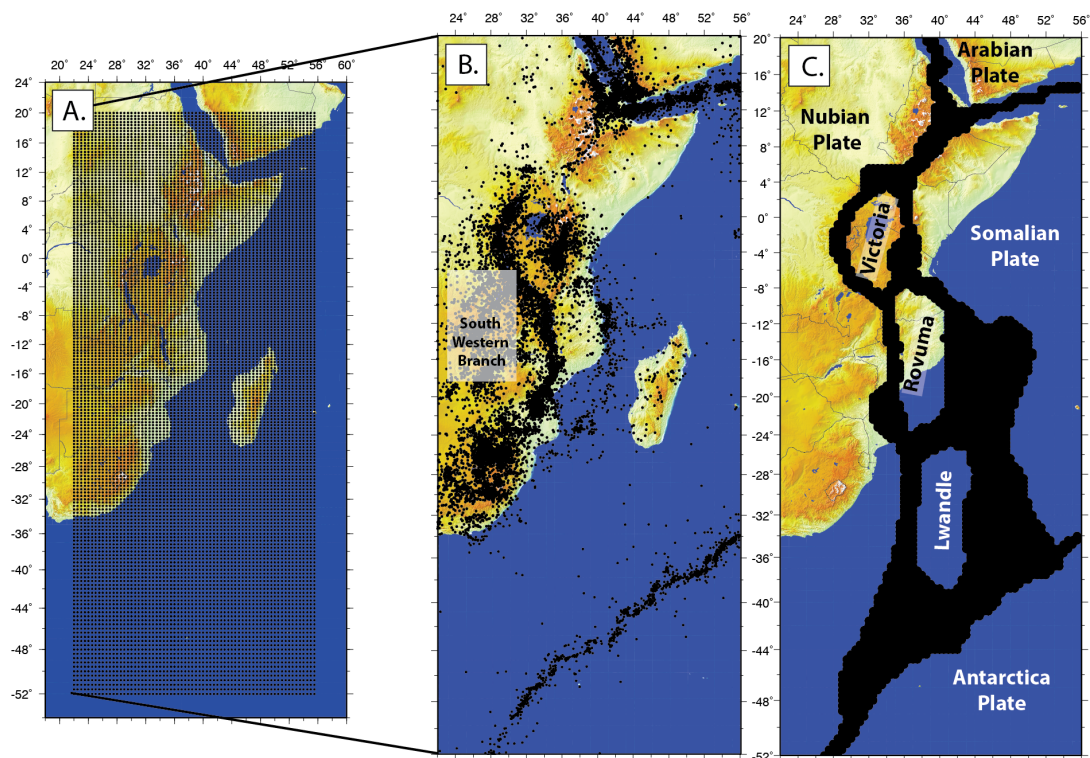


Figure 3.1 A. Locations of coordinates that define the mesh. B. Seismicity from the International Seismic Catalog. C. Black shows regions we define as deforming relative to areas we consider rigid.

3.2 Geodetic Velocity Solution

The geodetic data used in this work to constrain deformation in sub-Saharan Africa are a combination of both continuous and episodic Global Positioning System (GPS) observations. We require at least 2.5 years observations for continuous GPS data to minimize seasonal signals in the time-series (Blewitt and Lavallee, 2002). Episodic GPS sites must have at least 3 or more occupations spanning 4 or more years. In areas where transient deformation is known and/or observed in the time-series, we remove affected sites with one exception. In the Kivu Volcanic Province as separate analysis by Ji et al (in prep) isolated the tectonic signal by applying principal component analysis to the time-series.

We calculate a geodetic solution comprised of publically accessible data (Solution A) and a separate solution (Solution B) that includes newly acquired episodic GPS data in Tanzania (Stamps and Saria, 2015), Uganda (Stamps and Tugume, 2015), and Madagascar (Stamps and Rambolamanana, in prep.). The two solutions are combined by using common sites ABPO, TANZ, EBBE, MBAR, SRTI, REUN, and SEY1 to calculate transformation parameters and rotate the velocity solutions into a consistent Nubia-fixed reference frame. The RMS value is 0.68 mm/yr for the 56 common sites in Solution A and B after the transformation.

In both solutions GPS data are processed with using a three-step approach with GAMIT-GLOBK processing software (Herring et al., 2010) for precise positions and velocities. In a first step we estimate orbital parameters and loosely constrained daily positions with their variance-covariance matrices (quasi-observations), satellite state vectors, phase ambiguities, two horizontal tropospheric gradients per day, and seven tropospheric delay parameters per station per day using doubly differenced phase observables. We correct for solid Earth tides, oceanic loading, and polar tides by applying International Earth Rotation Service standards (McCarthy and Petit, 2003) and phase center corrections based on work by Schmid et al. (2007). For our quasi-observables we employ final orbits and Earth Orientation Parameters produced by the International GNSS Service (International Earth Rotation Service, 2003). Second, we combine our quasi-observations with precise MIT global Solution Independent Exchange (SINEX) files and solve for precise positions in a global reference frame (IGb08) by minimizing coordinate estimates at common, stable IGS reference sites. For solution A we apply the first-order Gauss Markov (FOGM) algorithm to estimate time-correlated noise (Reilinger et al., 2006) for continuous sites and add 1 mm/vyr to the standard error for all other sites to produce realistic and conservative uncertainty estimates. For solution B we do not employ FOGM, rather add 1 mm/vyr to the standard error to all sites and estimate conservative uncertainties. In the final step for both solutions we combine position estimates into a cumulative solution and solve for velocities. Following the procedures noted above we then merge Solution A and B to produce the final velocity solution used to constrain the SSA geodetic strain rate model (Figure 2).

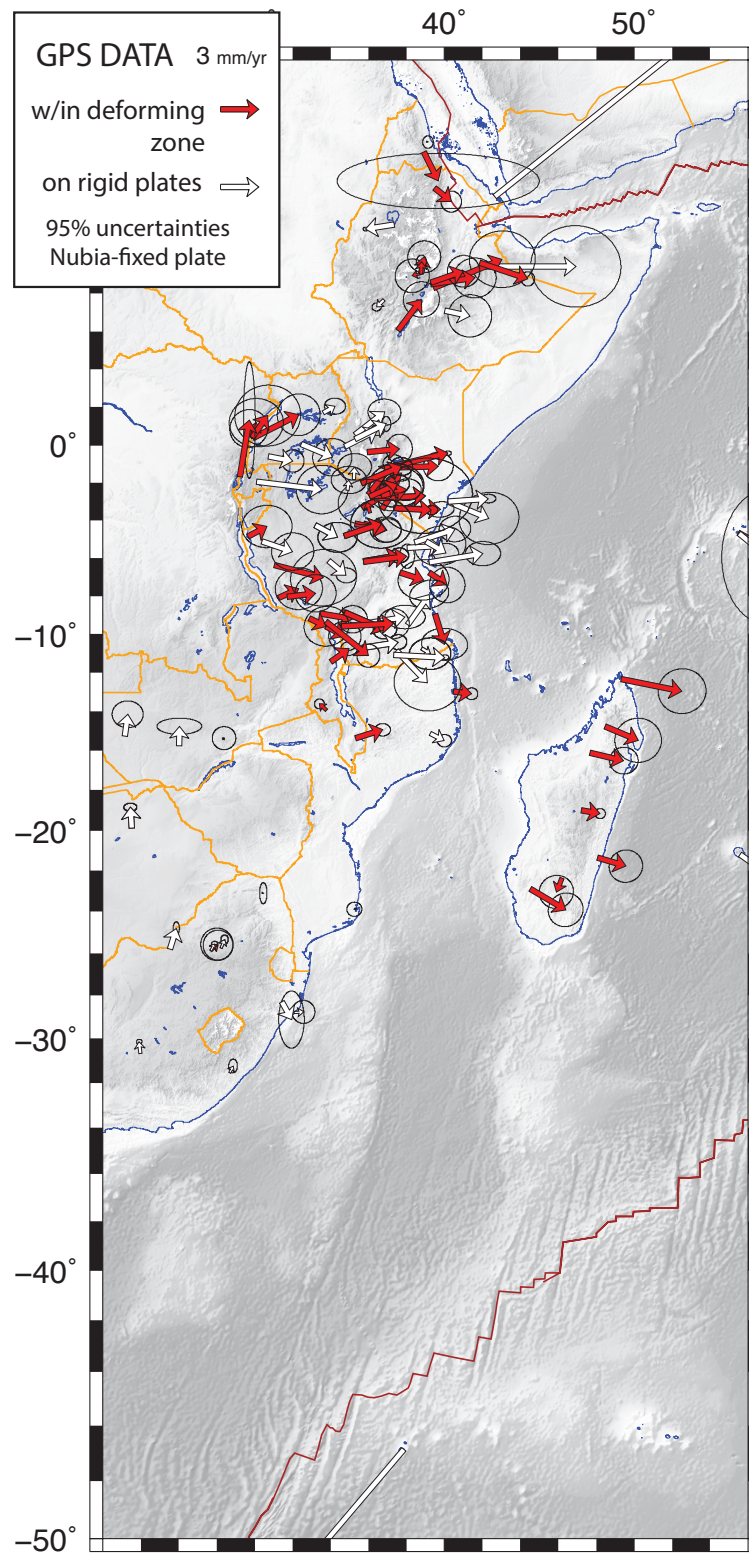


Figure 3.2 GPS velocity field in a Nubia-fixed reference frame (Saria et al. 2013). Red vectors are within the deforming zones as defined in this work. White vectors are positioned in rigid zones constrained by Euler poles. Uncertainty ellipses are 95%.

3.3 Geodetic Strain Rate Calculation

We use the methods of Haines and Holt (e.g., Haines and Holt, 1993; Haines et al, 1998; Holt et al., 2000; Beavan and Haines, 2001) to calculate a continuous strain rate field constrained by geodetic observations. We use this approach for compatibility with the GEM geodetic strain rate model (Kreemer et al., 2014). The Haines and Holt method involves defining zones of rigidity and deformation a priori and fitting bicubic splines to irregularly spaced velocities across pre-defined deforming zones at plate boundaries. To fit deforming regions with relatively higher strain rates compared to the rigid zones this method requires assigning a priori (co)variances to each mesh element in the deforming regions. We follow closely the application of the Haines and Holt method implemented by Kreemer et al. (2014) for the GEM geodetic strain rate model, which involves a two-step approach. First we assign uniform variances with standard deviations 10^{-9} yr^{-1} and $1/\sqrt{2} * 10^{-9} \text{ yr}^{-1}$ for the diagonal ($\dot{\epsilon}_{xx,yy}$) and off-diagonal ($\dot{\epsilon}_{xy}$) components of the strain rate tensor, respectively. In this first step the region is considered isotropic, thus we assign zero covariances (Figure 3A). In the second step, we use the second invariant ($\Omega = \sqrt{\dot{\epsilon}_{xx}^2 + \dot{\epsilon}_{yy}^2 + 2\dot{\epsilon}_{xy}^2}$) and $\Omega/\sqrt{2}$ of the strain rate calculation from the first step to constrain the a priori standard deviations for the diagonal and off-diagonal components of the strain rate tensor, respectively (Figure 3B).

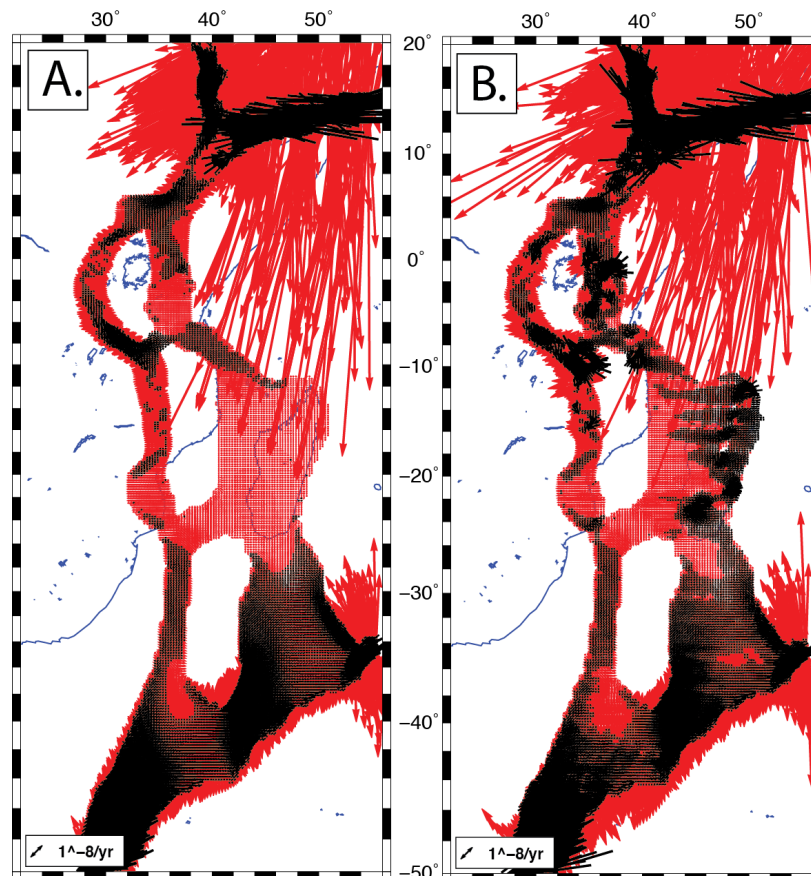


Figure 3.3 A. Step one. B. Step two of the methodology used in this work following Kreemer et al. (2014). Red represents extensional strain components and black represents compressional tensor components.

4 Results

Here we discuss regions in SSA that are geographically distinct from the spreading ridges to show the variations in strain rate tensor styles (Figure 4). Our new geodetic strain rate field in SSA derived from GPS velocities and angular velocity vector constraints in rigid regions fit input GPS observations with a weighted root mean square of 1.99 mm/yr (Figure 4A). In our model strain is largely E-W extensional across SSA (Figure 4B) with larger magnitudes of strain rates within deforming zones and low strain rates in rigid plate interiors, as expected per our definition of rigid and deforming zones. Strain rate magnitudes (Ω) in the SSA range from $\sim 0-2 \times 10^{-8}$ yr⁻¹ with the highest strain rates localized in the Main Ethiopian Rift, the Tanganyika Rift, and the intersection of the Victoria-Nubia-Rovuma plates (Figure 4C). Strain rates are characterized by extensional deformation with small regions of compression along branches of the central EARS and widespread low magnitude compression in eastern and northern Madagascar (Figure 4D).

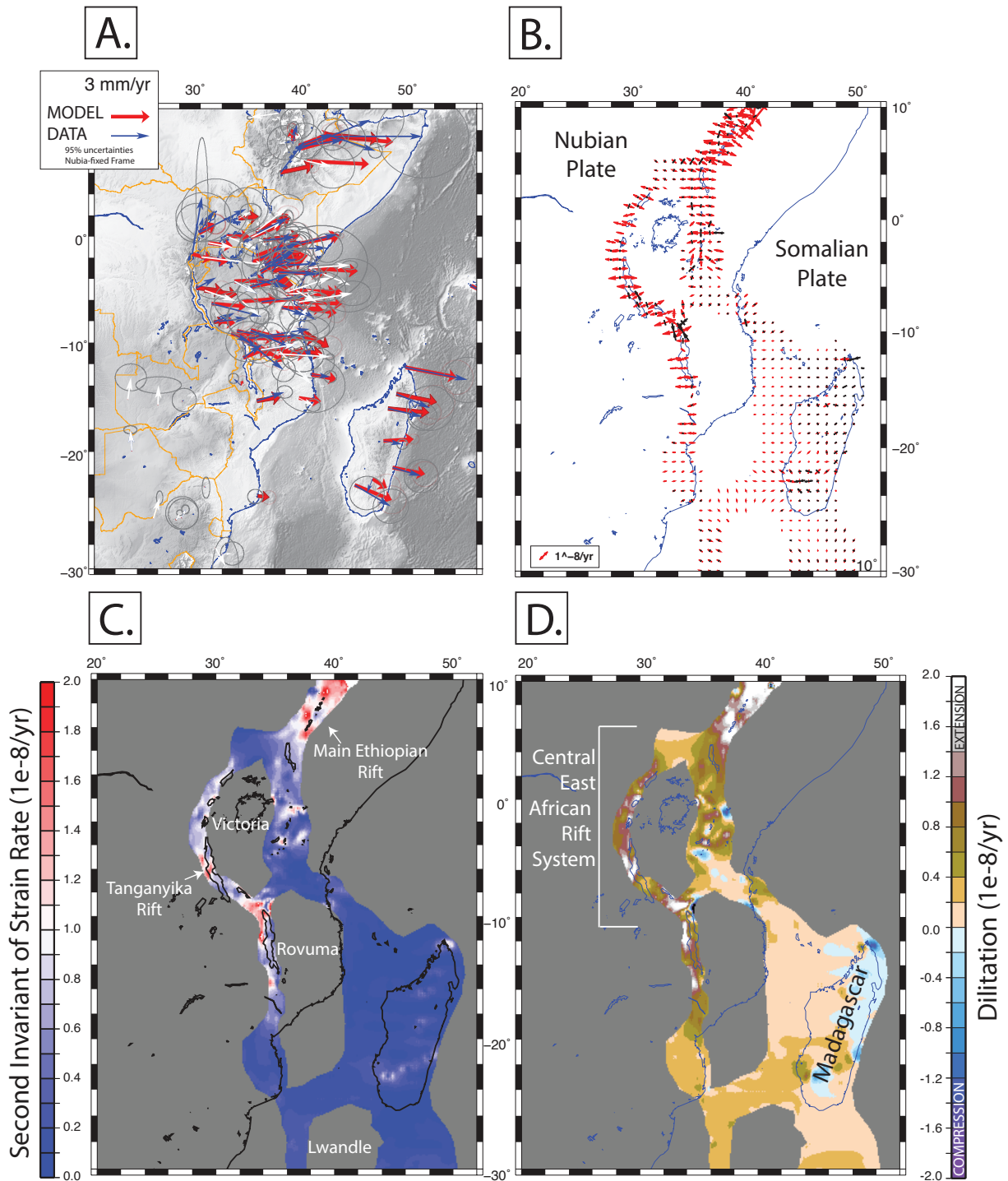


Figure 4.1 A. Input GPS data and modeled velocities. B. Strain rate tensor field. Red = extension, black = compression.

C. The second invariant of the strain rate tensor. D. The trace of the strain rate tensor.

5 Final Remarks

Our new geodetic strain rate field for sub-Saharan Africa (SSA-GSRM 1.0) is a contribution to the Global Earthquake Model Foundation (GEM) strain rate project. We provide gridded strain rate values with uncertainties and correlations, vorticity, and directions of no-length-change for the Global Earthquake Model website. We have used methods that are complementary to the existing GEM global geodetic strain rate field such that future iterations of the GEM global geodetic strain rate model can integrate this work. This work can be used to improve our ability to assess earthquake potential in sub-Saharan Africa.

REFERENCES

Document References

- Beavan, J., and H. Haines (2001), Contemporary horizontal velocity and strain rate fields of the Pacific-Australian plate boundary zone through New Zealand, *J. Geophys. Res.*, 106(B1), 741-770, doi:10.1029/2000JB900302.
- Blewitt, G., and D. Lavallee (2002), Effect of annual signals on geodetic velocity, *J. Geophys. Res.*, 107(B7), 2145, doi:10.1029/2001JB000570.
- DeMets, C., R. G. Gordon, and D. F. Argus (2010), Geologically current plate motions, *Geophys. J. Int.*, 181, 1–80, doi:10.1111/j.1365-246X.2009.04491.x.
- Haines, A. J., W. E. Holt, and D. C. Agnew (1998), Representing distributed deformation by continuous velocity fields, *Sci. Rept. 98/5*, Inst. of Geol. and Nucl. Sci., Wellington, N. Z.
- Haines, A. J., and W. E. Holt (1993), A procedure for obtaining the complete horizontal motions within zones of distributed deformation from the inversion of strain rate data, *J. Geophys. Res.*, 98(B7), 12,057–12,082.
- Herring, T. A., R. W. King, and S. M. McClusky (2010), Introduction to GAMIT/GLOBK Release 10.4, Massachusetts Institute of Technology, Cambridge, Mass.
- Holt, W. E., B. Shen-Tu, J. Haines, and J. Jackson (2000), On the determination of self-consistent strain rate fields within zones of distributed continental deformation, in *The History and Dynamics of Global Plate Motions*, *Geophys. Monogr. Ser. 121*, edited by M. A. Richards, R. G. Gordon, and R. D. van der Hilst, pp. 113–141, AGU, Washington, D. C.
- Kang Hyeun J, D.S. Stamps, H. Geirssone, N. Mashagiروف, M. Syauswaf, B. Kafuduf, J. Subiraf, and N. d’Oreye (in prep), Deep magma accumulation at Nyamulagira volcano in 2011 detected by GNSS observations, *Journal of African Earth Sciences*, Special issue on Active volcanism, continental rifting and geohazards with a special focus on the Kivu rift.

Kreemer, C., G. Blewitt, and E. C. Klein (2014), A geodetic plate motion and Global Strain Rate Model, *Geochem. Geophys. Geosyst.*, 15, 3849–3889, doi:10.1002/2014GC005407.

Malservisi, R., U. Hugentobler, R. Wonnacott, and M. Hackl (2013), How rigid is a rigid plate? Geodetic constraint from the TrigNet CGPS network, South Africa, *Geophys. J. Int.*, 192(3), 918–928, doi:10.1093/gji/ggs081.

McCarthy, D. D., and G. Petit (2003), IERS technical note 32, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie 127 pp., paperback, ISBN 3-89888-884-3.

Reilinger, R., et al. (2006), GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions, *J. Geophys. Res.*, 111, B05411, doi:10.1029/2005JB004051.

Saria, E., E. Calais, Z. Altmamini, P. Pascal, and H. Farah (2013), A new velocity field for Africa from combined GPS and Doris: Contribution to African reference frame, *J. Geophys. Res. Solid Earth*, 118, 1677–1697, doi:10.1002/jgrb.50137.

Saria, E., E. Calais, D. S. Stamps, D. Delvaux, and C. J. H. Hartnady (2014), Present-day kinematics of the East African Rift, *J. Geophys. Res. Solid Earth*, 119, doi:10.1002/2013JB010901.

Schmid, R., P. Steigenberger, G. Gendt, M. Ge, and M. Rothacher (2007), Generation of a consistent absolute phase-center correction model for GPS receiver and satellite antennas, *J. Geod.*, 81, 781–798, doi:10.1007/s00190-007-0148-y.

Stamps, D. S., L. M. Flesch, E. Calais, and A. Ghosh (2014), Current kinematics and dynamics of Africa and the East African Rift System, *J. Geophys. Res. Solid Earth*, 119, doi:10.1002/2013JB010717.

Datasets

Stamps, D.S. and E. Saria (2015), Tanzania 2014, UNAVCO, GPS Data Set, doi:10.7283/T5XD0ZZG

Stamps, D.S. and F. Tugume, (2015). Uganda 2014, UNAVCO, GPS Data Set, doi:10.7283/T5SN077.

Stamps, D.S. and G. Rambolamanana (in prep), Madagascar 2014, UNAVCO, GPS Data Set.

THE GLOBAL EARTHQUAKE MODEL

The mission of the Global Earthquake Model (GEM) collaborative effort is to increase earthquake resilience worldwide.

To deliver on its mission and increase public understanding and awareness of seismic risk, the GEM Foundation, a non-profit public-private partnership, drives the GEM effort by involving and engaging with a very diverse community to:

- Share data, models, and knowledge through the OpenQuake platform
- Apply GEM tools and software to inform decision-making for risk mitigation and management
- Expand the science and understanding of earthquakes.

GEM Foundation

Via Ferrata 1
27100 Pavia, Italy
Phone: +39 0382 5169865
Fax: +39 0382 529131
info@globalquakemodel.org
www.globalquakemodel.org

Copyright © 2015 GEM Foundation,
D.S. Stamps, E. Saria, C. Kreemer



Except where otherwise noted, this work is licensed under a [Creative Commons Attribution-ShareAlike 4.0 License](https://creativecommons.org/licenses/by-sa/4.0/)

SEPTEMBER 2015



GLOBAL EARTHQUAKE MODEL
working together to assess risk

The GEM logo features a stylized globe icon to the left of the letters 'GEM' in a large, bold, sans-serif font. Below this, the full name 'GLOBAL EARTHQUAKE MODEL' is written in a smaller, bold, sans-serif font, followed by the tagline 'working together to assess risk' in a regular weight sans-serif font.