TITLE:

THE OFFSHORE EAST AFRICAN RIFT SYSTEM: NEW INSIGHTS FROM THE SAKALAVES SEAMOUNTS (DAVIE RIDGE, SW INDIAN OCEAN)

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Abstract

The offshore branch of the East African Rift System (EARS) has developed during Late Cenozoic times along the eastern Africa continental margin. While Oligo-Miocene extensional tectonic deformation has been evidenced along the northern segment of the Davie Ridge, the spatial extent of deformation further south remains poorly documented. Based on recent and various oceanographic datasets (bathymetric surveys, dredgings and seismic profiles), our study highlights active normal faulting, modern east-west extensional tectonic deformation and Late Cenozoic alkaline volcanism at the Sakalaves Seamounts (18°S, Davie Ridge) that seem tightly linked to the offshore EARS development. In parallel, rift-related tectonic subsidence appears responsible for the drowning of the Sakalaves Miocene shallow-water carbonate platform. Our findings bring new insights regarding the development of the EARS offshore branch and tend to support recent kinematic models proposing the existence of an incipient plate boundary across the Mozambique Channel.

1. Introduction and geological settings

The Davie Ridge (DR, Fig. 1B) corresponds to a N170-trending bathymetric high, punctuated by successive seamounts, and crossing the Mozambique Channel from East Africa margin (~9°S) to Madagascar (~23°S). It has been broadly accepted that the DR, partly made of continental basement (e.g. Bassias, 1992), corresponds to the expression of a major transform margin resulting from the southward relative motion of Madagascar with respect to Africa between Middle Jurassic and Late Cretaceous times (~175-80 Ma; e.g. Coffin and Rabinowitz, 1987; Klimke et al., 2018). In parallel, recent studies (Klimke and Franke, 2016; Sauter et al., 2018) have shown that the northern extremity of the DR (i.e. the Wulu Ridge and Kerimbas Graben eastern flank) is not genetically related to Mesozoic transform tectonic activity but rather results from Cretaceous volcanism and Neogene East African Rift System (EARS) activity. The presence of mafic alkaline volcanic rocks with a geochemical signature showing analogies with Cretaceous volcanic rocks from southeast Africa and Madagascar was moreover previously mentioned by Leclaire et al. (1989) and Bassias and Leclaire (1990) along the southern part of the DR. Numerous studies concerning the Cenozoic evolution of the Mozambique Channel suggest that the DR is currently accommodating extensional tectonic activity related to the development of the offshore EARS (Fig. 1; Mougenot et al., 1986; Grimson and Chen, 1988; McGregor, 2015; Franke et al., 2015). Active plate deformation studies and kinematic models based on GPS and DORIS indicate one or more microplates between Madagascar and stable Africa (Nubia plate), including the Rovuma microplate between the Western rift and the Davie ridge (e.g., Hartnady, 2002; Calais et al., 2006; Saria et al., 2014; Stamps et al., 2015; Fig. 1A). These results are supported by an intense seismicity mostly associated with extensional earthquake source mechanisms (Fig. 1B, Dziewonski et al., 1981; Grimson and Chen, 1988; Ekström et al., 2012). The offshore branch of the EARS, firstly described by Mougenot et al. (1986), is marked by a transition from a mature rift basin offshore northern Mozambique (the Kerimbas Graben, Fig. 1B) to diffuse extension associated with juvenile faulting towards the Lacerda Graben and the DR (Franke et al., 2015). While the modern outline of the offshore EARS remains elusive southward, focused studies unraveling the geological evolution of the southern section of the DR throughout the Cenozoic and up to present-day are lacking.

The Sakalaves seamounts extend over 200km, following the NNW-SSE DR trend between 17°S and 19°S latitudes (Fig. 1B & 2A). These rough submarine reliefs are marked by an overall flat-top morphology of 275 sq.km (Fig. 2A & 2C) that corresponds to a drowned Oligocene-Miocene shallow-water carbonate platform whose flat top occurs around 400m below sea level (Courgeon et al., 2016). The Sakalaves carbonate platform is characterized by a dense network of normal faults that cut Miocene neritic carbonate sediments and, locally, by volcanic morphologies (Fig. 2C) that are tentatively interpreted as related to Late Cenozoic EARS development (Courgeon et al., 2016). Based on the analysis of dredged samples, seismic profiles and extensive bathymetry DEMs, this study aims at (1) investigating the modern structure and the Cenozoic evolution of the Sakalaves Seamounts and, (2) discussing their potential links with the development of the offshore EARS branch.

2. Data and Methods

This study is based on geophysical and geological data acquired during the 2014 PTOLEMEE (Jorry, 2014) and PAMELA-MOZ1 (Olu, 2014) cruises (RV *L'Atalante)* and during the 2015 PAMELA-MOZ4 (Jouet and Deville, 2015) cruise (RV *Le Pourquoi pas ?*). The seismic dataset was collected using the seismic acquisition system SEAL (Sercel, Ifremer) with a 24 traces and 600m streamer, and a 12.5 m hydrophone spacing. Bathymetric data were acquired with a Kongsberg EM122 multibeam system, processed using Ifremer CARAIBES^{TM} v4.2 software and were gridded into 30m resolution DEMs (WGS84). Stratigraphic data are based on: (1) foraminifera biostratigraphy (zones and letter stages after BouDagher-Fadel, 2008, 2013, 2015) (see table/Fig….), and/or (2) strontium isotopic stratigraphy (McArthur, 2012). Interpretation of volcanic rock samples is based on samples description and petrological analyses. Qualitative identification of crystalline phases was obtained from XRD data (BrukerD8 XRD instrument - Ifremer). Major element compositions of mineral phases were measured with a CAMECA SX100 electron microprobe at Laboratoire Magmas et Volcans (University of Clermont-Ferrand).

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3. Depositional and drowning history of the Sakalaves carbonate platform

Three dredges have been carried on top of the Sakalaves Platform (MOZ1-DW4, MOZ4-DW01 and MOZ4-DR03; Fig. 2C) and one was realized on the western slope (MOZ1-DR13; Fig. 2A). Eight distinct carbonate rock samples were collected (Tab. 1). Carbonate samples collected along the eastern flank of the carbonate platform (MOZ1-DR13-08) correspond to a Rupelian (Early Oligocene) skeletal packstone marked by typical shallow-water carbonate assemblage (e.g. robust Larger Benthic Foraminifera – LBF) and by abundant volcanic fragments (Fig. 3A) that suggest the occurrence of exposed volcanic reliefs at depositional time (Courgeon et al., 2016). These deposits suggest that colonization of volcanic reliefs by shallow-dwelling carbonate producers occurred during Early Oligocene times. Several Miocene shallow-water carbonate samples have been recovered on top of the Sakalaves carbonate platform and are also characterized by various shallow-dwelling carbonate producers like LBF, corals, red algae (Tab. 1). Finally, Pliocene and Pleistocene outer platform deposits were collected on top of the Sakalaves drowned carbonate platform. These facies, which correspond mostly to micritic packstone bearing planktonic foraminifera (Fig. 3B & 3C) mark the end of shallow-water carbonate production and the drowning of the carbonate platform below the euphotic zone. MOZ4-DR3-C3 is typified by the direct contact between Miocene shallow-water carbonate deposits and by Early Pliocene outer platform sediments (Fig. 3B) through an erosive unconformity that also reflects a Late Miocene – Early Pliocene drowning episode (Fig. 3D; see Godet et al., 2013 and references herein for details on drowning record in carbonate depositional sequences).

4. Geophysical investigation of the Sakalaves Seamounts: evidences for Late Cenozoic extensional tectonic and volcanism

The Sakalaves Seamounts submarine reliefs as well as the nearby seafloor and superficial basinal sediments are cut by an extensive network of normal faults and fractures presenting an overall N170 trend (Fig. 2), thus parallel to the DR structure. The profile crossing the northern extremity of the study area (Fig. 4A) displays multiple normal faults that locally reach the seafloor to form well-developed and continuous escarpments that are up to 200m-high and tens of kilometers long (Fig. 2A & 2B). The relatively flat submarine reliefs north of the Sakalaves Seamounts are also typified by numerous secondary faults and fractures (Fig. 2B). In addition, this domain is marked by an active seismicity characterized by extensional source mechanisms reflecting an east-west extension (Fig. 2A & 2B; Ekström et al., 2012). Seismic profiles acquired across the Sakalaves drowned carbonate platform (Fig. 2C) highlight the contact between low-amplitude carbonate slope deposits and higher-amplitude, volcanic substratum along the seamount flanks (Fig. 5A). The top of the Oligo-Miocene Sakalaves carbonate platform is characterized by eroded volcanic reliefs and is also cut by a dense network of fractures and normal faults delimitating distinct structural blocks (Fig. 2C). At the toe of the platform western flank, the seafloor is especially marked by a sharp and straight, 200m-high normal fault escarpment (Fig. 2C & 5). Our observations indicate extensional tectonic activity from the Neogene (potentially) and up to the present day along the Sakalaves Seamounts, i.e.

during or, most likely, after the growth of the Sakalaves shallow-water carbonate platform (Fig. 6D).

In addition to normal fault escarpments, the seafloor south to the platform is characterized by groups of monogenetic cones with circular depressions at their apices (Fig. 2D) and interpreted as volcanic build-ups. The seismic line carried out across these features show chaotic and steep-slope volcanic edifices locally covered by well-stratified pelagic sediments. These volcanic build-ups are also affected, locally, by normal faulting (Fig. 2D). The very-good morphological preservation of theses volcanic build-ups, coupled with their shallow depths (300-500m; locally above the top of the Oligo-Miocene Sakalaves Platform; Fig. 2D & 3B), suggests that associated eruptions probably occurred during Late Cenozoic times.

5. Petrographic and isotopic evidences for Late Cenozoic alkaline volcanism along the Sakalaves Seamounts

The volcanic nature of steep-slope and conic morphologic features observed on the seafloor and along seismic profiles (Fig. 2 & 4B) has been confirmed by dredging operations which led to the recovery of pyroclastic deposits, lavas and breccias belonging to a strongly alkaline volcanism (Fig. 6).

Samples of volcanic rocks dredged on the western flank of the Sakalaves platform (MOZ1-DR13; Fig. 2A) come from a breccia consisting of up to 10 cm large blocks of altered lava (basanites and nephelinites; Fig. 6A) cemented by carbonates. These lavas display an anaphyric to slightly porphyritic texture with varying proportions of mm-sized altered olivine phenocrysts set in a clinopyroxene-dominated glassy to microlitic groundmass that also contains nepheline, Fe-Ti oxides and apatite (± plagioclase, amphibole, Cr-rich spinel). Pyroclastic material consisting of vesiculated lapilli and scoriaceous fragments strongly indurated with carbonate cement (MOZ1-DR14; Fig. 6D) was dredged from the slope of one of the well-preserved volcanic cones south to the Sakalaves Platform (Fig. 2D and 4B). Stratification and sorting identified for some samples are symptomatic of tephra fallout deposits (Fig. 6D). These samples testify the pyroclastic character of these cones and their probable building in a subaerial environment. The mineral composition of the lapilli is seemingly close to that of the DR13 samples. The dating of carbonate cements (Tab. 2) indicates that the associated eruptive activity occurred during Neogene to Pleistocene times, confirming thus first hypothesis based on morphological analysis. The rocks dredged from the southernmost Sakalaves Seamounts (MOZ1-DR15) show a compositional bimodality with nephelinites (similar to MOZ1-DR13) and phonolites. Phonolites contain phenocrysts of sanidine, nepheline, biotite, amphibole, aegyrine, and titanite, in an altered glassy mesostasis with microcrystals dominated by K-feldspar, nepheline and Fe-Ti oxides (Fig. 6B). The sanidine crystals frequently show complex zoning involving successive resorption-crystallization processes that reflect physical and chemical changes of the melt from which crystals grew in magma reservoirs (Fig. 6C). Most of the volcanic samples collected along the Sakalaves Seamounts are strongly altered and thus cannot be dated trough radiometric methods.

6. Discussion and Conclusions

Normal fault escarpments observed along the Sakalaves Seamounts (Fig. 2) are overall parallel to the N170-trending DR structure (Fig. 1B), and appear similar to those reported further north between St Lazare and Paisleys seamounts (see Franke et al., 2015). Our findings suggest a continuum in Late Cenozoic diffuse and east-west extension from the Lacerda Graben and the Paisleys seamounts to the Sakalaves seamounts (Fig. 1B). This hypothesis is supported by the last decades' seismologic records revealing significant seismic activity coupled with extensional earthquake source mechanisms (USGS, Ekström et al., 2012) along this segment of the DR (Fig. 1B). In parallel, the drowning of the Sakalaves shallow-water carbonate platform, which seemingly occurred during Late Miocene - Early Pliocene times (Fig. 3D), coincides with the onset and the acceleration of rifting-related extension and tectonic deformation that led to the formation and the development of the Kerimbas Graben at the northern extremity of the Mozambique Channel (Franke et al., 2015). These observations suggest that this drowning was potentially triggered by rapid pulse(s) of rifting-related tectonic subsidence that outpaced carbonate accumulation potential.

In parallel, the Sakalaves Seamounts were affected by strongly alkaline volcanism associated with the edification of volcanic cones, the deposition of layered pyroclastic deposits and effusive activity. While the lavas remain undated, the dating of carbonate cements including pyroclastic deposits indicates Neogene to Pleistocene (Tab. 2) eruptions. This volcanism was most likely coupled to nearby extensional tectonic deformation as part of the Late Cenozoic development of the offshore EARS branch. Older studies (Hernandez and Mougenot, 1988) have also suggested EARS-related Neogene volcanism at the Kerimbas graben. Moreover, silica-undersaturated alkaline rocks (e.g. olivine nephelinite, ankaratrites, titanite-bearing phonolite) are commonly described in the recent volcanism in association with the EARS (e.g. Rogers, 2006; Neukirchen et al., 2010; Fontijn et al., 2012) or Madagascar (e.g. Cucciniello et al., 2017). Feldspar + nepheline-phyric phonolites can be regarded as evolved products from basanitic to nephelinitic parental magmas. The observed bimodality of the samples (basanite-nephelinite and phonolite) also represents a common feature of rift environments (Ivanov et al., 1998; Klaudius & Keller, 2006). Our findings as well as recent results on the origin of magmatism in Comoro Islands (Michon, 2016, see location in Fig. 1B) demonstrate that the offshore EARS is not devoid of magmatism, in contrast with earlier conclusions (Franke et al., 2015). However, part of the volcanism observed on the Sakalaves Seamounts occurred prior to the Oligocene, as it seemingly partly constitutes the substrate for shallow-dwelling carbonate producers (Fig. 3A), and can thus not be related to younger EARS development. Associated volcanic activity might had occurred during Cretaceous times as observed further north along the DR (Klimke and Franke, 2016; Sauter et al., 2018).

The timing, geometry and nature of the Late Cenozoic tectonic and volcanic activities reported along the Sakalaves Seamounts tend to confirm and extend previous hypothesis which suggest the southward development of the offshore EARS through the reactivation of transpressional lithospheric fabrics of the DR (e.g. Mc Gregor, 2015; Franke et al., 2015). As proposed by Franke et al., 2015, the Late Cenozoic extension observed along the Sakalaves Seamounts and the Davie Ridge might be facilitated by a gravitational collapse of the underlying folded Mesozoic structure. The associated subsidence would thus be partly accommodated trough isostatic adjustment mechanisms in response to the former Mesozoic compression phase. Late Cenozoic volcanism and extensional tectonic has also been reported in the southern central part of the Mozambique Channel in Bassas da India atoll and Europa Island realms (Fig. 1A; Courgeon et al., 2016; 2017), consequently supporting the kinematic models (e.g. Saria et al., 2014; Stamps et al., 2015) arguing that the EARS offshore branch extends further south following the Quathlamba Seismic Axis (Fig. 1A).

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Captions

Figure 1: (A) Modern East African Rift System outline. White lines correspond to major faults and fractures (from Chorowicz, 2005; Mc Gregor et al., 2015; Franke et al., 2015). The tectonic plates pattern is from Saria et al. (2004). Yellow dash line corresponds to active seismic corridor: the Quathlamba Seismic Axis (QSA). Ba means Bassas da India and locates the Southern Mozambique isolated carbonate platforms which are characterized by Late Cenozoic volcanism and extensional tectonic deformation (Courgeon et al., 2016; 2017). Sa means Sakalaves Seamounts and represents the study area. (B) Modern physiography of the northern Mozambique Channel. Red points correspond to records of earthquakes of magnitude >4 since 1950 (U.S. Geological Survey National Earthquake Information Center catalog). Earthquake source mechanisms come from Harvard CMT catalog (Dziewonski et al., 1981; Ekström et al.,

2012). Earthquake location accuracy is 20-30km.The graben and faulting (black dashed lines) designs are from Franke et al. (2015).

Figure 2: Bathymetric maps (30m resolution) of the Sakalaves Seamounts. White lines correspond to the main normal faults and fractures observed on the seafloor. Dashes along faults indicate, when appropriate, the down-thrown compartments. Records of earthquakes of magnitude >4 since 1950 (U.S. Geological Survey National Earthquake Information Center catalog) are represented by red points. Earthquake source mechanisms come from Harvard CMT catalog (Dziewonski et al., 1981; Ekström et al., 2010). Earthquake location accuracy is 20-30km. Red lines and lettering correspond to the location of seismic profiles presented in figures 4 & 5. Yellow lines and stars indicate the location of dredgings. (A) General morphology of the Sakalaves Seamounts, black dash squares locate close-ups presented in figure 2B, 2C and 2D. (B) Close up of the northern part of the Sakalaves Seamount characterized by a complex normal faults network and modern seismicity. (C) Close-up of the Sakalaves drowned carbonate platforms. The black dashed square locates a close-up presented in figure 4B. (D) Close up of the southern part of the Sakalaves Seamounts characterized by well-preserved conic volcanic morphologies in addition to normal fault escarpments.

Figure 3: (A) MOZ1-DR13-18: Oligocene (Rupelian) packstone bearing larger benthic foraminifera (LBF) and rhodoliths This limestone includes large and abundant altered volcanic fragments. (B) MOZ4-DR3-C3: Erosive unconformity between a Miocene grainstone of LBF and red algae (RA) and an Early Pliocene packstone rich in planktonic foraminifera (PF). (C)

MOZ4-DR3-C1: Pleistocene packstone with planktonic foraminifera. (D) Schematic and simplified Cenozoic evolution of the Sakalaves carbonate Platform (see details in the text).

Figure 4: (A) Seismic profile PTO-SR099 (see location on Figure 2A & 2B). Red lines represent normal faults. (B) Seismic profile PTO-SR112 (see location on Figure 2D). Red lines correspond to normal faults.

Figure 5: The Sakalaves carbonate platform (A) Seismic profiles PTO-SR108 and PTO-SR107 (See location on figure 2C). Red lines represent normal faults. Green line corresponds to the contact between the carbonate platform deposits and the underlying substratum, possibly volcanic in origin. The green dashed line corresponds to the tentative and simplified extrapolation of this contact at the seamount scale. The gray area represents the zone of seismic multiples. The yellow stars correspond to the projection of dredges along seismic profiles. (B) Morphologic close-up of 200m-high fault escarpment observed on the eastern flank of the Sakalaves carbonate platform (see location in figure 2C).

Figure 6: Photomicrographs (plane-polarized light), BSE image and photo of volcanic samples from the Sakalaves seamounts: (A) Nephelinite (MOZ1-DR13) with clinopyroxene microcrystals in a nepheline-bearing glassy groundmass; (B) Phonolite (MOZ1-DR15) with abundant sanidine and nepheline phenocrysts in an altered glassy groundmass. (C) BSE image of zoned sanidine crystals from a MOZ1-DR15 phonolite; (D) Volcanic breccia with vesiculated lapilli and ashes strongly indurated within carbonate cement (MOZ1-DR14).

Table 1: Synthetic table of age and nature of carbonate samples collected along the Sakalaves carbonate platform (see location of dredges in figures 2 & 5). PF: Planktonic Foraminifera. LBF: Larger Benthic Foraminifera. RA: Red Algae. Ech.: Echinoids.

Table 2: Strontium Isotope Stratigraphy of MOZ1-DR14 carbonate cements.