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Influence of pre-existing pervasive fabrics on fault patterns during orthogonal and oblique rifting: An experimental approach

A. Chattopadhyay*, M. Chakra

Department of Geology, University of Delhi, Delhi 110 007, India

A R T I C L E I N F O

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A B S T R A C T

Pervasive mechanical anisotropy (e.g. metamorphic foliation) in the pre-rift basement rocks often appears to control the orientation of new faults in natural rift systems, and thus tend to influence formation of fault-bounded sedimentary basins. However, the extent to which this influence works in nature has remained debatable, and contrasting ideas exist regarding the issue of structural inheritance in natural rifts like the East African Rift system. Earlier experimental works have investigated different kinematic aspects of faulting in simulated orthogonal and oblique rift systems, including the role of a crustal-scale pre-existing zone of weakness on continent-scale rifting. These experiments have tested the influence of discrete pre-existing weak zones (e.g. pre-existing faults or an ancient orogenic belt) on localization of subsequent rifting, but have not considered the control of pervasive fabric anisotropy (e.g. metamorphic foliation, etc.) in pre-rift basement rocks on the fault patterns during rifting. Here we present a series of simple, roughly scaled, analog model experiments where pervasive strength anisotropy in the basement was created by brushing plaster of Paris on a viscous (pitch) substratum. This way a transverse anisotropy of tensile strength was generated in the plaster of Paris layer due to thickness variation across the brush marks. The basement was overlain by a dry sand pack, simulating weak sedimentary rocks overlying a foliated crystalline basement. Orthogonal and oblique extension of the models at various angles, and with differently oriented strength anisotropy, exhibited the control of the anisotropy on the orientations of new faults in the sand layer. In general, anisotropy could significantly control the fault pattern only when it was at a high angle ($>45^\circ$) with respect to the maximum instantaneous horizontal stretching direction (ε_{H1}), otherwise they largely disregarded the anisotropy and formed orthogonal to ε_{H1}. Faults never formed orthogonal to the displacement vector (D) in oblique rifting, unless the fault-controlling anisotropy was perpendicular to D. Faults strongly following the anisotropy were much longer than those not following that trend. Faults oblique to the anisotropy were short, segmented and tortuous in nature, and mainly grew by segment linkage. The experimental results support many field observations made in the East African Rift system, and are likely to be applicable to other rift systems like Gondwana basins of India, where field data on such structural inheritance are meager.

1. Introduction

Continental rift systems commonly exhibit characteristic structural geometries and fault patterns that are significantly influenced by the pre-existing fabrics and/or weak zones in the underlying crystalline basement, as demonstrated from the East African Rift system (McConnell, 1972; Daly et al., 1989; Hetzel and Strecker, 1994; Ring, 1994; Theunissen et al., 1996), from the Tertiary rifts of Thailand (Morley et al., 2004), and from the Paleozoic Gondwana rift basins of India (Chakraborty et al., 2003). Some uncertainty lies in the nature of the pre-existing discontinuities that affects a rift system. Reactivation of major pre-existing discrete faults and shear zones under oblique extension seems to be a common cause of development of fault-bound basins non-perpendicular to the regional extension direction (e.g. Central Malawi Rift: Ring, 1994; Gulf of California: Withjack and Jamison, 1986; Gondwana basins of India: Chakraborty et al., 2003). However, these major faults generally define the rift boundaries, and do not directly explain the secondary fault patterns internal to the rifts. Moreover, all pre-existing faults are not necessarily prone to reactivation during subsequent tectonic activity. On the other hand, it has been experimentally verified that tensile strength of

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* Corresponding author. Tel.: +91 11 27666082; fax: +91 11 27666295.
E-mail address: anupamchatto@gmail.com (A. Chattopadhyay).

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layered rocks can be much lower than that of massive, non-layered rocks, when subjected to extension at a high angle to the foliations (Donath, 1961; Youash, 1969). Zang and Stephansson (2010) has recently shown that the Young's modulus of foliated gneissic rocks can be lower by up to 30% when measured perpendicular to the foliation in comparison to that measured parallel to the foliation. Pervasive metamorphic fabrics in the basement rocks (e.g. cleavage, schistosity, gneissic or mylonitic foliation) may therefore impart significant strength anisotropy in these rocks which can influence the orientation of new faults and transfer zones throughout the rift system during regional extension (Morley, 1999). For example, the western branch of the East African Rift system (Rukwa–Tanganyika rift) follows pervasive, NW–SE trending, subvertical metamorphic fabrics (Ubendian fabric) inherited from the Precambrian orogenic belts, and thus deviates from the general N–S orientation of the Eastern branch (Central Kenya rift system) (McConnell, 1972; Hetzel and Strecker, 1994; Theunissen et al., 1996; Morley, 1999). The influence of pervasive fabric-induced anisotropy on rift structures therefore needs better understanding.

Analog modeling has been widely used to understand the influence of pre-existing anisotropy on the rift structure (Withjack and Jamison, 1986; Serra and Nelson, 1988; Tron and Brun, 1991; Dauteuil and Brun, 1993; McClay and White, 1995; Keep and McClay, 1997; Bonini et al., 1997; Clifton et al., 2000; Corti et al., 2001; Henza et al., 2010). In all these experiments, the pre-existing anisotropy was created in the form of a pre-cut basal plate which imparted a velocity discontinuity at the base of a layered sand pack, or a wet clay block. Divergence of the basal plates at different angles created diverse kind of oblique rifting in the system that produced faults of different orientation, geometry and kinematics in the overlying sand/clay model. Although these analog model experiments have generated detailed information on the surface fault patterns, fault interaction and linkage, and fault shape/size/displacement distribution etc. characteristic of oblique rifts, they are unable to address the issue of possible influence of pervasive fabric anisotropy on rift geometry, principally because there was no vertical (or steeply inclined) layering/foliation in the sand/clay models. The sand packs or clay blocks were therefore mechanically isotropic, and could not influence the faults generated in the models by oblique divergence imparted at the base (see Morley, 1999 for detailed discussion). To circumvent this problem, at least partially, attempts have been made to simulate polyphase rifting in analog models where either an early orthogonal rifting of the sand-pack was succeeded by oblique rifting at different angles, and vice versa (Bonini et al., 1997; Keep and McClay, 1997), or the model was subjected to two phases of oblique rifting at different divergence angles (Henza et al., 2010), to study the influence of pre-existing faults (formed during first phase) on the subsequent rifting phase. These polyphase rifting experiments possibly better explains the pattern of faults observed in some natural rifts (e.g. Mohns ridge in the Norwegian Sea, and Central Graben in the North Sea Rift: Keep and McClay, 1997; part of Ethiopian rift: Bonini et al., 1997, Jeanne d'Arc rift near Newfoundland: Henza et al., 2010). However, they address the influence of discrete weak zones (brittle faults) only and not the influence of pervasive metamorphic fabric in the basement which seems to be important in many natural rift systems (e.g. Rukwa–Tanganyika Rift, as discussed in Morley, 1999). Corti et al. (2004) simulated a pre-existing orogenic belt by incorporating a weak vertical zone (sand–silicone mixture) of varied geometry in the lower crust (plasticine–sand–silicone mixture) in their centrifuge experiments. During extension, the main rift valley (a central depression with or without marginal smaller grabens) on the model surface followed the underlying weak zone in case of straight or slightly curved weak zone, while for more curved weak zones in the basement, there were offset rift segments developed in the upper crust with more complicated oblique-slip faulting. Later, numerical experiments (Corti et al., 2007) have simulated a smoothly curved orogenic belt (similar to that around the western margin of the Tanzanian craton in East Africa) as the crustal weakness zone. Extension of the model envisaged dip-slip faulting and deeper graben formation in the central part of the curved belt, where extension was nearly perpendicular to the weak zone, whereas the flanking portions, oblique to the regional extension, showed development of asymmetric, shallower grabens and more oblique-slip faulting. These two experimental works successfully demonstrated the influence of pre-existing crustal-scale weak zones on subsequent rift development and rift-related magma emplacement. However, they did not address the issue of pervasive gneissic/metamorphic foliation playing a major control on the development of obliquely oriented faults in many rift systems, especially in the Rukwa–Tanganyika segment of the East African Rift (Morley, 1999, 2010).

In the present paper we describe a series of analog model experiments with weak but pervasive strength anisotropy created by brushing a layer of plaster of Paris on pitch (bitumen) substratum. Orthogonal or oblique divergence of the substratum produced brittle faults in the plaster of Paris layer, the orientations of which were clearly influenced by the anisotropic nature of the brittle layer. Homogeneous sand models built on these anisotropic basal layers show fault orientations significantly influenced by the basal anisotropy, as described in the next section.

2. Experimental method

2.1. Model set-up and materials used

To observe and assess the influence of basement anisotropy on rift pattern, we used layered models: a rectangular block (20 cm × 15 cm × 3 cm) of pitch (80/100 bitumen from Indian Oil Corporation) was overlain by a thin (≈0.5 cm thick) layer of brittle plaster of Paris (wet mixture of gypsum powder:water ≈ 3:1 v/v). Such two-layered models were further covered with a 1 cm thick layer of dry, quartz-rich sand (Fig. 1). Rheological properties of the model materials are shown in Table 1. The wet plaster of Paris mixture was spread over the surface of the pitch block with the help of a flat, hard brush. Brushing was done systematically parallel to a desired direction (at an angle of 0°/15°/30°, etc. with the margin of the model) (Fig. 1). When dried up, these brush marks effectively stood as small ridges and grooves on the Plaster of Paris, imparting a systematic change in thickness of the material across the fabric (Fig. 1). As the tensile strength of plaster of Paris decreases with decreasing thickness (e.g. Berenbaum and Brodie, 1959), the ridges (thick) and grooves (thin) imparted a transverse anisotropy of tensile strength in the Plaster of Paris, which is somewhat analogous to the transverse strength anisotropy expected in vertically foliated metamorphic basement rocks. Similar tensile strength anisotropy of brushed plaster of Paris, as a proxy to foliation in rocks, was earlier used by Ghosh (1988) in his experiments on chocolate tablet boudinage. As described in the later sections, this pervasive strength anisotropy of plaster of Paris can significantly influence the fracture/fault patterns during slow extension of the models. Dry quartz sand was sieved manually over the pitch-plaster of Paris basement to make a three-layered model (Fig. 1). The modeling technique was somewhat similar to the brittle–ductile (sand overlying silicone putty) models of Tron and Brun (1991), except for the plaster of Paris layer between the sand and the pitch. The rationale behind the three-layered models in our experiments is that the lower pitch block, which extends homogeneously and slowly under extension, simulates the viscous deformation of deeper crustal rocks; plaster of Paris, which is brittle