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New sedimentary structures in seismites from SW Tanzania: Evaluating gas- vs. water-escape mechanisms of soft-sediment deformation

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ABSTRACT

Seismite horizons are abundant in Cretaceous sandstones of the Rukwa Rift Basin, southwestern Tanzania. Diverse morphologies of soft-sediment deformation are preserved, including two new, unusual sedimentary structures, herein referred to as 1) balloon-shaped inflation structures and 2) surface fractures with linked sandstone splays. This original description of new sedimentary structures contributes to the growing catalogue of seismically induced deformation features. Their unusual morphologies bring to the forefront an important, though seldom touched upon, question of how to differentiate between gas- and water-escape in soft-sediment deformation features. The recognition of the spectrum of soft-sediment deformation structures contained in strata and their deformational mechanisms is important because it permits the differentiation between triggering mechanisms, particularly seismic activity, and can constrain such events spatially and temporally. We interpret the surface fractures and linked sandstone splays to reflect a high gas effusion rate, formed by the release of high-pressure gas followed by a limited expulsion of water. The balloon-shaped inflation structures reflect lower gas effusion rates due to expulsion of lower pressure gas that did not breach the Cretaceous surface seal. When these gas pulses did breach the paleosurface, they formed gas-discharge pits. These seismogenic structures are consistent with deposition of Cretaceous strata in the Rukwa Rift during periods of active carbonatite volcanism, seismicity, and possibly hot spring activity. This documentation serves as an important data point for the re-examination of the classification scheme of soft-sediment deformation structures as primarily water-escape structures to accommodate for the genesis of some secondary sedimentary features by gas-escape.

1. Introduction

Soft-sediment deformation is attributed to the overpressuring of pore fluids in unconsolidated sediment, resulting in the modification and often destruction of primary sedimentary structures and the formation of new, secondary sedimentary structures (Lowe, 1975). A variety of mechanisms can initiate such conditions, including bedform shear, loading, slumping, seismicity, and many other actualistic processes (Allen, 1982; Obermeier, 1996; Owen, 1996, 1997; Jones and Omoto, 2000; Owen and Moretti, 2011). Water is universally called upon as the medium facilitating liquefaction and fluidization. Gases (e.g., biogenic, hydrothermal, etc.), however, are also a common component of sedimentary environments and may similarly instigate soft-sediment deformation. Although an extensive body of literature on soft-sediment deformation features exists, few studies have actually sought to distinguish between water- and gas-escape mechanisms of deformation and the resultant end products.

The majority of sedimentary structures formed by soft-sediment deformation are attributed to overpressure of the pore fluid, including convoluted bedding, folding, ball and pillow structures, flame structures, injectites, sand volcanoes, and many more types. Sedimentary structures solely attributable to gas expulsion are rarely documented (Cloud, 1960; Pralle et al., 2003; Jianhua et al., 2004; Frey et al., 2009). Some occurrences of gas-escape through sediments have been reported, although they are dominantly recognized and preserved in argillaceous and marine settings (Fleischer et al., 2001). Examples include chimneys and pockmarks related to gas hydrates (Cathles et al., 2010), air discharge pits on point bars (Jianhua et al., 2004), molar tooth structures in carbonates (Frey et al., 2009), circular gas-escape pits at a track site (Rindsberg, 2005), and gas bubble release due to biogenic gas build-up (Maxson, 1940; Cloud, 1960).

For soft-sediment deformation structures, the recognition of specific depositional settings, morphologies, and distributions are used to infer genesis via seismicity (McCalpin, 1996; Ettensohn et al., 2002; Reicherter et al., 2009), but identifying the triggering mechanism is

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often problematic (Owen and Moretti, 2011). Herein, we report on two new, small-scale soft-sediment deformation features identified in Cretaceous sandstones from the Rukwa Rift Basin, Tanzania. Based on several lines of evidence, these features are most likely attributable to seismic activity that caused the overpressuring and subsequent vertical migration of water and gas phases responsible for the preserved deformation. The newly identified balloon-shaped inflation structures and associated surface fractures with sandstone splays expand the understanding of gas migration effects on the generation of sedimentary structures, particularly in sand-sized sediments, and highlight the importance of considering gas-escape as a formation mechanism for soft-sediment deformation.

2. Geologic setting

The Rukwa Rift Basin (RRB) in southwestern Tanzania is a half-graben basin segment of the western branch of the East African Rift System (EARS; Fig. 1; Chorowicz, 2005). The thick deposits record changes in the kinematic stress regime throughout the polyphase history of the RRB from the Permian to Recent, including multiple phases of rifting (Kilembe and Rosendahl, 1992; Wheeler and Karson, 1994; Delvaux et al., 1998, 2012). The sedimentary packages preserved in the Rukwa Rift are valuable archives of long-lived fluvial and lacustrine deposition and provide key insights into the effects of volcanism and seismicity on deposition in a rift basin through time (Roberts et al., 2010; Hilbert-Wolf and Roberts, 2015).

The RRB records four episodes of rifting and associated sedimentary deposition. The Red Sandstone Group of the RRB was deposited above a thick, Carboniferous–Permian succession (the Karoo Supergroup) after a ~150 Ma hiatus, and is subdivided into the older Galula Formation and the younger Nsungwe Formation (Roberts et al., 2010). The Galula Formation is assigned a Cretaceous age based on paleontological, geological, and radioisotopic age constraints (Gottfried et al., 2004; Roberts et al., 2004; O'Connor et al., 2006), whereas the Nsungwe Formation has been firmly established as Oligocene, based on radioisotopic dating, magnetostratigraphy, and mammalian biostratigraphy (Roberts et al., 2010, 2012; Stevens et al., 2013). The Red Sandstone Group is overlain by the thick, late Neogene to Recent, Lake Beds succession (Grantham et al., 1958) that caps the rift fill sediment and is also an important archive of recent high magnitude seismic activity in the rift (Hilbert-Wolf and Roberts, 2015).

The Cretaceous Galula Formation is dominated by cross-bedded sandstones with minor conglomerates and thin mudstones that accumulated in a large amalgamated braided stream setting, which flowed northwest across the continent into the Congo Basin (Roberts et al., 2012). Sedimentation in the overlying Nsungwe Formation is characterized by a vertical progression from alluvial to fluvial to lacustrine settings, which indicates that at least a portion of the western branch of the East African Rift System developed into an internally draining lacustrine basin (Paleo-Lake Rukwa) much earlier than has been recognized previously in the basin or elsewhere along the western branch (Roberts et al., 2012).

Major Late Jurassic to Early Cretaceous rifting is supported by apatite fission track dates from the Rukwa and Malawi Rift flanks (Van der Beek et al., 1998). Additionally, Delvaux et al. (2012) recognize a succession of tectonic stress stages in the Mesozoic and late Cenozoic that correspond to preserved seismogenic sedimentary structures. Continuous and widespread tectonic activity and associated seismicity during the Cretaceous is clearly recognizable in the Rukwa Rift Basin sandstones (Figs. 2a, 3). Milga (1994) and Roberts et al. (2010) report extensive syndepositional soft-sediment deformation features from the Namba Member of the Galula Formation, including fluid-escape structures, clastic dykes, and growth faulting. These features are linked with intense tectonic activity and the emplacement of local intrusive/extrusive igneous bodies, such as the Panda Hill and Mbalizi carbonatites (Roberts et al., 2010; Fig. 1). Hydrothermal activity and CO_2 vents are current features of the basin system that may also influence the deformation of sediment.

3. Description of soft-sediment deformation

The soft-sediment deformation features discussed in this paper are located in the Songwe Valley, west of Mbeya, along the TanZam Highway at a locality called TZ7 (Fig. 1). At least four distinct 2–3.5 m-thick horizons with extensive soft-sediment deformation structures are recognized throughout the exposed Cretaceous Namba Member section.

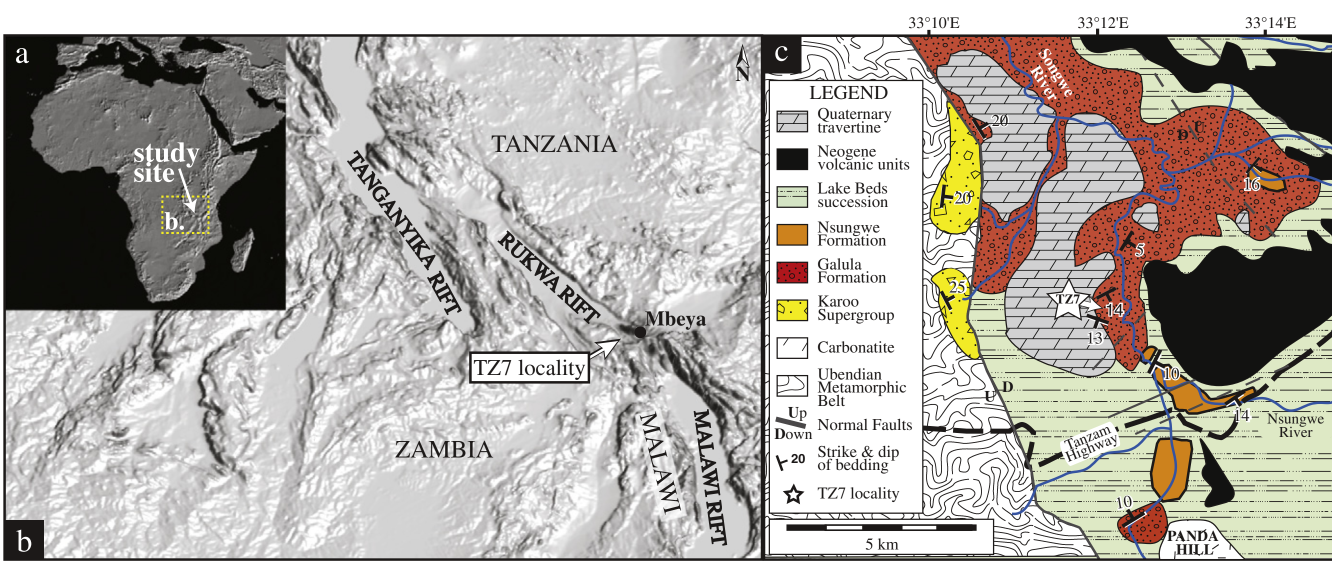

Fig. 1. Locality maps of the study site in the Rukwa Rift Basin. (a) Inset map showing the general location of the study area (yellow box) within eastern Africa. (b) Map of eastern Africa, highlighting the Tanganyika–Rukwa–Malawi rift segments. The arrow marks the study site in the Rukwa Rift Basin, southwestern Tanzania. Maps are modified from the NASA Shuttle Radar Topography Mission collection (http://www2.jpl.nasa.gov/srtm/cbanddataproducts.html). (c) Detailed geologic map of the TZ7 site in the Songwe sub-basin of the Rukwa Rift displaying volcanic and structural features (modified from Roberts et al., 2010).