GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 18, PAGES 2789-2792, SEPTEMBER 15, 1999

Secular and Tidal Strain Across the Main Ethiopian Rift

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Abstract. Using a combination of laser ranging and GPS data acquired between 1969 and 1997 we derive a separation velocity for the Somali and Nubian plates in Ethiopia (4.5±1 mm/yr at N108±10E). This vector is orthogonal to the NNE-trending neotectonic axis (Wonji fault belt) of the Ethiopian rift axis. Current rifting is concentrated within a 33-km-wide zone that includes a 7-km-wide belt of late Quaternary faulting where maximum surface strain rates are comparable to those at active plate boundaries (0.1 μstrain/yr). The strain-field suggests that thin (<5 km) elastic crust separates thick continental lithosphere, a geometry quite different from oceanic rifting, and a mechanical configuration that favors the amplification of regional strain. Semidiurnal strain tides, however, as measured by kinematic GPS methods are not amplified along or across the rift, indicating that the rift zone's low rigidity applies only at periods of years.

1. Introduction

For the past 30 million years, the African continental lithosphere has been fragmenting along a series of volcanic and seismic zones collectively called the East African Rift System (*Krenkel*, 1922; *Burke*, 1996). The Main Ethiopian rift is structurally embayed at the latitude of Addis Ababa, yielding an exceptional 120 km width. The rift flanks rise 1 km above the rift floor, steeply via 1 My-old step faults to the southeast and gently via tilt blocks to the northwest. The tectonic axis of the rift floor is offset markedly east from the geographic axis, and is defined both by intense surface faulting and fissuring, and by Quaternary volcanism (*Mohr and Wood*, 1976). Geological evidence from within the rift has been interpreted in terms of both rift-normal opening and oblique extension (*Mohr et al.*, 1978; *c.f. Boccaletti et al.*, 1992; *Bonnini et al.*, 1997) at rates of 3-5 mm/yr. Global plate reconstructions based on seismicity data suggest that the Somali plate at Ethiopian latitudes rotates eastward about an ill-defined point south of Africa at a rate of 5 mm/yr (*Jestin et al.*, 1994). Comparison of Nubia-Antarctica and Somalia-Antarctica rates from large compilations of plate motion data yields a Nubia/Somalia rotation pole at 27.3°S, 36.2°E with a rotation rate of 0.089 deg/My (*Chu and Gordon*, 1999), from which we derive an opening rate of 5.8±1.3 mm/yr at azimuth N95E across the Rift at 9°N.

Geodetic measurements in Ethiopia in 1940 lacked present day accuracies, and it was not until the late 1960s before precise laser ranging (EDM) measurements were initiated in the rift (*Mohr*, 1977; *Mohr et al.*, 1978). We recently measured the relative positions of surviving points of these surveys with GPS (Global Positioning System) geodesy.

The GPS data provide an insight into the widening rate of the Ethiopian rift east of Addis Ababa during the last thirty years. In addition, two linked GPS receivers have been placed on the opposing shoulders of the rift valley at this latitude, and sampling at 30 s intervals have provided information on the constitutive properties of the rift crust. This is achieved through determining the amplitude of strain produced by the application of a known periodic stress tensor (the Earth's body tides), from which is inferred the relative elastic strengths of the crust under rift floor and rift flanks. Although strain and tilt measurements have been used previously to probe local rheologies, their short baselines have made them vulnerable to near surface elastic inhomogeneity (*Evans et al.*, 1979). Our 119-km-long GPS strainmeter across the rift is two orders of magnitude longer than has been used hitherto for tidal strain studies.

2. Secular Strain Accumulation

Between 1969 and 1976 the neo volcano-tectonic zone of the Ethiopian Rift floor was surveyed by EDM methods to an accuracy of 10-15 mm for control points separated by 5-15 km (*Mohr*, 1977). A portion of the largest EDM network between the Alutu and Boseti rift offsets was remeasured in 1992, 1995 and 1997 using Global Positioning System (GPS) geodesy, and expanded at these times to monitor a 120 km wide segment of the rift zone (Figure 1). Control points in the floor of the rift consist of bronze bolts or 6 mm diameter holes in lava flows, and stainless steel pins are used for points on the flanks of the rift. In 1997 several reference marks were occupied in addition to the principal survey points. This permitted identification of an instability in one of the points we measured in 1992, whose inclusion as a valid point had led us to believe that net rift widening rates were close to zero (*Asfaw et al.*, 1992). Elimination of this point from the analysis indicates that the floor of the rift is widening monotonically.

The GPS data were processed using GIPSY software using orbits computed from the global tracking network (*Lichten and Border*, 1987), to yield ± 10 mm uncertainties in 1992 and 1995, and ± 3 mm in 1997. Weighted least squares fits to geodimeter and GPS line length changes are listed in Table 1 and shown graphically in figure 2. Of the two measurement epochs at SELA in 1992, we note that the first day is anomalous. Rejecting this sample and combining the remaining 15 SELA and BOLO GPS east and north data for the period 1992-1998 yields a secular widening velocity of 4.5±1 mm/yr at azimuth N108±10E, orthogonal to the mapped NNE faults of the Wonji Fault Belt. This vector is

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Paper number 1998GL005315.
0094-8276/99/1998GL005315$05.00

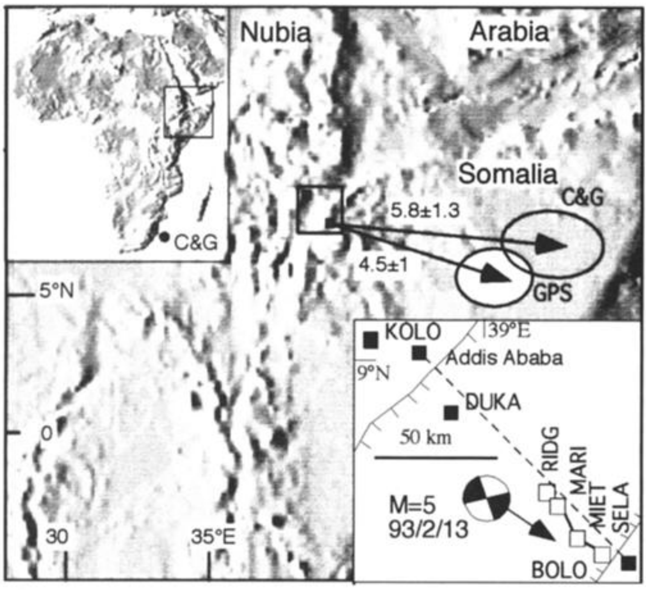

Figure 1. EDM (white) & GPS (black) measurement points in the northern Ethiopian rift. *Chu and Gordon* (1999) pole and slip vector (C&G), compared with new GPS vector (mm/yr with 1σ error). Dashed 119-km-GPS baseline is used to estimate the amplitude of the semi-diurnal lunar earth tide.

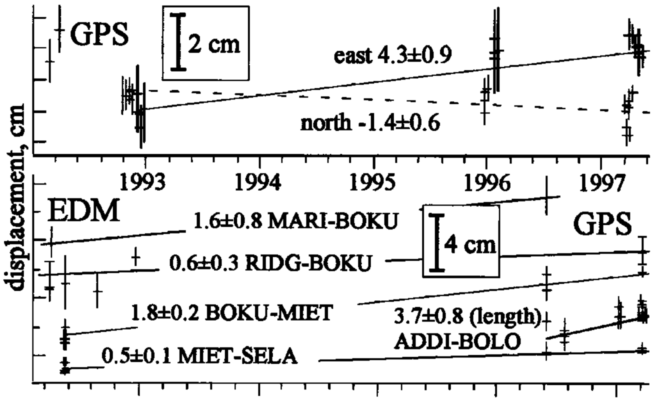

Figure 2. Least-squares fits to line length changes for laser ranging (EDM) and GPS observations. Error bars are 1σ. Top panel shows the east and north components of the 119 km ADDI/BOLO line artificially offset to avoid data overlap.

consistent with the geometry of meters-wide fissures opened in hard welded tuff on the rift floor (*Gibson*, 1974).

We remeasured insufficient EDM lines to retrieve shear strain from these early networks, but we derive from them a cumulative rift-normal rate of 3.9±0.6 mm/yr, similar to the rift-flank widening rate. Hence a substantial fraction of the rift widening signal occurs in a 33-km-wide region at the floor of the rift where Quaternary volcanism and faulting dominate the surface geology (*Morton et al.*, 1979). In 1993 a Mb=5 strike-slip earthquake occurred 12±5 km beneath this zone of maximum extension (Harvard CMT solution, Figure 1). That no significant shear strain is observed in the GPS data bracketing the event is consistent with predicted <2 mm surface deformation from an earthquake of that depth and magnitude. The low observed strain rates on the rift flanks (<0.01 μstrain/year) suggests that large extensional earthquakes (*Gouin*, 1979) must be infrequent.

Maximum strain rates in the Ethiopian Rift at the latitude of Addis Ababa exceed 0.1 μstrain per year, comparable to rates observed at other plate boundaries (Figure 3). Because our observations extend less than 30 km SE of the locus of maximum extension, the GPS data may underestimate maximum rift extension rates. We examine this possibility by comparing our data with an elastic model for rift widening in the direction of the survey lines (≈N135E). Assuming that observed surface strain rates are linear in time and attributable to homogeneous elastic processes, an inflating, buried, vertical dike can explain the narrowness of the observed strain field. Although the rates of fluid injection in our model are too slow for a fluid magma to remain viable, the model usefully simulates a localized transition from elastic to low-viscosity material. Three parameters (lateral position, depth, and extension rate) are varied to fit the observed tensile strain rates. Weighted least squares fits to the observations suggest that an inferred dislocation 3.2±1.5 km beneath the surface near the deepest part of the rift (Figure 3) responds to separation of the Nubian and Somali blocks at 3.7±1 mm/yr at N135W (1σ). Scaling this to the inferred rift-normal vector of N108E yields a rate of 4.2 mm/yr. This suggests that little extension lies SE of our control points. The maximum subsidence rate inferred from this model is 0.7 mm/yr in the zone of maximum extension, consistent with rates observed in the Kenyan Rifts (*Nakagawa et al.*, 1975).

Although the transition depth from higher to lower viscosity behavior is well constrained by the elastic model fit to the long term strain accumulation, the subsurface geometry of the system is not. Thus, the same surface strain field may be produced by a buried inflating dike or by two long sub-horizontal faults parting at a line corresponding to

Table 1. Extensional, east and north velocities across the Ethiopian rift. Distances are S45E from Addis Ababa.

	baseline km-km	length km	epoch	azimuth (NdegE)	length mm/yr	east mm/yr	north mm/yr
KOLO-ADD1	-21-0	-20.7	92-95-97	14	0.4±0.8	0.6±0.8	-0.1±0.6
ADD1-BOLO/SELA	0-119	119	92-95-97	47±1	3.7±0.8	4.3±0.9	-1.4±0.6
ADD1-DUKA	0-24	27.8	92-97	62	2.2±2	4.0±2.4	-0.8±2.0
RIDG-BOKU	74-81	6.99	71'2'4'5-97	39	0.6±0.3	-	-
BOKU-MIET	81-95	15.2	72-92-97	52	1.8±0.2	0.3±1.1	0.8±1.0
MIET-SELA	95-107	12.6	72-92-97	66	0.5±0.1	0.5±1.3	1.5±1.2
MARI-BOKU	65-81	16.3	71-92	44	1.6±0.8	-	-

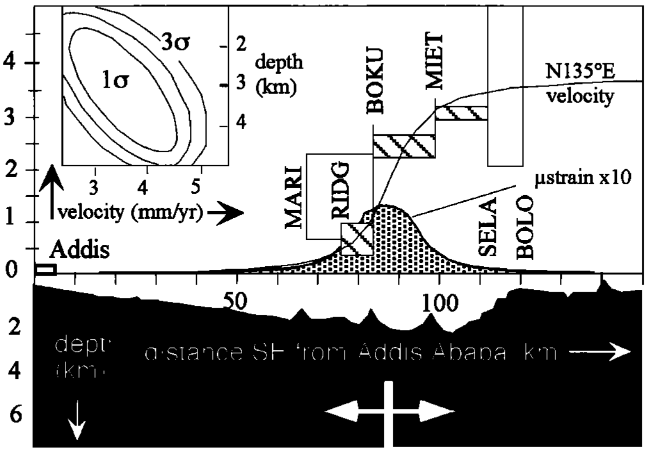

Figure 3. Best fitting velocity field for subsurface dike compared to 1997-1971 (hatched) and 1997-1992 data (open boxes, 1σ). Probability estimates shown top left.

the top of the dike. Indeed, a fundamental role for crustal detachments in the genesis of African rifts has been deduced from field mapping by *Talbot and Woldai Ghebreab* (1997). In the Ethiopian rift, magmatic intrusion levels suggest a downward, steep widening of ductile material under the brittle rift carapace (*Searle and Gouin,* 1972).

3. Tidal Strain Amplitudes

The peak theoretical amplitude of the M2 earth tide at 9°N for an homogeneous elastic Earth is 1.7 mm (*McCarthy*, 1992). The ocean load tide increases the rift-normal and decreases the rift-parallel tide by 5±2% (*Agnew*, 1997). A rift zone that has less rigidity than the model elastic earth, such as one that is cored by a layer of fluid, would be expected to amplify tidal strains across it and to be associated with reduced tidal strain on its flanks. Tidal amplification of shear-tides depends on the effective viscosity of the weak layer, such that low viscosity materials give tidal amplification and are sensitive to higher frequency forcing functions.

Five months of data from a pair of rock-mounted GPS receivers mounted on the east and west flanks of the rift (Figure 3), were operated for 5 months sampling at 30 second intervals with no gaps in the data. The resulting data from this 119-km-long baseline were processed kinematically using Bernese 4.0 (*Beutler and Rothacher*, 1997) such that a new length for the baseline was calculated at 10 minute intervals. Tropospheric delays to the GPS signal were estimated every 4 hours, and solutions associated with periods of low geometric precision were edited from the time series. These data were subjected to spectral analysis to examine the lunar tidal components (O1 and M2), since these are immune to thermal tides and other diurnal forcing functions in the atmosphere. Although the noise level is too high to resolve the lunar body tide at 24 hour periods (O1), the energy density of the M2 tide is a factor of four above our observed 0.2 mm noise level at 12 hour periods (Figure 4). The observed M2 tide is 0.8 ± 0.2 of the predicted strain tide in both rift-normal and rift-parallel directions. Thus at semi-diurnal periods the African rift does not represent a weakness in the Earth's crust for shear or dilatational strain. Longer period tides cannot be resolved in a time series of this length, and tilt tides are an order of magnitude below GPS vertical noise levels at diurnal periods.

4. Discussion and Conclusions

Our measurements provide the first direct velocity estimate for extension across the entire width of an East African rift (4.5±1 mm/year at N109±10E). This slip velocity is consistent at the 1σ level with the rate inferred by *Chu and Gordon* (1999) from plate tectonic analysis. The inferred transition from rigid to viscous behavior at ≈4 km depth can explain the observed narrow concentration of late Quaternary fissuring and near-vertical faulting along the neotectonic axis of the rift axis, while the absence of tidal amplification and presence of local earthquakes, and swarms of micro-earthquakes at 5-10 km depth (*Asfaw,* 1982) suggests that behavior of the crust within the rift to depths of several tens of km is purely elastic at daily periods or less. This behavior is known from other types of plate boundary. For example, the transition from elastic to inelastic behavior of the San Andreas transform system throughout much of its length (the locking depth) occurs at depths of 10-15 km, though occasional deeper earthquakes, as in the Ethiopian rift (*Gouin,* 1979), signify a transitional rheology at these depths.

Clearly our slow-widening dislocation model cannot correspond to magma injection into a dike, such as typifies rifting episodes in Iceland (*Thayer et al.*, 1981), for slow fluid-injection rates to be sustained over periods of decades would require melt conditions over a broad region. Heat flow, though high through rift crust in Africa (*Morgan,* 1972), is not known in sufficient detail to estimate rheological conditions as a function of depth. Our characterization of the earth-tidal response of the rift suggests that melt conditions are not widespread. The similarity between the geological opening rate and the present spreading rate, moreover, suggests that aseismic processes are important in rift widening. We envisage an underlying process similar to that recently proposed for slow ocean rift activity, where faulting is preferentially concentrated by self-organized critical stress processes that result in local high strain rates (*Buck and Poliakov*, 1998).

The Ethiopian rift evidently represents a formative stage in rift development. Unlike well-developed accretionary boundaries observed on land in Iceland and Afar (*Ruegg and Kasser*, 1987), which widen rapidly in a narrowly focussed

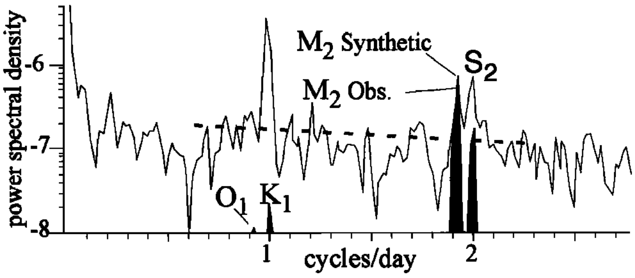

Figure 4. Power spectrum from 119-km-GPS line across the Ethiopian Rift. The observed lunar M2 tide is 24% less than the synthetic tide (2.4 mm amplitude). The mean noise level averages 0.5–0.3 mm (dashed line) in the tidal band.

zone during dike-injection episodes, but which widen over a distributed region between these episodes (*Foulger et al.*, 1996), the African rift in central Ethiopia appears to be widening steadily at the rift axis, with minor strain on the rift flanks. The 40-km-thick thick crust adjoining the rift (*Searle and Gouin*, 1971) evidently focuses tensile strain at the weakest point of the rift crust, maintaining a narrow zone of crustal stretching, that most of the time is apparently starved of magma.

Acknowledgments. The investigation was funded by NSF grants EAR 8916297& 9706356 and NASA grants NAG5-3072 & 2584. M. Jackson was instrumental in establishing the 1992 GPS rift points. We thank J. Beavan and D. Agnew for guidance on tidal analysis. P. Molnar. C. Ebinger and R. Gordon have provided much insight into our interpretation of the data. We thank Alemu Mamo for maintaining the GPS telemetry across the rift, the Ethiopian Mapping Authority and the Ethiopian Institute of Geological Surveys for support of the GPS surveys, and P. Gouin and J. Rolff for aid in the EDM surveys. RGB gratefully acknowledges support from a 1999-2000 Guggenheim Fellowship while at Oxford University.

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(Received October 22, 1998; revised July 27, 1999;
accepted July 28, 1999.)