Lithospheric strength and strain localization in continental extension from observations of the East African Rift

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[1] GPS observations along three profiles across the Ethiopian Rift and Afar triple junction record differences in the length scale over which extension is accommodated. In the Afar region, where the mantle lithosphere is nearly or entirely absent, measurable extension occurs over ~175 km; in the northern Ethiopian Rift, where the mantle lithosphere is anomalously thin and hot, extensional strain occurs over ~85 km, extending beyond the structural rift valley; in the southern Ethiopian Rift, where the mantle lithosphere approaches standard continental thickness, extensional strain occurs over <10 km. This trend of increasingly distributed deformation contrasts with the standard model where continental rifts become mid-ocean spreading centers through strain localization.


1. Introduction

[2] The formation of sedimentary and ocean basins is a fundamental tectonic process controlled by the mechanics of the lithosphere under extensional stresses. The most common conceptual models of basin formation and rifting such as Wilson [1966] rely on the assumption that progressive weakening of the lithosphere (decreased yield stress) results in increased localization of strain. These models and simulations suggest that the development of a mid-ocean ridge is the product of a monotonic progression toward extensional strain localization along a line of zero lithospheric thickness [McKenzie, 1978; Kuszniр and Park, 1987], starting from a zone of distributed normal faulting in lithosphere of normal or nearly normal continental thickness.

[3] Observations of the spatial scale of strain in a continental extensional system, when combined with independent observations of the mechanical properties of the lithosphere, can be used to test hypotheses of monotonic weakening and strain localization during rift evolution. The Main Ethiopian Rift (MER) is an appropriate location for such a comparison, as geodetic results show ongoing separation of Nubia and Somalia [Jestin et al., 1994; Bilham et al., 1999; Pan et al., 2002; Fernandes et al., 2004; Bendick et al., 2006], and lithospheric properties including thickness [Pasyanos et al., 2009], temperature [Maguire et al., 2006], crustal conductivity [Whaler and Hautot, 2006], crust and upper mantle composition [Rooney et al., 2005; Mackenzie et al., 2005; Ayalew et al., 2006], magmatism [Ebinger and Hayward, 1996; Casey et al., 2006], basin width [Ebinger et al., 1999], fault lengths and segmentation [Ebinger et al., 1999], distribution of seismic moment release [Yang and Chen, 2010] and total extension [Hayward and Ebinger, 1996] all vary along strike. We use GPS geodesy to measure both the total rate of extension and the distance over which it is accommodated in the Southern Main Ethiopian Rift (SMER), Central Main Ethiopian Rift (CMER) and Afar triple junction (Afar) for comparison with independent observations of crustal and lithospheric properties. Both the strain scaling, or the length scale over which extension is accommodated, and mechanical properties of each rift region are then compared with results from both numerical and analog methods addressing the role of particular parameters on the mechanics of the rifting process [e.g., McKenzie, 1978; Kuszniр and Park, 1987; Handy, 1989; Buck, 1991; Olsen and Morgan, 1995; Brun, 1999; Braun et al., 1999; Buck et al., 1999; Burov and Poliakov, 2001; Huismans et al., 2001; Corti et al., 2003; Buck, 2004; Davis and Kuszniр, 2004; Huismans and Beaumont, 2008; Regenauer-Lieb et al., 2008; Corti, 2009].

[4] Since the earliest models for the evolution of sedimentary basins and rifted margins, it has been recognized that continental failure in tension entails processes with competing effects on the length scale of deformation [Kirby, 1985; Handy, 1989; Buck, 1991; Kuszniр and Ziegler, 1992]. Table 1 summarizes 18 seminal papers on rift mechanics. To generalize, localization of extension into relatively narrow (of the order of the crustal thickness) zones with steep marginal gradients in crustal or lithospheric thickness is predicted where the integrated lithosphere is strong. Distributed extension in wide rift zones with shallow gradients in crustal...
or lithospheric thickness is predicted where the integrated lithosphere is weak. Most past work considers narrow and wide rifting to be distinct modes based on different initial lithospheric strength, such that composites of lithospheric materials that get stronger when deformed produce wide riffs and composites of lithospheric materials that get weaker when deformed produce narrow ones. Hence, the time evolution of narrow rifting is toward further strain localization, ending with mid-ocean spreading [Olsen and Morgan, 1995; Buck et al., 1999], and the time evolution of wide rifting is approximately steady state or, in a few cases where the cooling rate exceeds the advection of heat due to strain, the cessation of extension [Kuszniir and Park, 1987]. The role of total strain and strain rate is ambiguous, with different simulations demonstrating different scaling correlations [Corti et al., 2003; Davis and Kuszniir, 2004].

[5] Despite this existing exclusive classification of extensional modes, the possibility of a transition between modes appears to exist controlled by temporal changes in the lithospheric strength profile either related to or coincident with rifting. For example, because narrow rifting is grossly associated with a strong lithosphere and wide rifting with a weak lithosphere, processes which progressively weaken or attenuate the mantle lithosphere could be expected to excite widening of the zone of active extension rather than progressive strain localization toward ridge-like spreading. The same effect could be produced by weakening of the lower crust. Conversely, progressive strengthening of lithospheric layers, such as by crustal thinning and replacement of weak lower crust with strong mantle lithosphere could be expected to excite narrowing of extension. Comparing observations from actively extending continental regions with predictions from simulations is one way to explore the relative strength of the upper crust and the mantle lithosphere, as well as how these change over time.

2. Tectonic Setting

[6] The Main Ethiopian Rift (MER) forms the northernmost (Ethiopian) section of the East African Rift System (EARS), a southward propagating set of rift structures [Chorowicz, 2005; Bonini et al., 2005] which accommodate the clockwise rotation of the Somalian plate relative to a stable Nubia [Jestin et al., 1994; Chu and Gordon, 1999; Nocquet et al., 2006; Calais et al., 2009]. The MER terminates to the north in the Afar Depression, a triangle junction with the east-northeast-trending Gulf of Aden and the northwest-trending Red Sea, both ocean spreading ridges which accommodate the differential motion of Somalia and Arabia, and Nubia and Arabia, respectively [Manighetti et al., 1997, 1998; ArRajehi et al., 2010] (Figure 1). Following a brief period of extensive flood basalt volcanism around 31 Ma [Hofmann et al., 1997] likely related to prior emplacement of a mantle plume beneath the Afar [Ebinger and Sleep, 1998; Courtillot et al., 1999], basin formation initiated in the Red Sea and Gulf of Aden ~24 Ma [Wolfenden et al., 2005; Bosworth et al., 2005], coinciding with a marked decrease in convergent motion between Africa and Eurasia [Lemaux et al., 2002; ArRajehi et al., 2010]. Although a small amount of extension appears to have been accommodated between 11 and 20 Ma in the southernmost SMER [Ebinger et al., 2000] and the Yerrerte-Welle Lineament west of the CMER [Keravanen and Klemperer, 2008], extension in the MER appears to have begun in earnest at ~11 Ma [Ukstins et al., 2002; Bonini et al., 2005], approximately coinciding with a transition from basin development to seafloor spreading in the Gulf of Aden [Manighetti et al., 1997; Courtillot et al., 1999; Bosworth et al., 2005] and the initiation of extension in the northern Afar [Ghebreab et al., 2002; Redfield et al., 2003; Beyene and Abdelsalam, 2005]. Following a rearrangement of global plate motions around 5–3 Ma [Boccaletti et al., 1998; Calais et al., 2003; McClusky et al., 2010] attendant with initiation of seafloor spreading in the Red Sea [Ukstins et al., 2002], the principal extension direction in East Africa changed from NW-SE to ~ E-W, oblique to Cenozoic rift structures in the MER. Since that time, faults and aligned volcanic centers roughly orthogonal to the Quaternary extension direction have formed along the axis of the MER (e.g., the Wonji Fault Belt) [Boccaletti et al., 1998] and significant Nubia-Somalia extension has propagated far to the south [Chorowicz, 2005]. Spreading in the Afar continues to be NE directed [Manighetti et al., 1997, 1998].

[7] The paired MER and Afar (Figure 1) systems span a transition from continental rifting in the south and central EARS to mid-ocean ridges in the Red Sea and Gulf of

Table 1. Compilation of Results for Extensional Strain Scaling From Analog and Numerical Experiments

<table>
<thead>
<tr>
<th>Strain Scaling in Continental Extension</th>
<th>Delocalizing</th>
<th>Localizing</th>
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<tbody>
<tr>
<td>weak, thin or absent mantle lithosphere [Sokoutis et al., 2007; Huismans et al., 2001]</td>
<td>strong mantle lithosphere [Sokoutis et al., 2007; Buck, 1991]</td>
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<tr>
<td>weak crust or crust-mantle decoupling [Huismans et al., 2001; Davis and Kuszniir, 2004]</td>
<td>strong crust or crust-mantle coupling [Burov and Poliakov, 2001; Corti et al., 2003]</td>
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<tr>
<td>distributed magmatism [Corti et al., 2003]</td>
<td>localized magmatism [Buck, 1991; Corti et al., 2003]</td>
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<td>high strain rate [Buck, 1991; Corti et al., 2003]</td>
<td>high strain rate [Kuszniir and Park, 1987; Davis and Kuszniir, 2004]</td>
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<tr>
<td>low strain rate [Kuszniir and Park, 1987; Davis and Kuszniir, 2004]</td>
<td>low strain rate [Corti et al., 2003]</td>
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<tr>
<td>crustal necking [Buck, 1991; Davis and Kuszniir, 2004]</td>
<td>lithospheric necking [Huismans et al., 2001; Brun, 1999; Buck et al., 1999]</td>
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<tr>
<td>regional isostasy [Buck, 1991]</td>
<td>strong thermal buoyancy effects [Davis and Kuszniir, 2004]</td>
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*In general, strong lithosphere excites localized strain and weak lithosphere excites distributed strain. Other correlations are more ambiguous, such as the relations among strain rate, total strain, and length scale. See the text for further discussion.

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[7] The paired MER and Afar (Figure 1) systems span a transition from continental rifting in the south and central EARS to mid-ocean ridges in the Red Sea and Gulf of
Aden. Both regions encompass structures with characteristics of both continental and oceanic boundaries [Ebinger and Casey, 2001; McClusky et al., 2010]. The Afar is a region of complex faulting, diking and volcanism [Ebinger and Hayward, 1996; Wolfenden et al., 2005; Keir et al., 2009] which accommodates motion related to each rift arm in a diffuse R-R-R triple junction [Tesfaye et al., 2003]. Two distinct mechanisms act in concert to accommodate overall relative plate motion: magmatic rift segments which include dike injection, extrusive volcanism, and faulting; and distributed fault zones without known associated magmatism [Manighetti et al., 2001]. The tectono-magmatic segments are thought to accommodate most of the total strain, but faulting does provide some contribution [e.g., Manighetti et al., 1998; Vigny et al., 2007]. South of the Afar, the influence of magmatism decreases through the MER such that the SMER and EARS to the south primarily exhibit extension dominated by normal faulting on high-strength basin-bounding faults [Ebinger et al., 1993; Foster and Jackson, 1998; Ebinger et al., 2000].

The transition from continental to oceanic rifting is reflected in a progressive reduction in integrated lithosphere strength northward along the Ethiopian rift, as is evident from a growing body of work which shows: i. thinning of the mantle lithosphere, ii. elevated Moho temperatures, iii. magmatic attenuation of the crust and upper mantle, and iv. decreased lithospheric flexural rigidity. We discuss the evidence for each of these observations below.

2.1. Thinning of the Mantle Lithosphere

Lithosphere thicknesses determined for East Africa from long-period surface wave dispersion [Pasyanos et al.,...
2009] have a coarse resolution (~1°), but clearly show lithosphere thickness decreasing from ~100 km in the SMER to only ~30 km in the CMER and Afar. Thin lithosphere under the CMER and Afar is also implied from inversion of Raleigh wave group velocities and receiver functions [Dugda et al., 2007] with the possibility of entirely absent mantle lithosphere in the Afar. Yang and Chen [2010] show northward shallowing of seismicity, with earthquakes in the mantle lithosphere, but only south of Ethiopia. Meanwhile, crustal thicknesses remain fairly constant along the MER [Keranen et al., 2009]. 2D wide-angle seismic investigations [Mackenzie et al., 2005] reveal 30–35 km Moho depths, which decrease only slightly from south to north while controlled-source seismic data [Maguire et al., 2006] show a shallowing of Moho depth from the CMER to ~26 km in the southernmost Afar. Dugda and Nyblade [2006] found crustal thickness had decreased to 23 km under the east-central Afar in Djibouti. Xenolith suites from the MER and extruded lavas in the Afar provide evidence of ongoing destruction of the lithospheric mantle as the rifting style approaches oceanic-type extension [Rooney et al., 2005; Ayalew et al., 2006]. More detailed studies of the magmatic segments in the Afar [e.g., Doubre et al., 2007a, 2007b] suggest crust is further thinned by magmatism locally.

2.2. Elevated Moho Temperatures

[10] High Moho temperatures and partial melt in the upper mantle and lower crust have been inferred on the basis of anomalous Vp/Vs ratios [Dugda et al., 2007; Keranen et al., 2009], shear wave splitting delays [Kendall et al., 2005], and low resistivity [Whaler and Hautot, 2006] in the CMER. Surface heat flow measurements in the Afar [Lysak, 1992] of 150–250 mW m−2, compared to values ~100 mW m−2 to the south, imply further elevation of the geotherm toward the Afar.

2.3. Magmatic Attenuation of the Crust and Upper Mantle

[11] Differentiation of erupted lavas in the MER suggests that magma reservoirs sourcing rift volcanics decrease in depth as rifting evolves [Caricchi et al., 2006]. Magmatic activity (diking and volcanism) clearly increases toward the northern, more evolved rift segments [Ebinger and Hayward, 1996; Casey et al., 2006]. Kurz et al. [2007] and others describe the appearance in the CMER of a “tectonomagmatic” segmentation along the rift axis, which is indicative of certain types of ocean spreading ridges [van Wijk and Blackman, 2007]. Many seismic [Keranen et al., 2004; Keir et al., 2005; Kendall et al., 2005; Maguire et al., 2006; Keir et al., 2006a, 2006b], resistivity [Whaler and Hautot, 2006], and gravity [Cornwell et al., 2006] investigations show ample evidence for regions of partial melt and cooled mafic intrusions beneath these tectono-magmatic segments (TMS). In the Afar, the influence of magma on rifting is even more pronounced. Active magma emplacement occurs within the crust [Cattin et al., 2005; Wright et al., 2006; Ayele et al., 2007; Vigny et al., 2007; Grandin et al., 2009; Keir et al., 2009], mafic crustal replacement is pervasive [Barberi and Varet, 1975], and considerable extension may occur aseismically via magmatic accretion [Doubre et al., 2007a, 2007b].

2.4. Decreased Lithospheric Flexural Rigidity

[12] As the overall width of the rift basin in Ethiopia widens northward, individual extensional segments become shorter and narrower and faults exhibit closer spacing and smaller throws [Ebinger et al., 1999], concomitant with decreasing elastic thickness estimates [Ebinger and Hayward, 1996]. These observations are roughly correlated with the total extension of the rift basin, which ranges from ~20% in the SMER [Ebinger et al., 1993] to nearly 100% in the Afar [Hayward and Ebinger, 1996]. Elastic thickness estimates from flexural analyses are not always meaningful in continental settings [e.g., Maggi et al., 2000], but in this case they are consistent with independent measures of integrated lithospheric strength [Stampfli et al., 2010].

[13] Taken together, these observations clearly show that both thinning and heating related to rift processes progressively reduce the integrated strength of the lithosphere, especially the mantle lithosphere. This result is unsurprising, and has been understood on the basis of smaller data subsets for many years [i.e., ten Brink, 1991]. The abundant evidence for progressive weakening of the lithosphere provides a sound foundation on which to test models of strain localization. In this study, we use Ethiopian geodetic results from 1992–2010 to compare the surface strain fields in three regions with progressively weaker lithosphere: the southern Main Ethiopian Rift (SMER), the central-northern Main Ethiopian Rift (CMER), and the Afar Depression.

3. Methods

[14] We include in our investigation data from GPS surveys in Ethiopia from January 1992 to December 2010, with observations at 34 geodetic monuments including new survey sites (SGPS) and continuous stations (CGPS) installed since early 2007 (Table 2). The full GPS network forms roughly three arrays traversing the Southern Main Ethiopian Rift (SMER), Central Main Ethiopian Rift (CMER) and Afar (Figures 1 and 2a–2c).

[15] GPS data are analyzed with the GAMIT/GLOBK software [Herring et al., 2010] using a 4-step approach similar to that described by Reilinger et al. [2006]. In the first processing step, satellite orbits, earth orientation parameters, and station coordinates are estimated from the doubly differenced GPS phase observations at each day, applying only loose constraints to each parameter estimate. We include in this step data from 13 stations from the International GNSS Service (IGS) which link the regional (Ethiopian) measurements to data from the global network used in step two.

[16] In the second step, we combined the loosely constrained parameter estimates and their covariances with similar estimates from the global GPS processing for the IGS performed by MIT or the Scripps Orbit and Permanent Array Center (SOPAC) in order to estimate the satellites’ orbits and the Ethiopian site positions for each day in a global reference frame. We used MIT solutions for 1997–2010 and SOPAC solutions for prior years. We then used these daily combinations to generate time series, which we inspected for outliers and to determine the appropriate weights to apply to the observations. In generating the time series, we defined a consistent reference frame by estimating a translation and rotation of the coordinates which minimized the adjustments from the International Terrestrial...