

Slip re-orientation in oblique rifts

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ABSTRACT

Oblique extension is expected to result in a combination of dip-slip and strike-slip displacement along faults with strike orthogonal and oblique to the extension direction, respectively. This general concept is in disagreement with observations from natural oblique rifts, where faults show dip-slip kinematics indicating pure extension irrespective of the fault strike with respect to the regional extension direction. Consequently, along oblique structures, slip is re-oriented, and oblique to the applied extension direction. Besides, at fault scale, slip is re-oriented along strike such that it is dip slip at the fault center and becomes highly oblique slip toward the fault tips. Here, we use analogue experiments to show that this discrepancy can be resolved when a preexisting weak zone (WZ) is present in the crust at the onset of oblique extension. The WZ is implemented within the lower crust and strikes oblique to the extension direction. Our experimental results show that an inherited WZ within the ductile crust favors the re-orientation of slip such that oblique extension results in pure dip-slip displacement on faults that strike oblique with respect to the extension direction. Furthermore, we show that slip is re-oriented along strike of major faults, such that the fault center shows dip-slip kinematics, whereas its tips display strike-slip kinematics. These findings call into question the use of paleostress reconstructions to constrain plate kinematics in oblique extensional tectonic settings.

INTRODUCTION

Rifting of the continental lithosphere results from the interplay between far-field tectonic forces and/or magmatic processes (i.e., diking) (e.g., as reviewed by Ziegler and Cloetingh, 2004; Buck, 2004). The location of continental rifts is controlled by regional-scale inherited structures along which the deformation localizes. Rifts rarely strike orthogonal to the direction of far-field tectonic forces; in fact most of them are oblique. In this context, it is commonly expected that structures striking orthogonal to the extension direction show dip-slip kinematics whereas those being oblique display strike-slip kinematics (Withjack and Jamison, 1986; Tron and Brun, 1991). However, oblique rifts exhibit faults that are activated with pure dip-slip kinematics independent of their orientation with respect to the extension direction. This implies a local deflection of the regional extension direction and a slip re-orientation along oblique faults (e.g., Main Ethiopian rift [Agostini et al., 2011; Philippon et al., 2014]; Baikal rift [Petit et al., 1996]; western branch of the East African rift system [Morley, 2010]; Gulf of Aden [Autin et al., 2010, 2013]). Corti et al. (2013a) suggested that slip re-orientation along oblique rift-border faults may be controlled by a deep-seated weak zone (WZ) striking oblique to the extension direction. Additionally, it has been suggested that on individual faults, slip may be re-oriented from dip slip at the fault center toward highly oblique slip of the tip of the faults (Jackson et al., 1982; Michetti et al., 2000; Roberts and Michetti, 2004; Roberts, 2007; Maniatis and Hampel, 2008; Faure Walker et al., 2010). These natural phenomena of slip reorientation call into question the use of paleostress inversions as a constraint for plate kinematics. In this study, we use analogue experiments to investigate oblique extension and inherent slip re-orientation. We show that (1) the kinematics observed along oblique structures, whatever their obliquity, does not correspond to the applied extension direction, and slip is re-oriented orthogonally

to the fault strike; and (2) fault terminations often show strike-slip whereas fault centers display pure dip-slip kinematics.

MODELING SLIP RE-ORIENTATION

In order to investigate fault kinematics in oblique rifts, we employ crustal-scale brittle-ductile analogue models, which are scaled according to the principles of geometric and dynamic-rheologic similarities (Hubbert, 1937; Ramberg, 1981). Our models simulate 22.5 km of extension affecting a 35-km-thick continental crust at a rate of ~ 4 mm yr⁻¹ (refer to the GSA Data Repository¹ for further details). The obliquity of a WZ with respect to the direction of extension has been tested by increments of 15°, from 0° to 45°.

The long side of the experiment is orthogonal to the direction of extension and taken parallel to the geographic north to facilitate comparison with natural examples. In all experiments, two sets of normal faults developed at the end of the experiment: (1) large border faults that formed along the edges of the WZ, and (2) inner faults that developed above the WZ, within the model rift valley (Fig. 1).

When the obliquity is zero (i.e., the WZ strikes orthogonal to the applied stretching direction; Fig. 1A), all of the faults strike parallel to the WZ and orthogonal to the stretching direction (rose diagram, Fig. 1A). The direction of extension resulting from paleostress inversion of the whole model fault population does not deviate significantly from the applied direction of extension: faults accommodate extension without re-orienting the slip vector (stereonet, Fig. 1A).

From 15° to 45° of obliquity, the two distinct sets of faults can be clearly identified on the basis of their orientation: (1) the border faults develop strike directions in between the WZ trend and the orthogonal to the extension direction, and (2) the inner faults strike roughly orthogonal to the direction of extension, with a standard deviation on the order of 5° (rose diagrams, Figs. 1B–1D). For an obliquity of 15°, the border faults strike $N6.2^\circ E \pm 2.65^\circ$ (rose diagram, Fig. 1B). Paleostress inversion gives an extension direction differing by 16.6° clockwise (cw) compared to the applied direction of extension for the border faults, and by 3.5° counter-clockwise (ccw) for the inner faults (Fig. 1B). In the case of an obliquity of 30°, the border faults strike $N14.9^\circ E \pm 4^\circ$ (rose diagram, Fig. 1C). Along the border faults, paleostress inversion gives an extension direction deviating by 21° cw compared to the applied direction of extension, whereas the one given by inner faults differs by 5.6° cw (stereonet, Fig. 1C). For an obliquity of 45°, border faults strike $N20^\circ E \pm 5.78^\circ$ (rose diagram, Fig. 1D). For such an obliquity, the extension direction deviates from the direction of the applied kinematics boundary by 35.5° cw and 3° ccw, in case of border and inner faults, respectively (stereonet, Fig. 1D).

REGIONAL, OR RIFT-SCALE SLIP RE-ORIENTATION

Our experiments show that whatever the degree of obliquity of the WZ relative to the applied stretching, the strike of border faults bisects the angle between the orientation of the WZ and the orthogonal to the

¹GSA Data Repository item 2015056, methodology used for this study, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

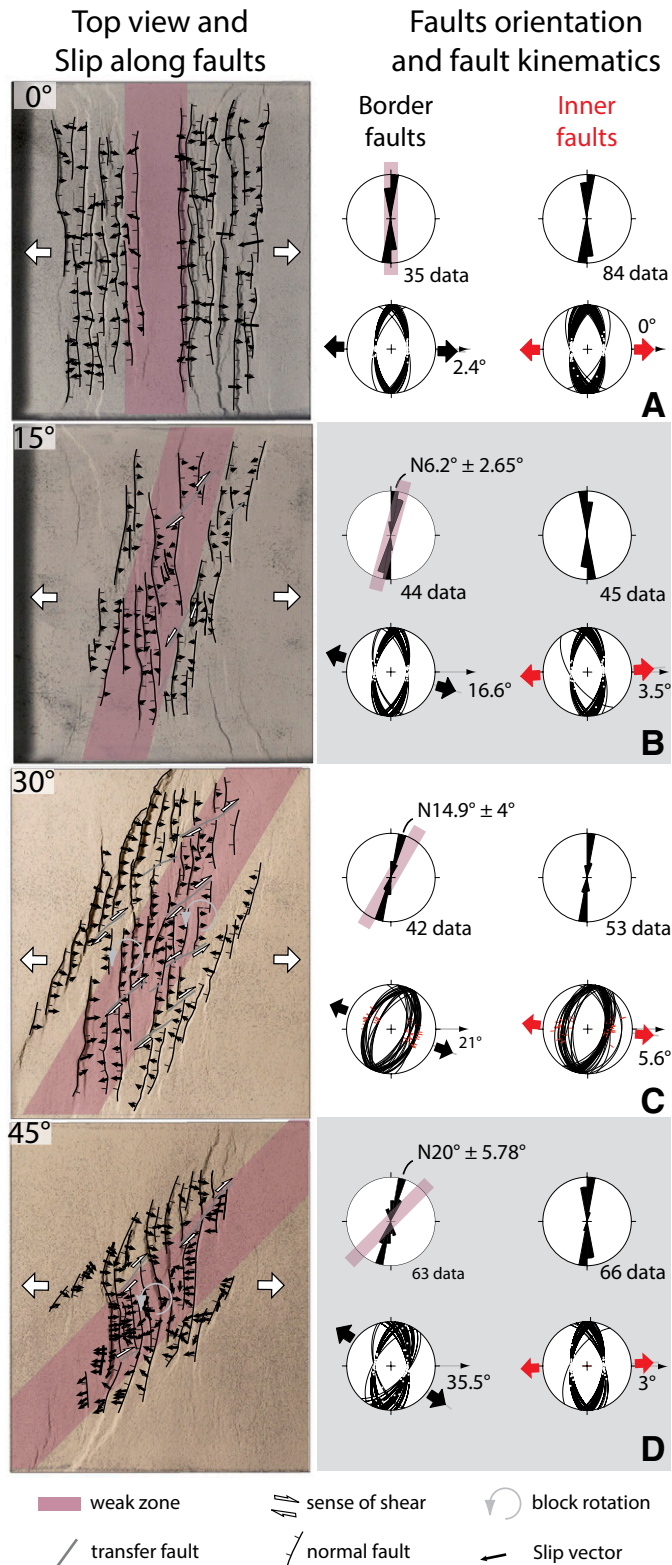


Figure 1. Experimental results obtained varying angle between strike of weak zone and applied extension direction: N0° (A), N15° (B), N30° (C), and N45° (D). Left panels: Top views of experiments and kinematics analyses of faults; thin black arrows represent slip vector; thick white arrows indicate direction of extension. Right panel: Rose diagrams showing trend of border and inner faults (top), and stereonet showing results of paleostress inversion (right dihedral inversion method) (Angelier, 1979) applied to whole border and inner fault data sets (bottom). Divergent black and red arrows refer to minimum horizontal stress computed along border and inner faults, respectively.

direction of extension, in accordance with Withjack and Jamison (1986) and Fournier and Petit (2007) (Fig. 1). These oblique border faults are activated in nearly pure dip slip, showing that fault strike influences the orientation of the slip vector, together with the applied direction of extension (Faure Walker et al., 2009; Wilkinson et al., 2014).

From 15° to 45° of obliquity, the reorientation of the direction of extension along the border faults increases while the angle between the border faults and the direction of extension decreases. The latter is clearly related to the degree of obliquity of the WZ. The inner faults show pure extensional kinematics, thus their slip vectors are at moderate to high angle with respect to the applied stretching direction. Different from previous studies inferring the activation of oblique-slip faults in transtension (Tron and Brun, 1991), our results suggest that the border faults have purely extensional kinematics, with their slip vectors being parallel to the fault dip and not to the regional extension. Within the rift floor, inner faults strike sub-orthogonal to the direction of extension in all of the experiments (Fig. 1). The reorientation of the direction of extension along these faults is minor and almost constant: slip vectors are parallel to both their dip direction and the extension direction. This suggests that the slip direction in oblique rifts can be significantly different between border and inner faults as a consequence of the orientation of inherited WZs in the crust. In agreement with Schlische and Withjack (2009), transfer zones accommodate the longitudinal change in dip of the inner faults affecting the rift floor; however, in our experiment they do not consist of localized fault zones (Fig. 1).

LOCAL, FAULT-SCALE SLIP RE-ORIENTATION

Field observations of individual normal faults show along-strike variations of the slip directions. Close to fault tips, slip directions are characterized by a significant strike-slip component, directed toward the center of the fault, whereas in the fault center the slip vector is dip slip (e.g., Corinth Gulf, Greece [Jackson et al., 1982]; Apennines, Italy [Michetti et al., 2000; Roberts and Michetti, 2004; Roberts, 2007; Faure Walker et al., 2010]) (Fig. 2A). Numerical models of single faults trending orthogonal to the direction of extension show an along-strike re-orientation of slip vectors similar to the one observed in nature (Maniatis and Hampel, 2008) (Fig. 2B). The obliquity of the slip vector at the fault tips (rake, noted as α in Fig. 2) depends only on the fault length and dip (Maniatis and Hampel, 2008). Analogue models show a similar behavior: for a fault forming orthogonal to the extension direction, the slip vector is re-oriented at the fault tip to point toward the fault center (Fig. 2C). The orientation of the slip vector (α) along the half-length of the fault has been monitored for each obliquity angle (Fig. 2D). Whatever the obliquity of the WZ and the orientation of the fault itself to the direction of extension, the faults in our experiments show the same bulk behavior: the rake decreases from the center to the fault tips where slip vectors tend to converge toward the fault center (Fig. 2D). This has been interpreted as reflecting local perturbations of the stress field at fault tips due to a greater hanging-wall subsidence compared to footwall uplift (Wu and Bruhn, 1994; Ma and Kusznir, 1995). Numerical and analogue models show a converging motion of the footwall toward the fault plane whereas the hanging wall is diverging from the fault plane. This locally disturbs the stress field and triggers along-strike fault slip re-orientation: the fault center shows dip-slip kinematics, whereas its tips display strike-slip kinematics. These results illustrate the variability of fault kinematics observed along strike of natural faults (Jackson et al., 1982; Michetti et al., 2000; Roberts, 2007; Maniatis and Hampel, 2008; Faure Walker et al., 2010) (Fig. 2).

IMPLICATIONS FOR PLATE KINEMATICS

Our results are consistent with natural examples of oblique rifts such as the East African rift and the Baikal rift. Within the African plate, a suture zone between Neoproterozoic mobile belts and the Tanzania craton has been localizing the deformation leading to development of the East

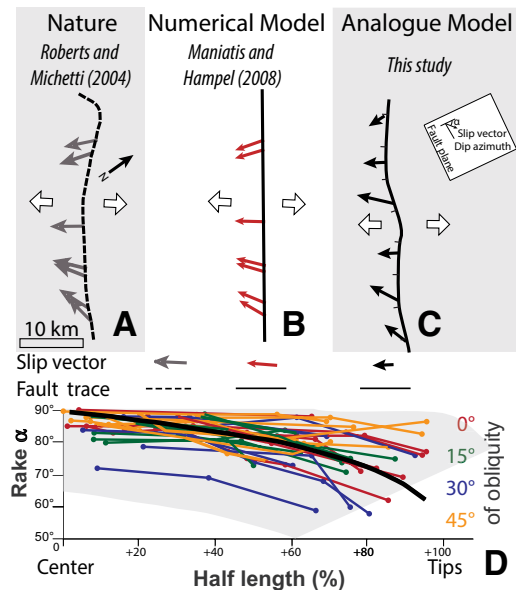


Figure 2. A–C: Slip vector behavior along a single fault plane observed in nature (A) (Apennines; Roberts and Michetti, 2004), in numerical models (B) (Maniatis and Hampel, 2008), and in crustal-scale analogue models (C) (this study). **D:** Graphics showing re-orientation of slip vector from center of fault to tips, for each tested obliquity. Thick black line is result of numerical modeling along a single fault for 0° of obliquity (Maniatis and Hampel, 2008). Colored dots correspond to different rake values determined along given model fault; model fault appears in diagram as segmented colored line that connects the dots.

African rift system (EARS). The northern segment of the EARS consists of the Main Ethiopian rift (MER), which separates Nubia from the eastward moving Somalia plate (Corti, 2008, and reference therein; Kogan et al., 2012) (Fig. 3A). Large border faults delimit the rift valley with a decreasing obliquity from north to south with respect to Somalia plate motion. Along these faults, slip is re-oriented and indicates a N110° to N102° direction of extension, whereas the inner faults yield an extension direction parallel to the N92°–96° regional direction of extension (Agos-

tini et al., 2011; Corti et al., 2013a, 2013b; Philippon et al., 2014). To the south, northwest-southeast- and northeast-southwest-striking weak zones control the western branch of the EARS, trending obliquely to the Somalia displacement (Fig. 3B). The faults delimiting the western branch are oblique to orthogonal to the direction of extension, although they are preferentially activated in pure extension (Delvaux and Barth, 2010; Morley, 2010).

Within the Eurasian plate, the Baikal rift localized at a suture zone between Neoproterozoic mobile belts and the Siberian craton (Petit et al., 1996, and references therein). The rift is sigmoidal with a central N20° segment and southwest and northeast extremities trending N75° and N60°, respectively (Fig. 3C). The obliquity of structures with the regional extension direction is high, and the large rift-bounding oblique faults are activated in pure extension (Petit et al., 1996).

In the MER, despite slip re-orientation, border fault-slip data are used to constrain Somalia's plate kinematics, leading to a model of poly-phased rifting implying a change in Somalia's kinematics (see discussion in Corti, 2008, and references therein). This model is in accordance with a plate kinematics model showing a clockwise rotation of Somalia (Lemaux et al., 2002). However, our study reveals that a single phase of oblique extension triggers slip re-orientation along oblique faults that may introduce a bias to the estimation of the paleo-direction of extension. As a consequence, a mono-phased evolutionary model, in accordance with both Somalia's steady-motion model (Royer et al., 2006; Iaffaldano et al., 2014) and recent analogue modeling results (Corti, 2008; Agostini et al., 2009, 2011; Corti et al., 2013a) (Table DR2 in the Data Repository), has to be favored for the MER.

To summarize, slip re-orientation is an efficient mechanism that may occur at oblique extensional plate boundaries at both regional and local scale. In particular, we have illustrated that (1) slip is re-oriented along the fault strike, varying from dip slip at the fault center to dominant strike slip at the fault tips (due to along-strike local stress changes), and (2) slip is re-oriented along oblique faults that show pure dip-slip kinematics. For this reason, paleostress data acquired along oblique structures should be taken with caution when used to constrain plate kinematics.

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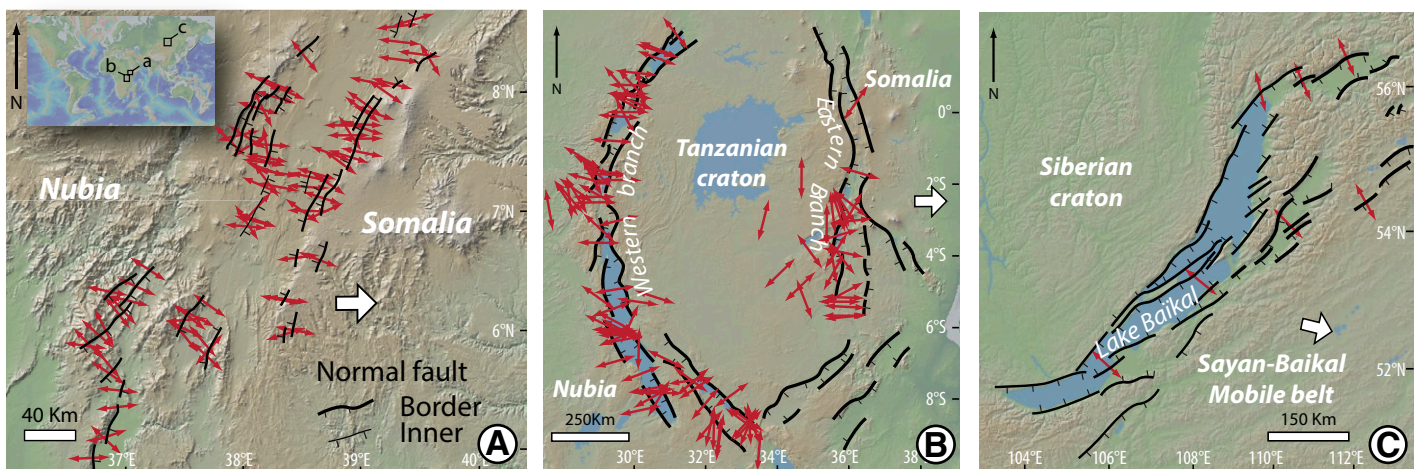


Figure 3. Digital elevation model of oblique rifts that developed within oblique weak zones. A: Main Ethiopian rift (Agostini et al., 2011; Philippon et al., 2014). **B:** Western and eastern branches of East African rift system (Delvaux and Barth, 2010). **C:** Baikal rift (Petit et al., 1996). White arrows indicate regional direction of extension (GPS motion); red arrows indicate local minimum horizontal stress deduced from either fault slip data or earthquake focal mechanisms.

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