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Dynamics and driving factors of late Holocene gullying in the Main Ethiopian Rift (MER)

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ABSTRACT

The issue of determining the driving factors in gullying, apart from land use, is somewhat lagging in comparison with the study of their physical modelling and control technology. Available information focuses on the basic ideas of climatic control, anthropic determinism and internal "authigenic" dynamics. High resolution chronology of cyclic systems, common in extensively gullied areas, can provide a clue to the weight of each factor. This paper reports a study of this kind, focusing on two gully catchments in the Main Ethiopian Rift (MER), but backed by an extensive regional survey. By integrating tracing and correlation of unconformity-bounded stratigraphic units and soils with radiocarbon dating, a detailed chronology was obtained for the last 5000 years. This could be compared with proxy climate reconstructions of similar detail. Clear evidence of climatic control emerged; gully filling is triggered by decreased stream transport capacity and increased sediment supply during transitions towards drier climate phases, while gully entrenchment appears to take place at the start of moist intervals, for the reverse reasons. A broader consideration of geological setting, however, puts forward a more general interpretation. These gullies actually formed, in the beginning, as part of the land surface response to sudden, very recent tectonic events, which created accommodation space for temporary sediment stores. They should then be seen in the frame of the Discontinuous Ephemeral Stream (DES) concept; as such, they are intrinsically non-linear and complex phenomena, whose response is linearized by a strong climatic–vegetational forcing, acting on both channel flow and sediment supply.

1. Introduction

A "geological" perspective on gullies, i.e. one fully considering both the time dimension and the weight of endogenic factors, is not strictly new; yet, it is often in the background in discussions about the phenomenon. A recent authoritative review (Valentin et al., 2005), after thoroughly surveying the issues of gully physics and the influence of land use (in a broad sense), states that "there is little information on how gully systems may respond to climatic change". It goes on to say that "The lessons derived from historical erosion show however that the main gully erosion periods correspond not only to rapid land use changes associated with denudation but also to a higher frequency of high-intensity rainfall". Such considerations are mainly based on studies focused on Europe and the historical period, such as Dotterweich et al. (2003), Stankoviansky (2003) and Vanwalleghem et al. (2005). Similar studies exist for the Southern hemisphere (Fryirs and Brierley, 1998; Mieth and Bork, 2005) and for the western United States (Leopold et al., 1966).

However, studies depicting evolution of gullies over longer time scales often evidence a cyclical behaviour. Prosser et al. (1994), establishing new standards in gully chronology, reconstructed incision and backfilling cycles back into Late Pleistocene. Their reconstruction put a strong emphasis on a nearly "bi-static" behaviour, in which long-lasting aggradation cycles were interrupted by sudden deep entrenchment events. Porter and Zhisheng An (2005) illustrate a glacial–interglacial gully cut-and-fill cycle going back to Marine Isotope Stage 11, about 0.42 Ma BP. These authors propose an interpretation model in which the incision phase is caused by precipitation and stream flow increases at glacial–interglacial transitions, while subsequent backfill is triggered by specular flow reductions at the next interglacial–glacial transition. A physical analog model, on a very different time scale, was proposed by Waters and Haynes (2001), supported by a high resolution chronology of Holocene gully cycles. Notwithstanding the different time scales, both models converge on the same basic causal hypothesis: transitions to moister climates bring rainfall levels that existing, dryland, vegetation cover cannot stand; this brings increased runoff, cutting of soft materials and increased stream flow competence to deepen the cuts. The opposite climate transitions reduce stream flow, then sediment transport capacity; this makes existing deep, box-shaped, channels overfit, so that they get choked by the increased sediment supply, from both devegetated catchment slopes and degradation of the vertical banks.

Both the "anthropic" and the "climatic" causal explanations can be grouped as "allogenic", inasmuch as they consider external controls as

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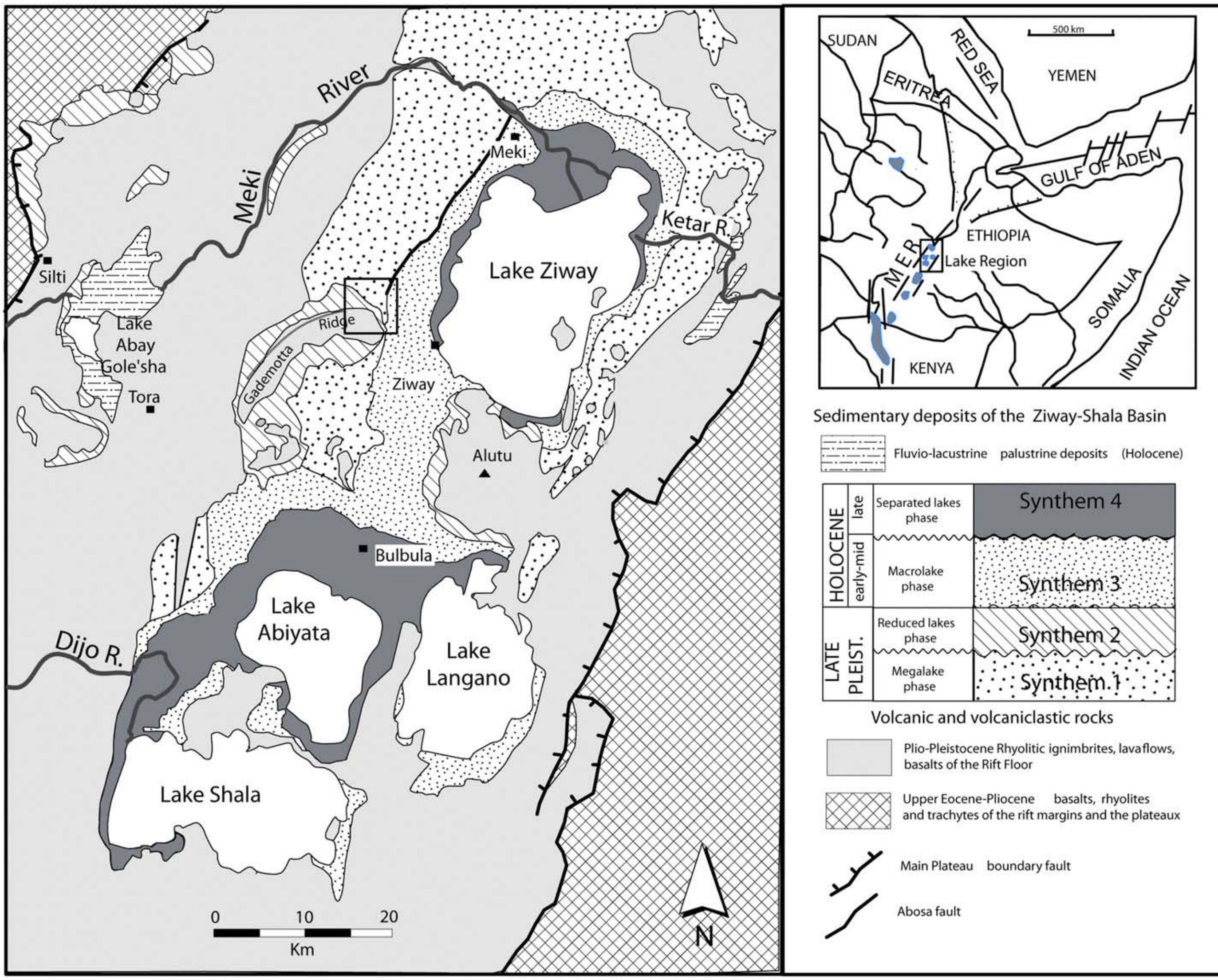

Fig. 1. Location and outline geological map of the Lakes Region in the Main Ethiopian Rift (MER, after Benvenuti et al., 2002); rectangle indicates study area.

the main driver of gully triggering and evolution. An "authigenic" hypothesis also exists, well expanded in Prosser et al. (1994). Starting from the general observation that the incision phase is much shorter than the fill phase, these authors maintain that incision is an episodic phenomenon, controlled by local conditions and independent of external controls, and that gullying is then a classical example of geomorphic "complex response" (Schumm, 1973). This analysis properly framed gullies as fluvial landforms, and took into full consideration basin geometry. Such a logical step brought gullies within the broader category of discontinuous ephemeral streams (DES, Bull, 1997), so involving such major geological concepts as vertical accommodation space and drainage network development. A prime determinant of a DES-dominated drainage (Bull, 1997) is known to be the rapid creation of vertical accommodation space in continental basins, either by mountain rise or by differential subsidence, as in the Main Ethiopian Rift (MER). This association acknowledged the role of tectonics and brought the gully issue into the broader framework of basin development.

A critical element in assessing the relative weights of climatic, anthropogenic and autocyclic drivers in gully development is chronology; the original case for autocyclic behaviour was in fact made by Prosser et al. (1994) essentially on a chronological basis. Supporters of the anthropic explanation often point out synchroneity between gully incision and major land use changes, such as deforestation in Europe and drainage of depressions in Australia. Chronological analysis of cyclical gully systems could demonstrate of refute the climatic control hypothesis, by succeeding or failing to evidence synchroneity between gully phases and climatic events.

Table 1
Summary of the Late Quaternary of the Lake Region (after Benvenuti et al., 2002)

Stratigraphic units	Description
Synthem 1 (100–22 ky BP, Megalake phase)	Colluvial, fluvio-deltaic and terrigenous lacustrine deposits, as well as lacustrine diatomites and volcaniclastic materials; sub-units 1a to 1c.
Synthem 2 (22–10 ky BP, Reduced Lakes phase)	Alluvial–colluvial and volcaniclastic deposits; made up of four distinct sub-units (2a to 2d). The typical upper bounding surface is the T'ora geosol (Benvenuti et al., 2002; Carnicelli et al., 2002).
Synthem 3 (10–5 ky BP, Macrolake phase)	Colluvial, fluvio-deltaic and terrigenous lacustrine deposits, as well as lacustrine diatomites and volcaniclastic materials. Characterized by a complex and variable stratigraphic architecture.
Synthem 4 (5ky BP-present, Separated Lakes phase)	Colluvial, fluvial, deltaic and lacustrine sediments, subdivided into sub-units 4a to 4b, each in turn subdivided in three third rank units (4a1–3 and 4b1–3, respectively).