Magnetic stripes of a transitional continental rift in Afar

David L. Bridges[1], Kevin Mickus[2], Stephen S. Gao[1], Mohamed G. Abdelsalam[1], and Abera Alemu[3]

[1]Department of Geological Sciences and Engineering, Missouri University of Science and Technology, Rolla, Missouri 65409, USA

[2]Department of Geosciences, Missouri State University, Springfield, Missouri 65897, USA

[3]Department of Geology and Geophysics, Addis Ababa University, Addis Ababa, Ethiopia

ABSTRACT

Magnetic stripes parallel to mid-ocean ridges are one of the most significant consequences of seafloor spreading, and have played an essential role in the establishment of the plate tectonics theory and the determination of seafloor spreading rates. Similar magnetic anomaly patterns have not been well documented subaerially in continental rifts transitioning into seafloor spreading centers. Here, using high-resolution magnetic data that were collected across the Tendaho Graben in the Afar Depression, Ethiopia, we document one of the first examples of subaerial magnetic lineations similar in pattern and amplitude to those that characterize seafloor spreading centers. The ~50-km-wide graben is the southernmost structural and geomorphological expression of the on-land continuation of the Red Sea propagator, which is taken to represent the Arabian-Nubian plate boundary within Afar. The graben is bounded by northwest-trending border faults, with the footwalls dominated by ca. 1.7 Ma basalts and the downthrown blocks constituting progressively younger basalts toward the center of the graben, reaching ca. 35 ka. The Tendaho magnetic field is characterized by an ~10-km-wide linear negative magnetic anomaly that corresponds to a normal-polarity zone that is flanked by two parallel, ~20-km-wide linear positive magnetic anomalies of reversed polarity. This work shows that magnetic stripes can be developed in transitional continental rifts before the development of oceanic spreading centers. The common assumption that magnetic stripes can be used to date the onset of seafloor spreading may need to be re-evaluated in light of the evidence provided here.

INTRODUCTION

The Afar area (Ethiopia) is a unique outdoor laboratory for the study of continental rifts transitioning to oceanic spreading centers (Fig. 1). Nearly all stages of continental rifting to oceanic spreading are exposed for study (Makris and Ginzburg, 1987; Hayward and Ebinger, 1996). The Afar Depression developed from a Miocene flood basalt province, believed to have originated from the Afar mantle plume (e.g., Hofmann et al., 1997). The Afar area has subsequently undergone extension that formed the triangular topographic depression where the Red Sea, the Gulf of Aden, and the Main Ethiopian Rift (MER) meet, separating the Arabian, Nubian, and Somalian plates (Fig. 1) (Beyene and Abdelsalam, 2005). Two oceanic spreading centers, the Gulf of Aden and the Red Sea, have stepped onto Afar to form the Gulf of Aden and the Red Sea propagators, respectively. These propagators are currently expressed as active axial magmatic centers in well-formed graben structures that do not meet on the surface but are separated by an ~120 km wide overlap zone that is dissected by northwest-trending faults (Fig. 1). This overlap zone is currently experiencing a dextral shear couple with individual blocks between the propagators exhibiting a clockwise rotation (Tapponnier et al., 1990; Manighetti et al., 2001).

The Tendaho Graben (TG), which represents the southeastern extension of the Red Sea propagator (Fig. 1), initiated at ca. 1.8 Ma (Acton et al., 1991, 2000). It is ~50 km wide, representing the largest graben in central Afar. Normal faulting is dominant, although some sinistral strike slip is present (Abbate et al., 1995). The Stratoid basalts with a mean age of ca. 1.7 ± 0.2 Ma (Acton et al., 2000) are the major lithologic unit that forms the footwalls of the graben. The age of the Stratoid basalts is progressively younger toward the middle of the graben (Fig. 2B). The graben is filled with lacustrine deposits that in some places are over 1.6 km thick (Abbate et al., 1995; Aquater, 1996). Volcanic rocks as young as 35 ka are found in the graben center and primarily consist of basalts with a subordinate amount of rhyolites and pyroclastics (Abbate et al., 1995). A rift-in-rift structure is formed in these younger volcanics.

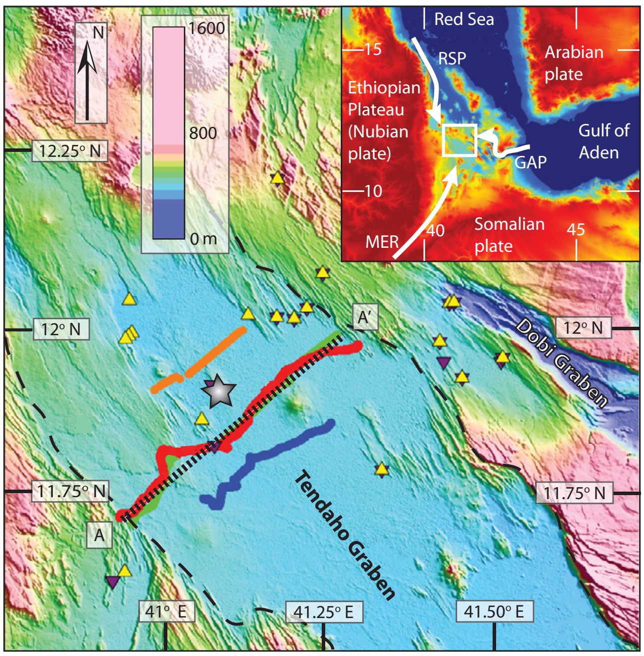

Figure 1. Magnetic profiles, paleomagnetic station locations, and geochronology station locations. Colored lines show location of the magnetic profiles and correspond to the profile colors in Figure 2A. Red and blue profiles are the high-resolution data collected by our group. Yellow triangles are geochronology sample locations from Lahitte et al. (2003) and Kidane et al. (2003). Inverted purple triangles are paleomagnetic sample locations from Acton et al. (2000) and Kidane et al. (2003). Thick black dashed line A–A′ is used as the projection plane for all profiles and supporting data used in this paper. Long dashed lines show approximate extent of Tendaho Graben. Ayrobeara Geothermal Field is shown by the star. Background is Shuttle Radar Topography Mission (SRTM) data. Inset shows regional tectonic overview of study area. Rifts: RSP—Red Sea propagator; GAP—Gulf of Aden propagator; MER—Main Ethiopian Rift.

OBSERVATIONS OF MAGNETIC STRIPES

Data used in the study were obtained by a high-resolution ground magnetic survey across the TG conducted in the winters of 2008 and 2009. The survey utilized a cesium optically pumped magnetometer (COM) coupled with a GPS on a backpack frame. Base station readings were collected using a proton precession magnetometer that was used to correct for diurnal variations. The COM instrument records data at a rate of 5 Hz with an absolute accuracy of <2 nT, with the base station having an absolute accuracy of 1 nT. Two high-resolution profiles perpendicular to strike of the TG were acquired with a station interval of ~1 m. One of the profiles crosses the entire width of the graben,

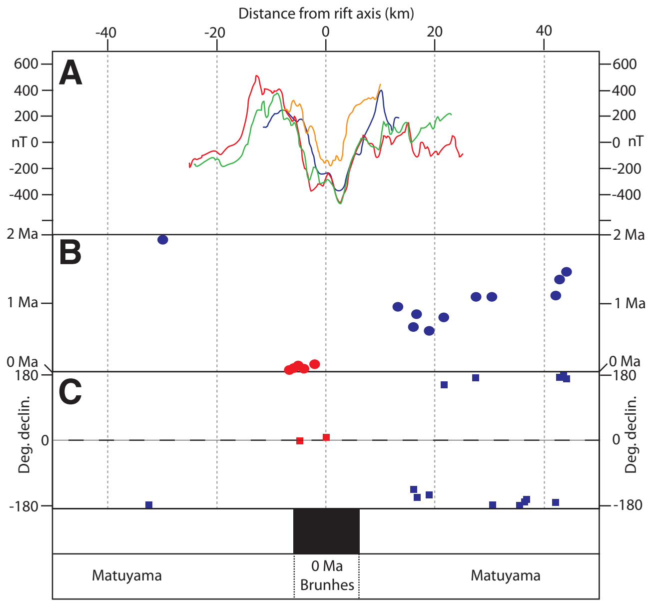

Figure 2. Magnetic profiles, geochronologic data, and paleomagnetic data projected to line A–A′. A: Magnetic profiles from Figure 1 (colors correspond). Data smoothed with a 500 m moving mean window. B: Geochronologic data as a function of distance from rift axis. Red circles and squares (C) represent data from the current normal-polarity period, and blue symbols are data from the reversed-polarity Matuyama Chron. Data are from Lahitte et al. (2003) and Kidane et al. (2003). C: Paleomagnetic declination with same horizontal projection as A and B. Data are from Acton et al. (2000) and Kidane et al. (2003). Units are degrees of declination (Deg. declin.). Bottom panel shows a general magnetic timescale with corresponding chrons. Geochronologic and paleomagnetic data that sampled the recent basalts on top of the older reversely magnetized basalts are omitted for clarity (see Fig. 4).

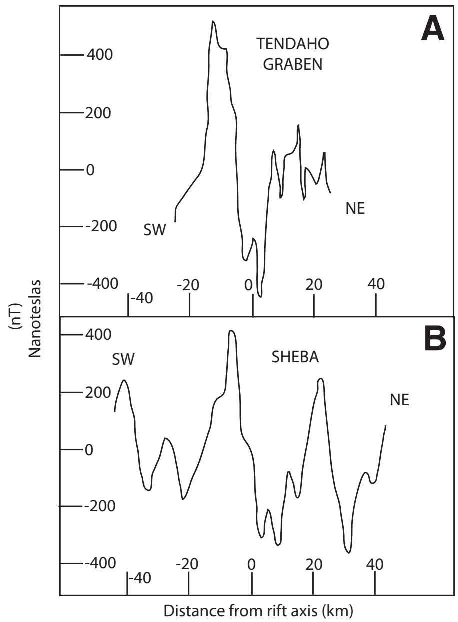

Figure 3. Comparison of magnetic anomalies across the Tendaho Graben and Sheba oceanic spreading center. Data for the Sheba spreading center are from Barberi and Varet (1977).

while the other profile is located across the central portion of the graben (Fig. 1). Furthermore, Aquater (1996) collected two additional magnetic profiles in 1980 (Fig. 1). The Aquater data set has an average station spacing of 250 m and was collected with two proton precession magnetometers with one magnetometer used as the base station.

All the magnetic profiles demonstrate a near-symmetric pattern in which the central part is dominated by a negative total-field magnetic anomaly flanked by positive total-field anomalies with amplitudes similar to those observed over oceanic spreading centers (Prevot and Gromme, 1975) (Figs. 2A and 3). Similar to the well-known magnetic stripes in ocean basins, the magnetic lineations that we observed in the TG might originate from graben-parallel linear magmatic bodies. All the profiles show a higher positive anomaly on the southwest side of the profiles. In addition, a smaller relatively positive total-field magnetic anomaly is also apparent in the central part of the negative anomaly feature (Figs. 2A, 3, and 4B) that might be related to high heat flow that is observed in the region (Aquater, 1996; Berktold et al., 1975).

The high-resolution profile that crosses the entire TG was modeled using an ensemble of finite-length, right rectangle prisms (Webring, 1985) under the assumption that the features being modeled are two-dimensional structures parallel to the strike of the graben. Since the survey was conducted over basalts of varying age, remanent magnetism (RM) must be

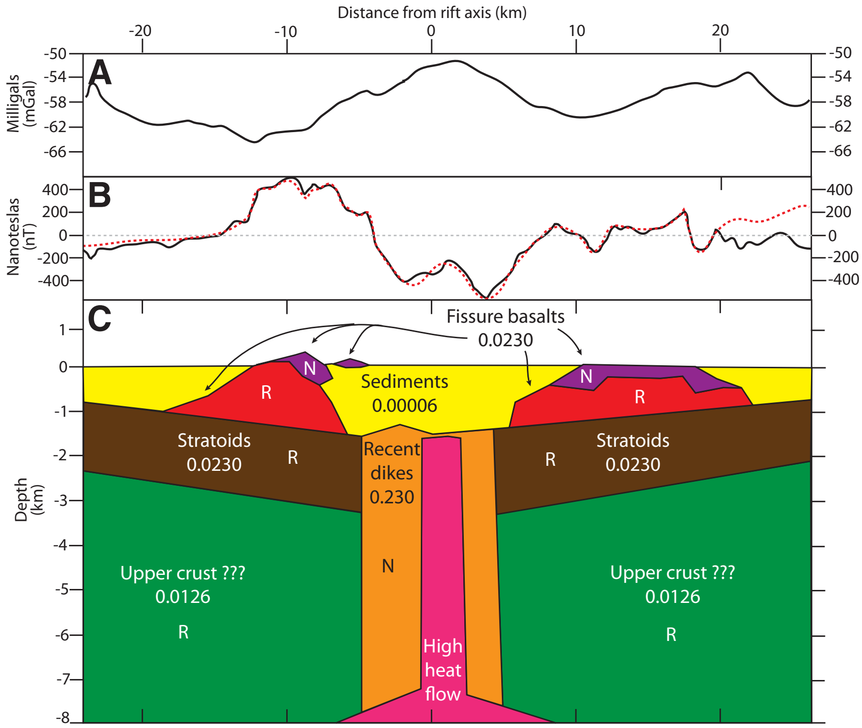

Figure 4. Conceptual crustal model for the Tendaho Graben based on magnetic, paleomagnetic, geochronologic, and geological constraints. A: Bouguer gravity anomaly profile approximately following A–A′. B: Magnetic profile data (shown by red line in Fig. 1). Black line is the observed data, and red line represents the modeled data. C: Final magnetic model with yellow being lacustrine sediments, green being diked undifferentiated upper crust, brown being Afar Stratoid basalts, purple being normal-polarity recent basalts, red being reverse-polarity basalts (older than 0.78 Ma), orange being recent normal-polarity basalts, and pink being the area of highest heat flow along the rift axis. Numbers are magnetic susceptibilities in SI volume units. N—normal remanent polarity; R—reverse remanent polarity.

considered in the models. RM can completely mask the current induced-component and is the reason that reverse-polarity events recorded in the geologic record are well documented. In our case, the RM is most likely caused by thermal remanent magnetization of minerals such as titanomagnetite present in the basalts (Courtillot et al., 1984; Reynolds et al., 1990). RM often decreases with age of the rocks as oxidation and hydrothermal interactions develop in the ferromagnetic minerals (Prevot and Gromme, 1975).

Our modeling shows that the only possible way to explain the large amplitude of the observed anomalies is to include both the induced magnetic field and a significant quantity of RM in the model. A multitude of models using only induced magnetization were tried and none were able to match the amplitude of the observed anomalies. As with all potential-field modeling, any one model is not a unique solution. Our model is the most plausible with the given geological constraints and magnetic properties. For the Afar Stratoid basalts, the range of measured natural remanent magnetism (NRM) intensities was between <1 and 31 A/m, with an average value of 4.65 A/m, whereas the mean susceptibility in SI volume units is 0.023 (Kidane et al., 1999; Acton et al., 2000). The recent (<0.3 Ma) basalts in the TG have a mean declination (D) of 4.4° and inclination (I) of 17.8°, very similar to the present field direction (D = 0°, I = 22°) (Kidane et al., 1999; Acton et al., 2000). The older basalts (0.6–1.1 Ma) of the TG have two dominant mean NRM directions (D = 13.7°, I = 0.8°, and D = 203.2°, I = −7.1°) corresponding to the current normal-polarity and reverse Matuyama Chron (Kidane et al., 1999; Acton et al., 2000). These parameters were used in our models. The older Stratoid basalts were modeled with a NRM intensity of 2.0 A/m, and the younger axial rift volcanics with a NRM of 5.00 A/m. These values are similar to those observed over some oceanic spreading centers (Courtillot et al., 1984). The final model shows that an ~10 km wide stripe along the axis of the graben exhibits normal polarity (Fig. 4C) surrounded by wider zones of dominantly reverse-polarity units. The large-amplitude negative anomaly shown in Figures 2A, 3, and 4B is the result of an ~10 km region of dominantly normal-polarity intrusions and/or diking that follows the rift axis. In equatorial regions such as our study area, a normal-polarity RM field roughly parallel to the inducing field produces a negative anomaly. Conversely, reverse-polarity RM, when overprinting the inducing field, will exhibit positive anomalies in equatorial regions during normal-polarity periods such as the present time.

GRAVITY ANOMALIES

To further independently validate the results of our magnetic modeling, especially the presence of mafic diking or higher abundance of diking along the axial part of the TG, a high-density Bouguer gravity anomaly profile was acquired that nearly coincides with the longer high-resolution magnetic profile. The gravity profile shows a high-amplitude gravity maximum in the center of the TG (Fig. 4A), in spite of the fact that this part of the basin has the thickest lacustrine sediments, which should lead to negative Bouguer gravity anomalies. It is not possible with the current data available to determine if the high-density sources in the center of the graben, as suggested by the gravity data, are produced by a jump in diking frequency or if there was a gradual increase of diking as the lithosphere became stretched by extension.

The recent rifting episode just north of the TG, along the Dabbahu rift segment, provides evidence that supports our model. The intrusion of large dikes into the upper crust has been well documented along the Dabbahu rift axis (Wright et al., 2006; Ayele et al., 2009), and this process repeated several times over millions of years can create a crustal structure similar to one we proposed in the TG.

DISCUSSION

Our Model

On the basis of the modeling of the magnetic data, gravity data, surface geology, geochronology, and paleomagnetic studies, we propose a model (Fig. 4C) of the upper crust that has been extensively modified by diking and intrusions during the emplacement of the Stratoid basalts, and subsequently, as spreading continued, a 10 km zone of dominantly normal-polarity intrusions has been recording the past ~0.8 m.y. of extension (Fig. 4C).

The Local High at the Center and Its Formation Mechanisms

The high-resolution magnetic profiles provide a remarkable insight into the structure of the upper crust across the TG. The 2–3-km-wide zone of slightly elevated magnetic anomalies in the axial area (Fig. 4B) might be the result of higher crustal heat flow. This would reduce the intensity of the RM by raising a portion of the contributing upper crust above the Curie point, thereby reducing the RM to the measured magnetic field. Geothermal studies suggest that a nearly vertical fault coincides with this zone (Aquater, 1996). This is supported by surface manifestations of geothermal activity along the rift axis and geothermal exploratory well drilling (Aquater, 1996; Gianelli et al., 1998; Battistelli et al., 2002) near Ayrobeara (Fig. 1).

The Implications of the Magnetic Stripes

The presence of linear magnetic anomalies in Afar has been previously qualitatively described. Barberi and Varet (1977) argued their existence based on an aeromagnetic campaign completed during the late 1960s. They pointed to the existence of many linear magnetic anomalies associated with the Red Sea and Gulf of Aden propagators in Afar. They also argued for the existence of oceanic crust beneath these segments based on crustal thickness, gravity data, lack of any crustal xenoliths in the Afar floor, and geochemical data. Courtillot et al. (1980, 1984) describe distinct linear magnetic anomalies typical of those associated with oceanic spreading centers in the area between the Asal and Abhe Rifts, part of the Gulf of Aden propagator (Fig. 1). They argued that the anomalies in western Afar cannot be matched with the magnetic timescale due to the lack of paleomagnetic and geochronologic data.

We provide evidence here for the first time of a transitional continental rift exhibiting magnetic stripes that can be correlated with the current geomagnetic time scale of Cande and Kent (1992). Hayward and Ebinger (1996) provide a conceptual model for the evolution of rift morphology from the onset of rifting to fully developed seafloor spreading for the MER and Afar. The areas of linear magnetic anomalies as shown by Barberi and Varet (1977) correspond remarkably well with the middle and later stages of Hayward and Ebinger's model. During these stages smaller rifts are forming within the rift system. The TG is at this development stage and principally records the change from the Matuyama Chron (reverse polarity) to the current Brunhes Chron (Fig. 2C).

Bastow and Keir (2011) show that the crust across southern Afar (<13°N) is overthickened. This is likely due to magmatic intrusions accommodating extension rather than faulting or ductile stretching. In the perspective of this model, the intrusions of the TG have become focused along the rift axis at a stage in which the crust is still relatively thick. This is similar to the active Dabbahu segment to the north (Wright et al., 2006) and could represent a transitional phase from extension maintained by crustal intrusion to that of rapid crustal stretching and the onset of efficient adiabatic decompression melting along a focused spreading center.

Documenting a continental rift that hosts magnetic stripes is further supported by the findings of Bronner et al. (2011). Bronner et al. (2011) provide evidence for the presence of magnetic stripes similar to the TG in the Newfoundland-Iberia rift system. The magnetic stripes were formed by mafic intrusions in a magma-poor rift system. Our data corroborate the findings of Bastow and Keir (2011) and Bronner et al. (2011). The implications of these results could have profound effects on the timing of continental breakup at rifted margins elsewhere.

CONCLUSIONS

Magnetic data along with gravity, surface geology, geochronology, and paleomagnetic data from the TG clearly document a subaerial version of the magnetic stripes typically associated with oceanic spreading centers. The magnetic anomaly pattern is analogous in dimension and amplitude to that observed at oceanic spreading centers. We provide clear evidence that magnetic stripes can form as a result of magmatism during late stages of continental rifting. Our work has an implication that magnetic stripes observed near rifted margins worldwide that include magmatism are not necessarily indicative of the timing and location of the onset of seafloor spreading.

ACKNOWLEDGMENTS

This research was funded by Statoil, Norway. We would also like to thank the Geologic Survey of Ethiopia for their help with field logistics, and the Afar National Regional State government for granting us permission to collect the magnetic and gravity data. We would also like to thank Vincent Courtillot, Derek Keir, and an anonymous reviewer for their constructive reviews. This is Missouri University of Science and Technology Geology and Geophysics Program contribution #36.

REFERENCES CITED

Abbate, E., Passerini, P., and Zan, L., 1995, Strike-slip faults in a rift area: A transect in the Afar Triangle, East Africa: Tectonophysics, v. 241, p. 67–97, doi:10.1016/0040-1951(94)00136-W.

Acton, G.D., Stein, S., and Engeln, J.F., 1991, Block rotation and continental extension in Afar: A comparison to oceanic microplate systems: Tectonics, v. 10, p. 501–526, doi:10.1029/90TC01792.

Acton, G.D., Tessema, A., Jackson, M., and Bilham, R., 2000, The tectonic and geomagnetic significance of paleomagnetic observations from volcanic rocks from central Afar, Africa: Earth and Planetary Science Letters, v. 180, p. 225–241, doi:10.1016/S0012-821X(00)00173-4.

Aquater, 1996, Tendaho Geothermal Project, Final Report, Volume 1: San Lorenzo in Campo, Italy, Aquater S.p.A., 324 p.

Ayele, A., Keir, D., Ebinger, C., Wright, T.J., Stuart, G.W., Buck, W.R., Jacques, E., Ogubazghi, G., and Sholan, J., 2009, September 2005 mega-dike emplacement in the Manda-Harraro nascent oceanic rift (Afar depression): Geophysical Research Letters, v. 36, L20306, doi:10.1029/2009GL039605.

Barberi, F., and Varet, J., 1977, Volcanism of Afar: Small-scale plate tectonics implications: Geological Society of America Bulletin, v. 88, p. 1251–1266, doi:10.1130/0016-7606(1977)88<1251:VOASPT>2.0.CO;2.

Bastow, I.D., and Keir, D., 2011, The protracted development of the continent-ocean transition in Afar: Nature Geoscience, v. 4, p. 248–250, doi:10.1038/NGEO1095.

Battistelli, A., Yiheyis, A., Calore, C., Ferragina, C., and Abatneh, W., 2002, Reservoir engineering assessment of Dubti geothermal field, Northern Tendaho Rift, Ethiopia: Geothermics, v. 31, p. 381–406, doi:10.1016/S0375-6505(01)00039-6.

Berktold, A., Haak, V., and Angenheister, G., 1975, Magnetotelluric measurements in the Afar area, *in* Pilger, A., and Rosler, A., eds., Afar Depression of Ethiopia: Proceedings of an International Symposium on the Afar Region and Related Rift Problems, Bad Bergzabern, Germany, 1974, Volume 1: Stuttgart, Germany, E. Schweizerbart'sche Verlagsbuchhandlung, p. 66–79.

Beyene, A., and Abdelsalam, M.G., 2005, Tectonics of the Afar Depression: A review and synthesis: Journal of African Earth Sciences, v. 41, p. 41–59, doi:10.1016/j.jafrearsci.2005.03.003.

Bronner, A., Sauter, D., Manatschal, G., Peron-Pinvidic, G., and Munschy, M., 2011, Magmatic breakup as an explanation for magnetic anomalies at magma-poor rifted margins: Nature Geoscience, v. 4, p. 549–553, doi:10.1038/NGEO1201.

Cande, S.C., and Kent, D.V., 1992, A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic: Journal of Geophysical Research, v. 97, p. 13,917–13,951, doi:10.1029/92JB01202.

Courtillot, V., Galdeano, A., and Mouel, J.L.L., 1980, Propagation of an accreting plate boundary: A discussion of new aeromagnetic data in the Gulf of Tadjurah and southern Afar: Earth and Planetary Science Letters, v. 47, p. 144–160.

Courtillot, V., Achache, J., Landre, F., Bonhommet, N., Montigny, R., and Feraud, G., 1984, Episodic spreading and rift propagation: New paleomagnetic and geochronologic data from the Afar nascent passive margin: Journal of Geophysical Research, v. 89, p. 3315–3333, doi:10.1029/JB089iB05p03315.

Gianelli, G., Mekuria, N., Battaglia, S., Chersicla, A., Garofalo, P., Ruggieri, G., Manganwlli, M., and Gebregziabher, Z., 1998, Water-rock interaction and hydrothermal mineral equilibria in the Tendaho geothermal system: Journal of Volcanology and Geothermal Research, v. 86, p. 253–276, doi:10.1016/S0377-0273(98)00073-0.

Hayward, N.J., and Ebinger, C.J., 1996, Variations in the along-axis segmentation of the Afar Rift system: Tectonics, v. 15, p. 244–257, doi:10.1029/95TC02292.

Hofmann, C., Courtillot, V., Feraud, G., Rochette, P., Yirgu, G., Ketefo, E., and Pik, R., 1997, Timing of the Ethiopian flood basalt event and implications for plume birth and global change: Nature, v. 389, p. 838–841, doi:10.1038/39853.

Kidane, T., Carlut, J., Courtillot, V., Gallet, Y., Quidelleur, X., Gillot, P.Y., and Haile, T., 1999, Paleomagnetic and geochronological identification of the Réunion subchron in Ethiopian Afar: Journal of Geophysical Research, v. 104, p. 10,405–10,419, doi:10.1029/1999JB900014.

Kidane, T., Courtillot, V., Manighetti, I., Audin, L., Lahitte, P., Quidelleur, X., Gillot, P.-Y., Gallet, Y., Carlut, J., and Haile, T., 2003, New paleomagnetic and geochronologic results from Ethiopian Afar: Block rotations linked to rift overlap and propagation and determination of a ~2 Ma reference pole for stable Africa: Journal of Geophysical Research, v. 108, 2102, doi:10.1029/2001JB000645.

Lahitte, P., Gillot, P.-Y., Kidane, T., Courtillot, V., and Bekele, A., 2003, New age constraints on the timing of volcanism in central Afar, in the presence of propagating rifts: Journal of Geophysical Research, v. 108, 2123, doi:10.1029/2001JB001689.

Makris, J., and Ginzburg, A., 1987, The Afar Depression: Transition between continental rifting and sea-floor spreading: Tectonophysics, v. 141, p. 199–214, doi:10.1016/0040-1951(87)90186-7.

Manighetti, I., Tapponnier, P., Courtillot, V., Gallet, Y., Jacques, E., and Gillot, P.-Y., 2001, Strain transfer between disconnected, propagating rifts in Afar: Journal of Geophysical Research, v. 106, p. 13,613–13,665, doi:10.1029/2000JB900454.

Prevot, M., and Gromme, S., 1975, Intensity of magnetization of subaerial and submarine basalts and its possible change with time: Geophysical Journal of the Royal Astronomical Society, v. 40, p. 207–224.

Reynolds, R.L., Rosenbaum, J.G., Hudson, M.H., and Fishman, N.S., 1990, Rock magnetism, the distribution of magnetic minerals in the Earth's crust, and aeromagnetic anomalies, *in* Hanna, W.F., ed., Geologic applications of modern aeromagnetic surveys: U.S. Geological Survey Bulletin 1924, p. 24–45.

Tapponnier, P., Armijo, R., Manighetti, I., and Courtillot, V., 1990, Bookshelf faulting and horizontal block rotations between overlapping rifts in southern Afar: Geophysical Research Letters, v. 17, p. 1–4, doi:10.1029/GL017i001p00001.

Webring, M., 1985, SAKI: A Fortran program for the generalized linear inversion of gravity and magnetic profiles: U.S. Geological Survey Open-File Report 85-122, p. 29.

Wright, T.J., Ebinger, C., Biggs, J., Ayele, A., Yirgu, G., Keir, D., and Stork, A., 2006, Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode: Nature, v. 442, p. 291–294, doi:10.1038/nature04978.

Manuscript received 27 July 2011
Revised manuscript received 25 September 2011
Manuscript accepted 29 September 2011

Printed in USA

ERRATUM

Transient change in groundwater temperature after earthquakes

Chi-yuen Wang, Michael Manga, Chung-Ho Wang, and Chieh-Hung Chen
(Geology, v.40, p. 119–122, doi: 10.1130/G32565.1.

A typesetting error occurred in Equation1 of this paper. The correct equation should be: $\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} - \gamma q_z \frac{\partial T}{\partial z}$