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Active fault system across the oceanic lithosphere of the Mozambique Channel: Implications for the Nubia–Somalia southern plate boundary

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ABSTRACT

Seismic reflection and multibeam echosounder data were acquired in the Mozambique Channel in 2014 and 2015 during the PTOLEMEE, PAMELA-MOZ02 and -MOZ04 marine surveys aboard the *RV Atalante* and *Pourquoi Pas?* These data revealed that an active fault system is deforming the oceanic lithosphere of the Mozambique Basin which has developed during Jurassic-Cretaceous times. The correlation between the fault system and the arrangement of earthquake epicenters suggests that this tectonically active zone directly connects northward with the southern part of the eastern branch of the East African Rift System which corresponds to the seismically active graben system bounding the northern part of the Davie ridge. The fault zone extends southwestward of the Mozambique Ridge along the same trend as the Agulhas-Falkland transform fault zone. The general organization of the fault zone shows the characteristics of an extensional system north of the Mozambique Channel (north of the Europa Island) and a right-lateral transtensional system with coeval normal faults and strike-slip faults south-west of Europa. This tectonic activity is associated with volcanic activity since at least Late Miocene times. Our findings emphasize that the eastern branch of East African Rift System is extending largely toward the south, not only in continental domains but also through the oceanic lithosphere of the Mozambique basin. This fault zone is participating to the complex plate boundary between the main African continent (Nubia Plate) and Madagascar (Somalia Plate).

1. Introduction

The East African Rift System (EARS), originally described by Suess (1891), corresponds to the northern part of the divergent plate boundary system between the Nubian (West African) and Somali (East African) plates. This rift system is connected northward to the Afar hot spot which is related to the opening of the Red Sea and the Gulf of Aden, which began being active about 30 Ma ago. However, it is considered that the EARS began to be active only later, starting 24 Ma ago in the Afar area (Chorowicz, 2005). Although the EARS is commonly considered as the modern archetype of rifted plate boundaries, the current Nubia–Somalia kinematics is among the least well-known of all the major plate boundaries (Calais et al., 2006; Stamps et al., 2008). The plate boundary between Nubia and Somalia developed over thousands of kilometers across the eastern part of Africa during Late Oligocene and Neogene times (Chorowicz, 2005; Ebinger, 2012; McGregor, 2015). The location of the plate boundaries is well-defined along the continental branches of the EARS which include a western branch and an eastern branch (Fig. 1). The eastern branch (Gregory Rift) is characterized by high volcanic activity (including Mount Kilimanjaro, the highest point of Africa) and the western branch (Albertine Rift) is characterized by a moderate volcanic activity relative to the eastern branch and by deeper basins, containing lakes and sediments. The Great Lakes (Albert, Tanganyika, Rukwa, Malawi) are located in highly rifted basins bounded by normal and strike-slip faults of the western branch of the EARS. The two branches of the EARS delineate major rel-

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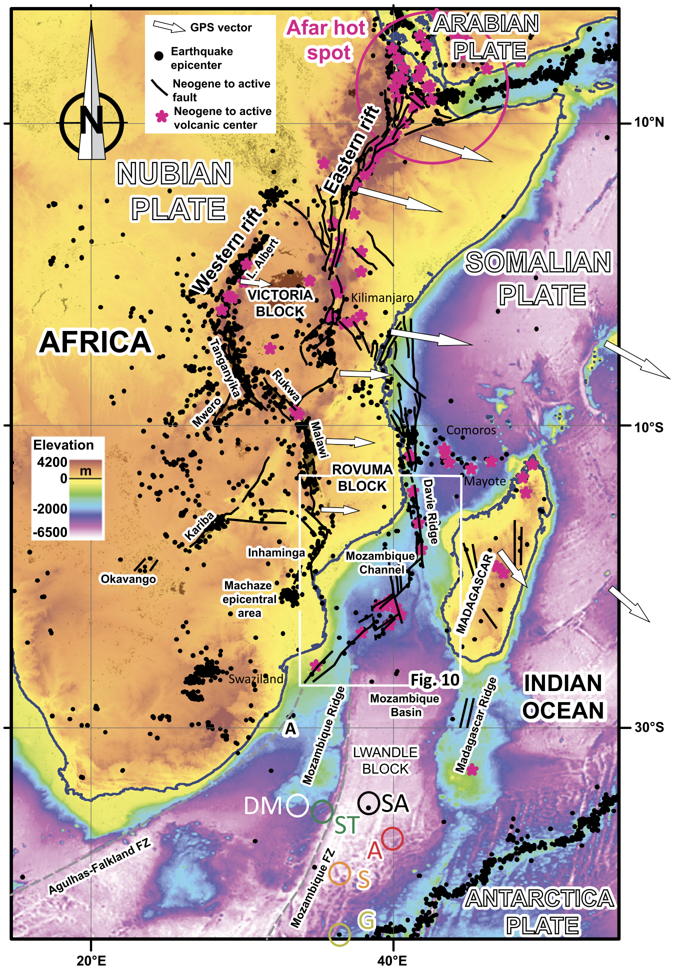

Fig. 1. Location of the study area in the context of plate boundary between the Nubian and Somali plates. Elevation/bathymetry grid from GEBCO. Black dots represent earthquake epicenters from the NEIC catalog (USGS). Black lines represent major faults along the EARS (compilation from Chorowicz, 2005; McGregor, 2015 on land; Franke et al., 2015 and this study offshore). Vectors show GPS velocities in a Nubia-fixed reference frame from Saria et al. (2013). The location of the rotation poles of Nubia *versus* Somalia are from Stamps et al. (2008) (ST), DeMets et al. (2010) (DM), Argus et al. (2010) (G), Altamimi et al. (2012) (A), Saria et al. (2013) (S), Saria et al. (2014) (SA). The Victoria, Rovuma and Lwandle plate are considered by these authors as relatively rigid poorly deformed blocks between the Nubia and Somalia plates. The limits of the Lwandle plate are poorly constrained by structural data. Point A corresponds to the location of the 31/12/1932 M 6.8 earthquake offshore South Africa.

atively poorly deformed blocks: Victoria and Rovuma (Hartnady, 2002; Calais et al., 2006; Stamps et al., 2008, 2014; Fernandes et al., 2013; Saria et al., 2014; Fig. 1). The eastern branch of the EARS extends off Tanzania and in the northern part of the Mozambique offshore, bounding notably the Davie Ridge (Mougenot et al., 1986; Mahanjane, 2014; Mahanjane et al., 2014; Franke et al., 2015; Mulibo and Nyblade, 2015). But south of the Davie Ridge in the eastern branch and south of the Machaze epicentral area in the western branch (Figs. 1 and 2), the exact location of the EARS still remains a topic of discussion. Scattered extensional structures associated with seismic activity are found onshore in Mozambique, Swaziland and South Africa (Foster and Jackson, 1998; Yang and Chen, 2010; Fonseca et al., 2014; Domingues et al., 2016) and also along the Comores and Mayotte islands and within Madagascar (Grimison and Chen, 1988; Bertil and Regnoult, 1998; Kusky et al., 2007, 2010; Michon, 2016; Fig. 1). Active tectonics across Madagascar has been interpreted as a possible extension connected to the East African Rift System (Kusky et al., 2007, 2010). It forms a segment running through Comores, across Madagascar and finally extends to the Southwest Indian spreading ridge. This extension is associated to Neogene-Quaternary alkaline volcanic activity associated with active hot springs. It also causes high and young topography and seismic activity and it is probably associated to mantle rise under Madagascar (Kusky et al., 2010). Earthquakes have also been recorded within the Mozambique Channel (Hartnady, 2002; Stamps et al., 2008) but prior to this study no data were available to characterize structural evidence for recent to active deformation within the Mozambique Channel (Fig. 1). Marine geophysical surveys carried out in 2014 and 2015 provided evidence for a recent/active fault system running crossing the Mozambique Basin (Fig. 4). This paper aims providing an analysis of the spatial distribution of active faults as well as faults sealed by recent sediments within this area. We notably present some examples of bathymetric data and seismic lines showing these structures and we discuss the significance of this fault system in the plate tectonics framework of the East African offshore.

2. Geodynamic and geological framework

North of the Mozambique Channel, the southern extension of the eastern branch of the EARS off Tanzania and Mozambique (eastern boundary of the Rovuma block) has been well-established by seismic reflection data (Mougenot et al., 1986; Mahanjane, 2014; Franke et al., 2015), earthquake slip vector data and GPS data (Calais et al., 2006; Stamps et al., 2008; Saria et al., 2014), and spatial distribution of earthquake focal mechanisms (Grimison and Chen, 1988; Yang and Chen, 2010; Delvaux and Barth, 2010; Franke et al., 2015). The offshore segment of the eastern branch of the EARS is characterized from north to south by Neogene extension tectonics overimposed on former strike-slip structures of the Tanzanian–northern Mozambique transform margin which have developed during Mid Jurassic-Cretaceous times in relation with the drift of Madagascar with respect to Africa (Rabinowitz et al., 1983; Coffin and Rabinowitz, 1987; Storey et al., 1995; Reeves, 2014; Franke et al., 2015). Regarding the current kinematics of the plate boundary between Nubia and Somalia, Chu and Gordon (1999) analysis placed the pole of rotation of Nubia versus Somalia in the offshore of southeastern cost of South African, in the Mozambique Ridge or south of the Mozambique basin (Fig. 1), which imply that south of the rotation pole, the southern part of the Nubian–Somali plate boundary is a diffuse zone of convergence (up to $\sim$2 mm yr^{-1}). This interpretation is consistent with subsequent work integrating seismicity studies (Horner-Johnson et al., 2007) and coupled seismicity-GPS studies (Calais et al., 2006; Stamps et al., 2008; Argus et al., 2010; DeMets et al., 2010; Saria et al., 2014; Stamps et al., 2014; Fig. 1).

Clusters of earthquake epicenters are located in continental Africa (Fonseca et al., 2014). In addition, evidence for volcanism and tectonic activity characterized by earthquakes has been reported along faults in the Comoros and Mayotte (Emerick and Duncan, 1982; Michon, 2016) and Madagascar (Kusky et al., 2007, 2010). This seismic activity shows that the deformation between the Nubian and Somali plates is distributed over a wide area, in several segments. In this complex tectonic setting, the exact location and the processes of deformation related to plate tectonics movements in the area of the Mozambique Channel remain poorly understood. West of the Mozambique Channel, surface structural evidence for rifting appears to stop around 22°S, south of the Lake Malawi and the Inhaminga fault, in the Machaze epicentral area (Fig. 1), whereas seismic activity at depth extend farther to the south in Swaziland and South Africa (Fonseca et al., 2014). On the other hand, east of the Mozambique Channel, the presence of active volcanism, recent faults, and seismic activity suggest that active deformation running through wide parts of Madagascar might correspond to the western boundary of the