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Pliocene volcano-tectonics and paleogeography of the Turkana Basin, Kenya and Ethiopia

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ABSTRACT

The distribution of hominin fossil sites in the Turkana Basin, Kenya is intimately linked to the history of the Omo River, which affected the paleogeography and ecology of the basin since the dawn of the Pliocene. We report new geological data concerning the outlet channel of the Omo River between earliest Pliocene and final closure of the Turkana Basin drainage system in the latest Pliocene to earliest Quaternary. Throughout most of the Pliocene the Omo River entered the Turkana Basin from its source in the highlands of Ethiopia and exited the eastern margin of the basin to discharge into the Lamu embayment along the coast of the Indian Ocean. During the earliest Pliocene the river's outlet was located in the northern part of the basin, where a remnant outlet channel is preserved in basalts that pre-date eruption of the Gombe flood basalt between 4.05 and 3.95 Ma. The outlet channel was faulted down to the west prior to 4.05 Ma, forming a natural dam behind which Lake Lonyumun developed. Lake Lonyumun was drained between 3.95 and 3.9 Ma when a new outlet channel formed north of Loiyangalani in the southeastern margin of the Turkana Basin. That outlet was blocked by Lenderit Basalt lava flows between 2.2 and 2.0 Ma. Faulting that initiated either during or shortly after eruption of the Lenderit Basalt closed the depression that is occupied by modern Lake Turkana to sediment and water.

Several large shield volcanoes formed east of the Turkana Basin beginning by 2.5–3.0 Ma, volcanism overlapping in time, but probably migrating eastward from Mount Kulal on the eastern edge of the basin to Mount Marsabit located at the eastern edge of the Chalbi Desert. The mass of the volcanic rocks loaded and depressed the lithosphere, enhancing subsidence in a shallow southeast trending depression that overlay the Cretaceous and Paleogene (?) Anza Rift. Subsidence in this flexural depression guided the course of the Omo River towards the Indian Ocean, and also localized accumulations of lava along the margins of the shield volcanoes. Lava flows at Mount Marsabit extended across the Omo River Valley after 1.8–2.0 Ma based on estimated ages of fossils in lacustrine and terrestrial deposits, and possibly by as early as 2.5 ± 0.3 Ma based on dating of a lava flow. During the enhanced precipitation in latest Pleistocene and earliest Holocene (11–9.5 ka) this flexural depression became the site of Lake Chalbi, which was separated from Lake Turkana by a tectonically controlled drainage divide.

1. Introduction

The paleogeography of the famous hominin fossil sites of the Turkana Basin, Kenya and Ethiopia is intimately linked to the history of the Omo River, which affected the paleogeography and ecology of the basin since the dawn of the Pliocene (Brown and Feibel, 1991; Feibel et al., 1991). Key events in the history of the river's drainage include diversion from the Nile to the Turkana drainage basin by the Early Pliocene, episodic expansion and contraction of lakes that alternated with periods of dominantly fluvial deposition, and lastly closure of the Omo River's outlet to the Indian Ocean. Here, we review geological evidence from the southeastern margin of the basin which shows that closure of the river's outlet began roughly 2 Ma when Lenderit basalts erupted and flowed over the floodplain north of Loiyangalani and along the river channel east of the basin. Closure culminated with eruption of the Balo Basalt at ~1.8 Ma, accompanied by normal faulting that created the present topographic divide separating the Turkana Basin from the Chalbi Desert. We also discuss circumstantial evidence which places the outlet channel at the northeastern edge of the basin during the earliest Pliocene, and speculate that disruption of that outlet by faulting created Early Pliocene Lake Lonyumun within the Turkana Basin. The outlet then moved to the southeastern edge of the basin prior to eruption and deposition of the Moiti Tuff at 3.970 ± 0.032 Ma (McDougall and Brown, 2008).

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The history of normal faulting in the Turkana rift has been intensely studied, and faulting certainly controlled loci of subsidence over time (Dunkelman et al., 1988; Bosworth, 1992; Morley et al., 1992,a; Hendrie et al., 1994; Ebinger et al., 2000; Vetel et al., 2004; Le Gall et al., 2005). However, large shield volcanoes dominate the landscape to the east, where the Omo River exited the Turkana Basin and flowed towards the Indian Ocean. Construction of volcanic shields presumably depressed the crust into a broad moat that extended around the base of Mount Kulal and eastward between Asie, Huri Hills and Marsabit volcanoes. Flexural models of volcanic loads on an elastic lithosphere suggest that subsidence within this moat was sufficient to steer the Omo River eastward, while also becoming a locus for lava that flowed over the river's flood plain and channel.

2. Background

Studies of the stratigraphy and paleontology of the Omo Group provide the foundation for recreating the paleogeography and paleoenvironment of the Turkana Basin throughout the Late Neogene (Fig. 1; Feibel et al., 1991; Brown and Feibel, 1991; Stewart and Murray, 2008). Fossils with Nile drainage affinity provide evidence that by the Early Pliocene the Omo River was diverted from the Nile drainage into the Turkana Basin, with an outlet on the eastern margin of the basin that connected to the Indian Ocean (Brown and Feibel, 1991). Diversion of the river into the basin was triggered by renewed faulting and volcanism during Early Pliocene (Morley et al., 1992a; Haileab et al., 2004). Formation of the Lonyumun Lake and widespread eruption of Gombe Basalt (4.05–3.95 Ma) was followed by fluvial deposition within low-energy meandering river channels and floodplains. Episodes of lacustrine expansion were followed by reestablishment of dominantly fluvial environments. The relative role of climatic versus tectonic processes in lacustrine cycles remains controversial, but expansion of lacustrine environments correlates better with episodes of faulting and volcanism, than with climatic cycles, in the Turkana Basin during the last 4–5 Ma.

Direct evidence for the outlet of the Omo River and connection to the Indian Ocean includes fossils in freshwater lacustrine and fluvial deposits at Algas along the Marsabit Road 100 km southeast of Lake Turkana (Wilkinson, 1988; Nyamweru, 1986), and *Dasyatis africana*, an immigrant stingray from the Indian Ocean that appears at $\sim$1.9 Ma in the upper Burgi member of the Koobi Fora Formation (Feibel, 1988, 1993; Brown and Feibel, 1991). There is uncertainty concerning the age of the deposits at Algas; according to paleontologist M. Pickford the deposits are 1.8–2.0 Ma, but Nyamweru and Bowman (1989) cite an age of 2.5 ± 0.3 Ma for an overlying lava flow. We pursue this topic further in the discussion, following presentation of our new geological data concerning the nature of the Omo River drainage within and east of the Turkana Basin.

Erroneous assignment of age to geologic strata near Loiyangalani in the southeastern Turkana Basin proved a major impediment to resolving the paleogeography of the Omo River. Pliocene deposits surrounding Loiyangalani were originally mapped as pre-Pliocene (Ochieng' et al., 1988; Wilkinson, 1988; Rop, 1990), forcing paleogeographic reconstructions to place the river's outlet at the southeastern corner of the Koobi Fora lowlands, about 100 km north of Loiyangalani (Brown and Feibel, 1991). However, subsequent reconnaissance work followed by detailed mapping revealed that strata in the Loiyangalani area are Pliocene Koobi Fora Formation that were deposited in large part by the Omo River (Gathogo et al., 2008). This motivated our search for the outlet of the Omo River discussed herein.

3. Research methods

Research integrated remote sensing and field observations to map geological units over a broad region along the eastern side of Lake Turkana. Field traverses were made to collect rock samples for stratigraphic correlation, and to check the accuracy of mapping by remote sensing. Remote sensing data included Advanced Spaceborne Thermal and Emission Reflection Radiometer (ASTER) and Landsat 7 imagery, Shuttle Radar Topography Mission (SRTM) digital elevation models (DEM) (Rodriguez et al., 2005), and custom DEM created by image parallax with ASTER data.

Data processing of ASTER imagery included corrections for atmospheric scattering and absorption, and computation of band ratio, band absorption index, and vegetation index images to facilitate mineral and rock type discrimination (Rowan et al., 2003a,b). Support Vector Machine (Cortes and Vapnik, 1995) and binary Decision Tree algorithms were used to classify rock types. False color composite images were constructed from image bands 7, 4, 2 and Principal Component bands of Landsat 7 data. Combinations of elemental and absorption index bands derived from ASTER imagery were also used to construct false color images for visual inspection and mapping.

Discriminant analysis enables basalts from different eruptions to be identified on the bases of their major and minor element concentrations (expressed as oxides). For this study, representative basalt samples were analyzed for major elements by standard techniques of X-ray fluorescence spectroscopy. Trace elements and rare earth elements were measured by inductively coupled plasma mass spectrometry (ICP-MS) at Activation Laboratories Ltd., Ancaster, Ontario. Precision is generally on the order of 1% of the amount present. Thirteen samples of Gombe Group Basalts were analyzed; representative analyses are given in Table 1. Fifteen samples from Balo, Lenderit, Kankam, and Mt. Kulal basalts were analyzed, for which representative analyses are also given in Table 2. The sample localities are shown in Fig. A1 of the appendix.

Two features of these analyses are worth pointing out. First is that the Gombe Basalts form a very tight compositional group, characterized particularly by their high TiO_2 content (see also Haileab et al., 2004). Second is that samples from individual basalt flows such as those along the Lowasera-Gus Road (K09-595; K86-2731), Balo (K89-3465, K09-607), Kankam East (K09-614, -615), Gus Junction (K09-589, -590, -597, -598, K90-4581), Hoi (K08-552, -588, -643A, -644) and Lenderit (K89-3463, K91-3534) are distinct from one another, and appear to be recognizable from the composition alone. In this sense, they can be used in the same way as volcanic ash layers for stratigraphic control. Some are similar, for example the Hoi Basalt and the Gombe Basalt Group in having high TiO_2 content, but are immediately distinguishable by their CaO, and Al_2O_3 contents which differ significantly and consistently. Geochemical differences also extend to minor and trace elements, and even the alkali metals appear to be useful. It is probable that such distinctions can be made because the lavas with which we are dealing are either aphyric or only sparsely porphyritic. The lavas of Mt. Kulal are, in general, much richer in alumina.

Three-dimensional computer visualizations of geological features and contact relationships were created by draping lithologic classification and false color composite images over DEMs. Hillshade images with simulated sun azimuths and elevations were also used to map drainage pattern, fissures and faults, and locations of volcanic cones and lava flows. Elastic plate flexural models of volcanic loading of the lithosphere were created to estimate vertical displacements of the earth's surface caused by the construction of large shield volcanoes. Flexural modeling used computer programs flex2D and flex3D written by Cardozo (2009).