The Extent of Continental Material in Oceans: C-Blocks and the Laxmi Basin Example

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Abstract

We propose a tectonic interpretation for the outer-SDRs (SDRs: Seaward-Dipping Reflectors) and Pannikar central ridge in the aborted Laxmi Basin west of India from wide-angle seismic reflection data. The outer-SDRs comprise syn-tectonic extrusives (lavas and/or volcaniclastics) emplaced above passively exhumed mid-to-lower mafic crust of continental origin. They erupted following sudden lithosphere weakening associated with isolation of a continental block (a "C-Block"). Continuous magmatic addition during crustal extension allowed stretching of the lower crust whilst maintaining constant or even increasing thickness. A similar process occurred at both conjugate margins allowing bulk, pure-shear plate separation and formation of linear magnetic anomalies. The Laxmi example can explain enigmatic features observed in mature oceans such as presence of distal buoyant plateaus of thick continental crust away from the margins.

Keywords: Continental margins: divergent, Continental tectonics: extensional, Crustal structure, Crustal imaging, Indian Ocean

1. Introduction

Volcanic passive margins (VPMs) form when continental extension is coeval with extensive mantle melting (*e.g.*, Skogseid, 2001). Onshore surveys, coring and offshore deep-penetration seismic reflection profiles show that upper-crustal extension at VPMs is accommodated by both dyking (*e.g.* Klausen and Larsen, 2002; Kendall et al., 2005) and major continentward-dipping detachment faults (*e.g.* Larsen and Jakobsdottir, 1988; Geoffroy et al., 2001; Stica et al., 2014; Geoffroy et al., 2015). These faults bound thick wedges of syn-tectonic seaward-dipping volcanics that constitute the inner seaward-dipping reflectors (SDRs; Fig. 1).

At VPMs, successive SDR wedges grow from continent to ocean (Fig. 1a). We distinguish inner- and outer-SDRs (Planke et al., 2000). Inner-SDRs develop during extensional necking of the continental crust (Geoffroy, 2005; Geoffroy et al., 2015) (Fig. 1a). When observed, their bounding faults die out along the top of a thick lower crust characterized by high seismic velocities (HVLC) (*e.g.*, Schnabel et al., 2008; Funck et al., 2017) and strong reflections (*e.g.*, White et al., 2008; Geoffroy et al., 2015). This lower crust is best interpreted as heavily sill-injected continental crust (*e.g.*, White et al., 2008; Geoffroy et al., 2015). Its upper part (LC1 in Fig. 1a) contains large-scale solid-state-flow structures associated with continental extension and continentward shear such as kilometric-scale S-C structures (Geoffroy et al., 2015; Clerc et al., 2015) (Fig. 2a).

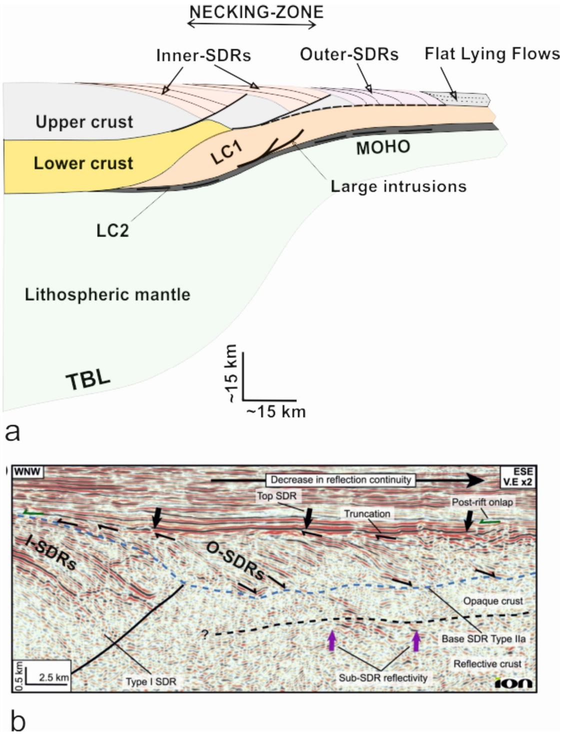

Figure 1. a. Sketch of a volcanic passive margin with crustal types. LC1 and LC2: High-velocity continental lower-crust (see Geoffroy et al., 2015). TBL: lithosphere thermal boundary layer. b. Transitional region between the inner-SDRs (here labelled by the authors Type I-SDRs) and outer-SDRs (here labelled by the authors Type II-SDRs) offshore Uruguay (from McDermott et al., 2018). See also Pindell et al. (2014). Note the flat-lying base of the outer-SDRs.

Ongoing excessive 'seaward' (or, rather, outward) magmatism and extension builds geometrically distinct distal outer-SDRs (Fig. 1a,b) (Planke et al., 2000; Franke et al., 2010; Quirk et al., 2014; McDermott et al., 2018). These are more arcuate than inner-SDRs (Fig. 1b) and associated with a high-velocity magmatic crust, which is thicker than averaged oceanic-crust (>7 km) (Fig. 1a). This crust shows a low- to sub-horizontally dipping Moho, in strong contrast to the necked, inner-SDR domain (Fig. 1). As observed in the S and NE Atlantic oceans (Franke et al., 2010; Quirk et al., 2014; McDermott et al., 2018), outer-SDRs are bent over a flat-lying horizon which divides the crust into two parts (Fig. 1b). In the S Atlantic, the crust beneath the outer-SDRs has a similar velocity structure to continental ductile middle crust LC1 observed beneath the necked part of VPMs (Geoffroy et al., 2015). This is also seen in the NE Atlantic when both reflection and refraction data are available (Funck et al., 2017; White et al., 2008). A third type of crust may exist at the extremity of VPMs. It is characterized by flat-lying igneous flows in the upper section and has been interpreted as non-oceanic crust (Franke et al., 2010; Soto et al., 2011; Geoffroy et al., 2019). We refer to this type of crust herein as FLF-crust (Fig. 1a).

Our understanding of the SDRs, and especially outer-SDRs, is currently incomplete (Fig. 2). Outer-SDRs are generally considered to be associated with enigmatic oceanic-crust accretion (*e.g.*, Franke et al., 2010; Paton et al., 2017) as inner-SDRs were earlier thought to be (*e.g.*, Mutter et al., 1982). The gravity-driven flexure model for paired SDR wedges (either inner- or outer-) (*e.g.* Buck, 2017) involves the feeding of SDR lavas by an axial, lithospheric-scale, feeder dyke with magma injected from bottom to top. Following each magma injection and dyke cooling event, the localized increase in weight of the lithospheric column results in downward flexure of the newly erupted surface lavas. As described hereafter, this model does not match common observations at exposed inner-VPMs and in many seismic reflection studies. Not only are major normal listric faults with throws of over 2 km observed bounding the fan-shaped lava wedges, but angular unconformities due to secondary synthetic faults are common in SDR piles (*e.g.*, Geoffroy et al., 2001; Pindell et al., 2014; McDermott et al., 2018; Chauvet et al., 2019). Inner-SDRs thus appear to develop in a similar way to hanging-wall basins on roll-over anticlines associated with listric detachment-type faults dipping continentward. In addition, many dykes crosscut inner-SDRs during their development at any location, most of them feeding the upper lavas at considerable distances from the edges of SDR wedges and related major faults (Klausen and Larsen, 2002; Lenoir et al., 2003; Abdelmalak et al., 2015). This indicates that the magma is not all injected from a stable, permanent axial zone, a fundamental starting point in the model of Buck (2007) for a single SDR wedge. Dykes beneath SDRs or cross-cutting them during their development are usually thin— less than 6 m on average in East Greenland (Klausen and Larsen, 2002) and less than 4.5 m in Iceland (Gudmundsson, 1983). Considering dykes to be mode-I cracks in an elastic medium, they are of moderate vertical extent and probably restricted to the upper crust (*e.g.*, Gudmundsson, 1983). Mafic dykes in active volcano-tectonic systems (*e.g.*, Einarsson and Brandsdóttir, 1980; Sigmundsson et al., 2014; Grandin et al., 2017) and in SDRs (e.g. Callot and Geoffroy, 2004) propagate predominantly laterally away from the localized magma chambers that feed them. Those chambers and their distribution thus exert the primary control on magma feeding.

The mechanisms of formation of outer-SDRs (Fig. 1b) are not constrained by direct observation. Iceland could be the only place worldwide where SDRs of Neogene age do outcrop close to an acknowledged oceanic rift (*e.g.* Palmason, 1981). Considering the distance from nearby inner-VPMs (E-Greenland and Faroe Islands) it is possible to assume that SDRs in Iceland are outer-type. The few detailed structural surveys from the eroded part of the island would show development similar to that associated with inner-SDRs, i.e. fault-controlled (Bourgeois et al., 2004). This was also the conclusion of Planke et al. (2000) from seismic reflection data collected at several VPMs worldwide. Admittedly, however, our knowledge on the origin of outer-SDRs as well as on the type of middle/lower crust (oceanic or continental) underlying them, remains incomplete. We tentatively address this topic below by considering the mode of continental breaking-up at VPMs.

It is observed that syn-magmatic detachment faults bounding inner-SDRs dip continent-ward at conjugate VPMs (Fig. 2a). From the onset of continental extension such geometry at a developing pair of conjugate margins must partition between them a continental block (C-Block). The C-Block is the common footwall of the continentward-dipping detachment faults controlling the inner-SDRs development (Fig. 2a). Recent thermomechanical modeling supports this geometry and suggests that the existence and stability of such C-Blocks depend on the existence of an initial high-viscosity layer (LC2) in the lowermost, pre-extension, continental crust (Geoffroy et al., 2015). As the outer-SDRs develop, the C-Block is expected to evolve, forming a progressively more dissected and extended magma-intruded microcontinent (Fig. 2b).

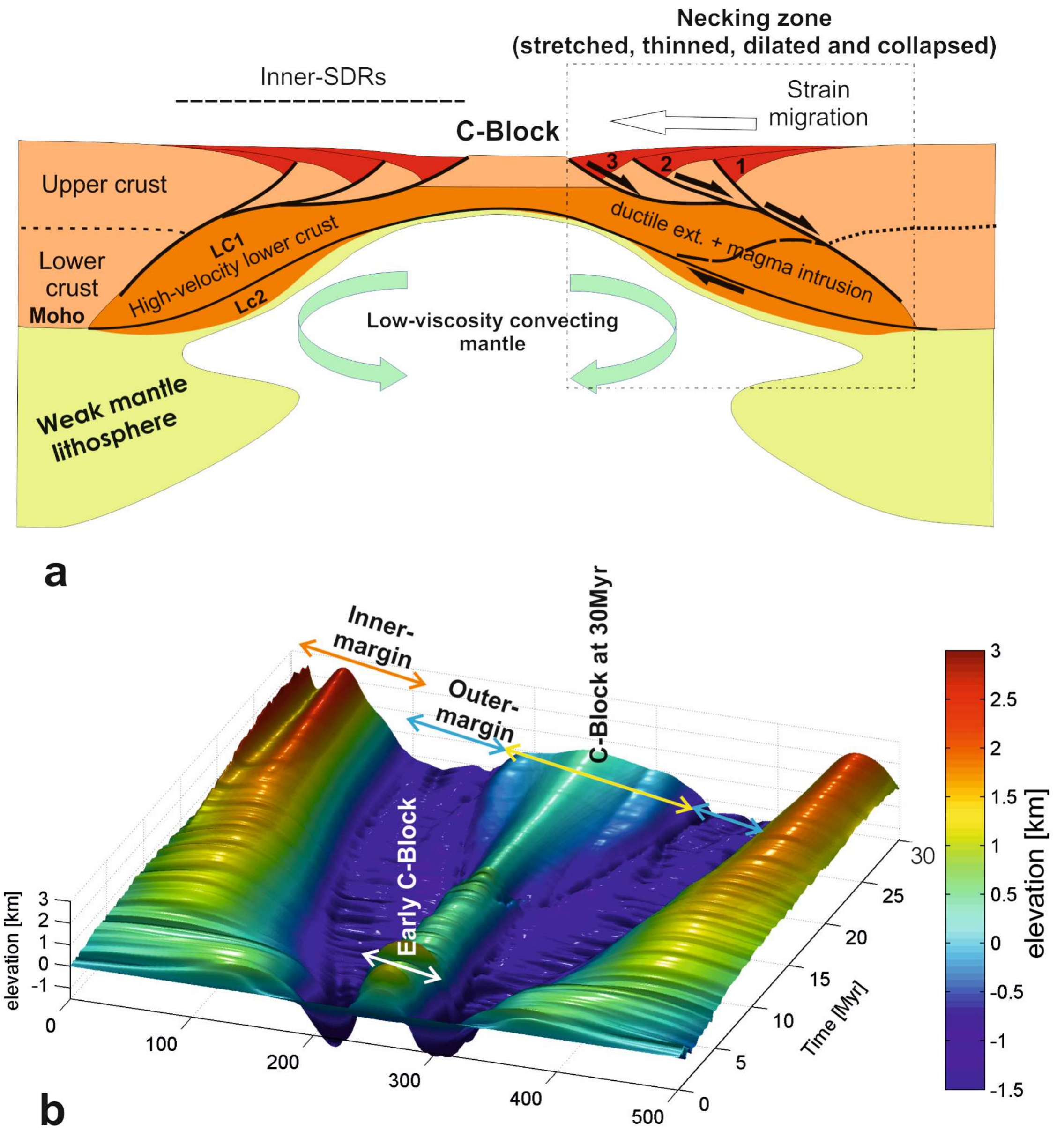

Figure 2. Top: Conjugate VPMs at the initial necking stage, before the formation of outer-SDRs. There is no oceanic lithosphere at this stage. The inner-SDRs develop sequentially (1 to 3, right side). LC1 is highly mobilized, magma-injected middle-lower continental crust and LC2 is supra-Moho mafic lower crust acting as a rigid lid over convecting mantle below. Bottom: Basement depth evolution of paired conjugate VPMs with time over a 30 Myr period. This figure is the outcome of a thermomechanical modelling involving mantle melting (from Geoffroy et al., 2015). It notably illustrates (1) the C-block evolution with time, (2) its buoyancy and progressive dislocation and widening with time, (3) the shallow depth of the basement on both sides (outer-SDR basement domain) and (4) the increasing topography of the inner parts of the margins (inner-SDRs domain).

To date, C-Blocks and the tectonic relationships between them and outer-SDRs have not been reported. In this paper we present the first case-history of a C-Block between aborted conjugate VPMs in the well-studied Laxmi basin, west of India. The relationships between this C-Block and nearby outer-SDRs bring into question the nature of outer-SDR lower crust and, by extension, the definition of the continent-ocean transition across VPMs. Finally, we propose a tectonic model for outer-SDRs in the light of our findings.

2. The Laxmi rift system

The Gop and Laxmi basins formed before the Arabian Sea and lie between it and the Indian craton (Fig. 3a) (Minshull et al., 2008). In the Arabian Sea, syn-magmatic break-up occurred between the Seychelles and a basement high, the Laxmi Ridge (Misra et al., 2015). The earliest oceanic accretion in the Arabian Sea occurred at C28n (Paleocene) (Collier et al., 2008) (Fig. 3a) immediately after extrusion of the Deccan Traps at C29r (Courtillot and Renne, 2003).

North of 18°N, the Gop basin trends approximately EW. It is bounded to the south by a *ca.* 17-km-thick ridge, the N-Laxmi Ridge, probably of continental affinity (Minshull et al., 2008) (Fig. 3a). The central part of the Gop basin, the so-called Gop Rift, may be oceanic although the crust is thicker and with lower seismic velocity than that beneath the nearby oceanic Arabian Sea (ibid.). Both the Gop Basin and the N-Laxmi Ridge lie parallel to the earliest Arabian Sea magnetic anomaly A28 (Fig. 3a). This led Collier et al. (2008) to propose a sequential magmatic break-up history from the Gop Basin in the north, to the Arabian Sea in the south.

Further south, the NNW-trending Laxmi Basin and S Laxmi Ridge are clearly oblique to Arabian Sea magnetic anomalies and transforms (Eagles and Hoang, 2014) (Fig. 3a). A transform-like fault system separates the S Laxmi Ridge from Arabian Sea oceanic crust (Figs. 3b and 3c) (Misra et al. 2015). The Pannikar Ridge lies in the middle of the Laxmi Basin and features a positive Free Air gravity anomaly in the north that reduces and becomes negative to the south (Fig. 3a). A positive linear magnetic anomaly is also discernable along the northern part of the Pannikar Ridge (Fig. 3a). Linear magnetic anomalies have been described in the Laxmi basin on both sides the Pannikar Ridge (Bhattacharya et al., 1994) (Fig. 3a).

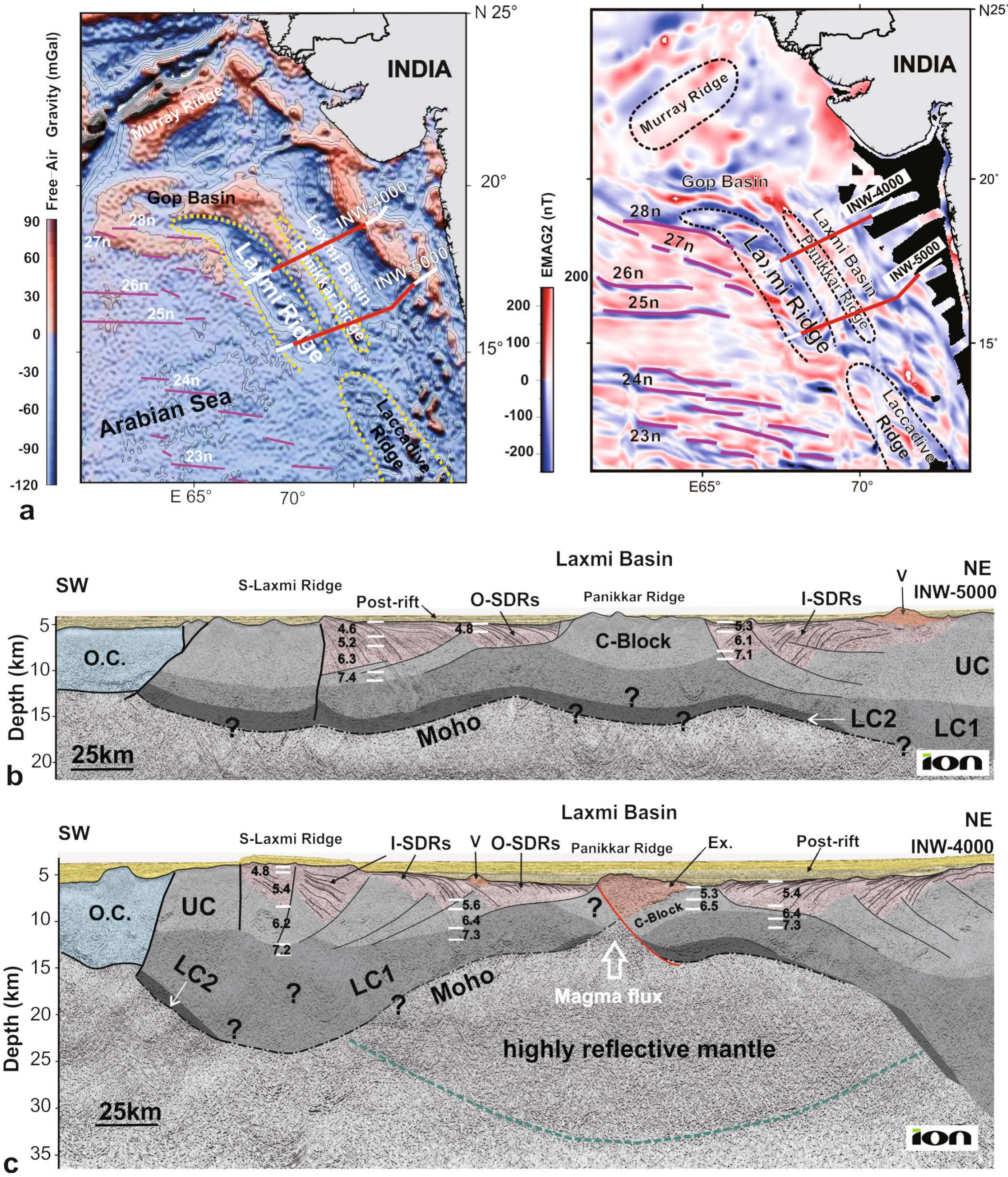

Figure 3. a. Left: Free Air gravity of the Gop and Laxmi Basin (WGM 2012 database). Right: Magnetic anomalies from EMAG2 (v3) (doi:10.7289/V5H70CVX). b and c: INW-5000 and INW-4000 ION seismic lines. The buoyant Pannikar Ridge is interpreted as a C-Block cut from north (c) to south (b) by southeastward-propagating breakup. O.C.: oceanic crust. O-SDRs: Outer-SDRs, I-SDRs: Inner-SDRs, Ex.: extrusive/intrusive complex, V: volcano, UC: upper crust, LC1: lower crust type 1, LC2: lower crust type 2.

The nature of the crust of the Laxmi Ridge, Laxmi Basin and Pannikar Ridge (hereafter referred as 'Laxmi system') is controversial. Bhattacharya et al. (1994) propose the Laxmi basin (and Pannikar Ridge) to be oceanic crust based on the identification of irregular magnetic anomalies. Talwani and Reif (1998) argue that the Laxmi Ridge was probably continental based on kinematic reconstructions. Misra et al. (2015) propose the whole Laxmi system to be oceanic crust on the basis, mainly, of the ION™ wide-angle seismic reflection lines. They notably interpret localized reflections in the deep lower crust as SDRs down to the Moho. For those authors, this would favor oceanic-type crust. Yet, such an assertion is unusual in the field of crust with SDRs, regardless of what is considered oceanic (e.g. Palmason, 1980) or continental (e.g. Clerc et al., 2015; White et al. 2008). In contrast, Krishna et al. (2006) favour, for the Laxmi system, the hypothesis of stretched continental crust injected and covered with mafic magma. They base their conclusions on low seismic velocities in the middle crust (Figs 3b and 3c), the gravity lows of the Laxmi and central Pannikar ridges (Fig. 3a) and the correlation of some of the observed magnetic anomalies (Fig. 3a) with mafic intrusive bodies mapped at the top of the basement. Guan et al. (2016) and Nemčok and Rybár (2016) recognized from the ION™ wide-angle seismic reflection data the typical pattern of conjugate VPMs and also interpret the Laxmi system as probably fully continental.

We reevaluated this crust using the ION Geophysical IndiaSPAN™ long-offset seismic reflection data (Figs 3 and 4). Our interpretation, described below, was constrained by the few seismic refraction data that are available (Naini and Talwani, 1982). In the upper-crust (extrusive sections) we distinguished seismic reflection facies and features using the classical volcano-stratigraphic seismic analysis of Planke et al. (2000), Rey et al. (2008) and Calves et al. (2011). In the sub-SDR basement with high seismic velocities (Vp>7km.s^{-1}), we interpret, following several authors, seismic layering and/or high-amplitude oblique reflectors with positive polarities like single and/or group of sub-parallel mafic intrusions (or magma intruded along shear-zones) (*e.g.* Planke et al., 2000; White et al., 2008; Clerc et al., 2015; Wrona et al., 2019).

In accordance with the interpretation of Nemčok and Rybár (2016) we find that the Laxmi Basin and bordering areas are an aborted continental extensional system with conjugate volcanic passive margins which probably developed from extended continental crust (Guan et al., 2019) (Figs 3b and 3c).

The SDRs are well-developed across the INW-4000 and INW-5000 lines (Fig. 3). Both inner- and outer-SDRs are detected along the edges of the basin (Figs. 3b and 3c). The SDRs face the central Pannikar Ridge (Fig. 3a) and present high-amplitude, linear magnetic anomalies (Krishna et al., 2006). We thus interpret the Pannikar Ridge in line INW-5000 as a C-Block. Its thickness is uncertain but is probably similar to Laxmi Ridge thickness visible in line INW-5000 (Fig. 3b). The C-Block (~40 km in length along INW-5000) was probably subaerial before thermal subsidence of the basin because large stratovolcanoes developed at its surface.

To the north (INW-4000; Fig. 3c), this C-Block is cut by a large fault, probably associated with southward propagation of an oceanic breakup axis (Guan et al., 2016; Nemčok and Rybár 2016). This fault may have functioned as a large-scale conduit that fed the 4-km-thick magma extrusion complex beneath which the basaltic upper crust flexed down (Fig. 3c). We interpret the reflective sub-Moho mantle beneath the break-up area as magma-impregnated mantle that fed the extrusive pile (Fig. 3c). Above the Moho, the lower crust is locally highly reflective with subparallel layers (LC2 in Geoffroy et al., 2015; see Fig. 1a). The overlying lower crust LC1 (see Fig. 1a) has seismic velocities of 7.2-7.4 km.s^{-1}. These velocities are typical of the HLVC beneath VPMs (Bauer et al., 2000; Funck et al., 2017). LC1 exhibits disrupted high-amplitude seaward-dipping reflections, probably intrusions, a typical pattern of LC1 in the necked and sheared parts of VPMs (*e.g.*, Clerc et al., 2015). Although they may locally parallel the upper-crust reflections (Misra et al., 2015), their higher amplitude clearly distinguishes them from the weaker reflective horizons in the upper-crustal SDRs (Fig. 4).

The outer-SDRs are especially well developed SW of the profiles (Figs. 3b, 3c and 4). They have a regular arcuate shape with a small radius of curvature. The extremity of the reflectors ends abruptly top of a crustal layer which is poorly reflective compared to the deeper crust and whose top is sub-horizontal, similar to what is observed elsewhere beneath distal parts of the VPMs that have outer-

SDRs (*e.g.*, Franke et al., 2010; McDermott et al., 2017) (Fig. 2). The 7±1 km thick lower crust beneath the outer-SDRs has seismic velocities of about 7.3 km.s^{-1} (Fig. 3c), typical of LC1 crust (Geoffroy et al., 2015). The Moho dips gently continent-ward. As observed elsewhere (see Introduction), outer-SDRs overlie at high angle a flat-lying sub-horizontal horizon at the top of the reflective deeper crust. In both seismic profiles (Figs. 3b, 3c and 4) a 'lateral' fault is visible W of the C-Block, apparently dying out along the flat-lying surface. In profile INW-5000, a symmetrical fault E of the Pannikar Ridge is defined by data of somewhat lower quality (Nemčok and Rybár, 2016).

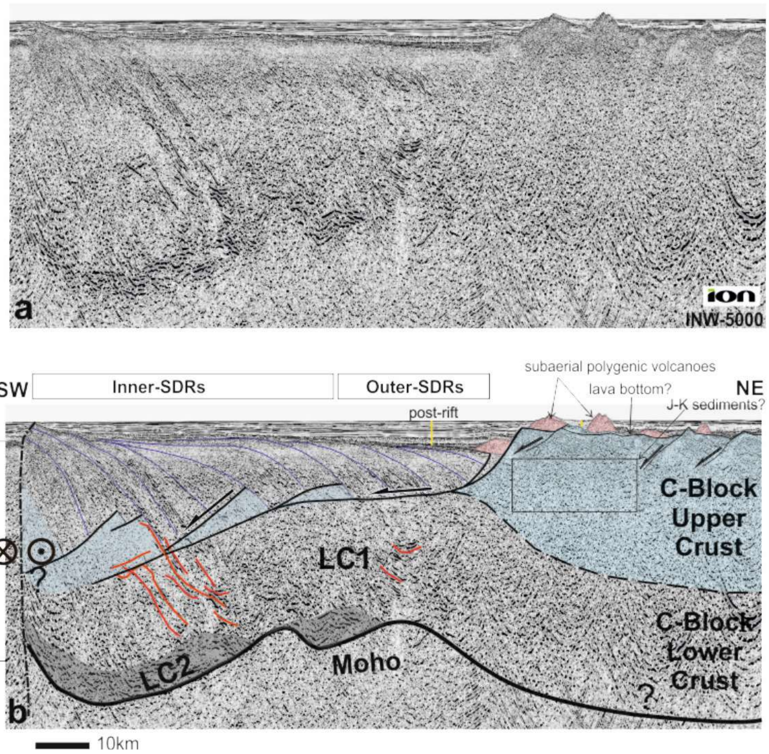

Figure 4. Detailed interpretation of the SW part of line INW-5000 (a: not interpreted, b: interpreted). Blue: probable upper crust. Red lines: mafic intrusions. Post-SDR sinistral strike-slip faulting is suggested to the left of the section along with post-SDR transtension during Arabian Sea breakup (see Fig. 3). Weak sub-horizontal layering suggests post-rift sediments (see also Guan et al., 2019). In red: selection of high-amplitude positive reflectors interpreted as major sheet intrusions. Note that some of those intrusions appear to be late (postdating inner-SDRs).

3. A model for outer SDRs and C-Blocks

Laxmi Basin illustrates (1) the structure of conjugate VPMs with a central C-Block, (2) the relationship between SDRs and the C-Block, and (3) the location of earliest break-up in this system. In the light of these findings, we propose a new tectonic model for outer-SDRs and C-Blocks as follows (Fig. 5).

The thin, sedimentary, post-rift sequence top of the C-Block suggests that it remained buoyant and subaerial or shallow long after the end of continental extension in the Laxmi Basin (Fig. 4). Carbonates are described top the volcanic basement highs in the area (Misra et al., 2016). The sub-horizontal boundary marking the end of the seaward-dipping reflectors beneath the outer-SDRs is an important feature (Fig. 4). It is not a reflective horizon but a flat-lying discontinuity bounding two seismically distinct units—the outer-SDRs and the underlying crust (Fig. 1b; Franke et al., 2013). We interpret this horizon as a syn-magmatic detachment fault and the continentward-dipping, high-angle normal fault bounding the C-Block as the breakaway fault (Figs. 4b and A' in Fig. 5). This detachment appears to be located on top of crust characterized by seismic velocities typical of lower crust, which appears to be exhumed below syn-tectonic lavas to the SW of the C-Block (Fig. 4b). The outer-SDR lavas are rotated by both basal shear along the detachment fault and probably also by progressive loading by additional lavas (Palmason, 1971).

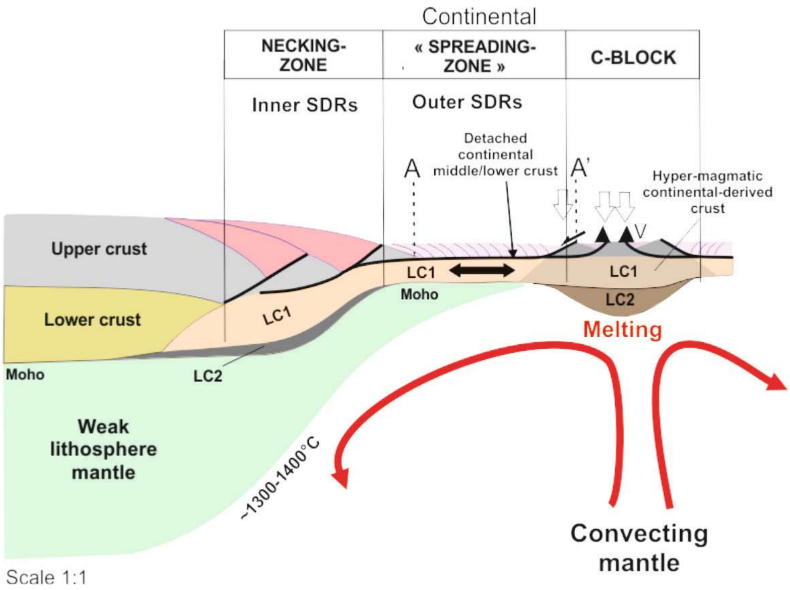

Figure 5. Tectonic model. Inner VPM upper-crust (left of A) is detached from the C-Block (A') along a sub-horizontal plane. A' is the location of the breakaway fault. This is responsible for the passive exhumation of LC1 which is syn-tectonically covered by outer-SDRs over the active melting zone. Extension beneath the detachment surface is achieved via a combination of ductile crustal flow and magma dilatation. Divergence between the inner margin and the C-Block is driven by tectonic extension, gravity and magma dilation in the central active melting zone. C-Blocks may be very small, but they are suggested to be a geometric necessity to account for the geometry of inner-SDRs at conjugate VPMs. They may become indistinguishable with time due to their progressive digestion by on-going magmatism and bottom erosion due to mantle advection. V: volcanoes. Vertical white arrows indicate possible locations of final oceanic break-up (see also Fig. 3c).

In our model, the upper crust outboard of the C-Block solely comprises the outer-SDRs. Therefore, outer SDRs must form simultaneously to the exhumation of the continental middle-lower crust injected with syn-tectonic magma. In the active volcano-tectonic area new SDR-related lavas are fed by dykes and possibly also magma rising along the major fault zones (Quirk et al., 2014). Extension in the lower crust is facilitated by both ductile flow, possibly magma-assisted, and magmatic dilation through dyking. Coeval major sill emplacement maintains and even increases crustal thickness with time. Middle/lower crustal exhumation accompanies reduction in lithosphere strength when the C-Block becomes separated from the inner-VPM (Fig. 2). At this point continuity of rigid upper crust is lost and cannot be compensated by strength in the mantle lithosphere because of its high temperature (Kusznir and Park, 1987; Geoffroy, 2005; Geoffroy and Gac, 2008; Burov, 2011). This stage thus offers a definition for the mechanical breakup of the continental lithosphere that is not based on the onset of oceanic crustal formation. In other words, the mechanical breakup of the lithosphere may preserve the continuity of the compositional continental lithosphere. It defines breakup as a development phase related to plate-tectonic extensional forces reinforced by gravity-driven collapse (Pindell et al., 2014; Geoffroy et al., 2015) (Fig. 2).

Our proposal is compatible with the depth-dependent deformation model of Huismans and Beaumont (2011). This predicts exhumation of the lower crust when early decoupling of the mantle lithosphere occurs in extending lithosphere in hot environments. In our model lower-crustal ductile stretching and continuous magmatic dilation brings about steady-state, pure-shear extension in the outer-part of VPMs. We call this steady-state process 'continental spreading' (Fig. 5). There is to date no seismic evidence for significant seaward, pressure-driven active channel flow of the lower crust during lithosphere break-up but we do not exclude it. In distal parts of VPMs lower crustal exhumation could be a passive mechanism that follows detachment of the C-Block from the inner part of the margin (AA' in Fig. 5).

4. Concluding remarks

The Laxmi Basin case example is important in that it illustrates the early stage of continental breakup in a magma-rich environment. Our seismic interpretation is supported by similar observations made elsewhere (*e.g.*, Franke et al., 2010) and thermomechanical modeling of extension and breakup of warm continental lithosphere (Geoffroy et al., 2015). It includes important aspects of continental breakup relevant to passive margins elsewhere. We highlight the following main points.

1. The existence of a large buoyant C-Block as a consequence of conjugate VPM development agrees with theoretical models. In the Laxmi basin, breakup may occur in the middle of the C-Block (Fig. 3c). However, it could also occur adjacent to the C-Block which would then ultimately become part of the distal section of one of the VPMs. It is possible that C-Blocks are discrete features difficult to recognize in mature conjugate VPMs. This is especially true if frequent rift jumps occur during breakup.

2. The Laxmi basin example suggests that outer-SDRs may overlie highly intruded continental mid-to-lower crust with high seismic velocities. Seismic refraction studies show no significant lateral variation in velocities for the HVLC beneath inner- and outer-SDRs suggesting they may have a similar provenance.

3. At non-volcanic or magma-poor margins, extension of cold continental lithosphere is frequently associated with an early necking stage followed by later exhumation of serpentinized continental mantle (*e.g.*, Boillot and Froitzheim, 2001). Break-up of the crust predates that of the rigid mantle (Huismans and Beaumont, 2011). At VPMs—hot mantle lithosphere has little or no strength (Callot et al., 2002; Gac and Geoffroy, 2008). High thermal gradients result from small-scale convection, voluminous magma input and rapid extension (Lenoir et al., 2003; Gac and Geoffroy, 2008). The time and space transition from inner- to outer-SDR formation is diagnostic of mechanical break-up of the whole continental lithosphere ("whole lithosphere failure"; Kusznir and Park, 1987) as a consequence of the splitting of the C-Block from the inner-margin (Figs. 2 and 5).

4. We distinguish two main areas at VPMs: the inner, continental, high-strength necking-zone with the inner-SDRs, and the mechanically weak spreading-zone with the outer-SDRs (or FLF), whose probable steady-state development is a combination of ductile extension and magma addition (Fig. 5). Contrary to former views (*e.g.,* Paton et al., 2017), we see no objections to a continental origin of the crust underlying outer-SDRs even if this crust is highly magmatic. We do not claim that all outer-SDRs form in the same way or that other processes, which must be both geologically and mechanically realistic, may be encountered.

5. We infer from this study, onshore observations (*e.g.* Lenoir et al., 2003) and other seismic interpretations (*e.g.* Quirk et al., 2014) that tectonic extension operates simultaneously with mantle melting throughout the process of plate separation at VPMs. Dykes and sills continuously intrude the

upper and lower crust, respectively. During the earliest stage of lithosphere thinning and mantle melting, horizontal and vertical magmatic dilation of the crust may be more important than stretching and thinning driven by far-field tectonic stresses (Klausen and Larsen, 2002; Geoffroy, 2005). No SDRs form at this stage. Volcanism solely builds subaerial plateaus of lava flows and possibly hyaloclastites (ibid.; Planke et al., 2000). Strong, rapid lithosphere necking with SDR formation on the upper crust and lower crustal flow beneath, follows this initial, short-duration stage (*e.g.*, Clerc et al., 2015; Geoffroy et al., 2015). Although huge amounts of magma continue to intrude the crust, high-rate tectonic thinning/stretching in the crust outstrips magma addition, thus enabling the crust to thin. Estimating lithosphere thinning and stretching (β factor) from the thickness of the crust only is thus not possible in magma-rich continent-ocean transition regions.

6. The Afar area is a magma-rich breakup region early in its development to which we can apply the model we describe above. A recent compilation of receiver function data (*e.g.*, Hammond et al., 2011; Reed et al., 2014) suggests a crustal-thinning gradient similar to that observed at VPMs, with continentward-dipping faults accommodating extension (Stab et al., 2016). Inner-SDRs have been identified in the Ethiopian margin necking zone where crustal flexure is observed (Wolfenden et al., 2005). Away from this flexure zone, the Afar depression is underlain by crust 18-23 km thick with a gently dipping crust-mantle boundary (Stab et al., 2016).

By analogy with VPM sections, these observations could suggest that the active Afar depression is floored by outer-SDRs and/or FLF-crust (Fig. 1a). Although representing just one stage in a ca. 30 Myr tectonic period, this area illustrates that dyking from distinct upper-crustal magma chambers occurs during plate breakup (*e.g.*, Wright et al., 2006). However, active and/or very recent fault-accommodation of stretching and thinning also occurs in the area. This is observed both inside the central depression (Stab et al., 2016) and at the tip of both the southward-propagating Red Sea (the Danakil depression) (Bastow and Keir, 2011; Bastow et al., 2018) and the northward-propagating Gulf of Aden oceanic rifts (Djibouti) (*e.g.*, Manighetti et al., 2001; Geoffroy et al., 2014).

The relationship between the current extension and mantle melting processes is not fully understood. An important observation in the Afar depression is the apparent decrease in the effective elastic thickness (Te) to values of <7 km west and south of the Danakil Block (Pérez-Gussinyé et al., 2009; Daniels et al., 2014). There, the crust is thick, however, with an apparent flat-lying or gently dipping Moho (*e.g.*, Stab et al., 2016 and references therein). Taking into account the existence of early inner-SDRs bounding the depression (Wolfenden et al., 2004), or at least arrays of continentward-dipping faults (Stab et al., 2016), this Te value would fit well a model of ongoing emplacement of outer-SDRs over a ductile crust similar to the Laxmi case,. In such case, most of the plate effective elasticity would be located in the upper crust lava section. A key question would then be whether the Danakil area can be considered to be a C-Block. Another question is if an elongated volcanic system such as the Erta Ale (*e.g.* Pagli et al., 2012) can, or not, generate SDRs through isostatic response to the weight of lava accumulation (Bastow and Keir, 2011) or axial dyke-swarm thickening with time. Also if such a spectacular feature is, or not, discernable in other, older volcano-tectonic divergent systems?

7. In oceans, it is difficult to distinguish "true" oceanic crust from continent-derived mafic crust. Magma-rich continental breakup obscures the true extent of purely igneous oceanic lithosphere, not only beneath the margins but also further out in the ocean basins. Some continent-derived mafic crust may be thick (*e.g.*, Rio Grande rise) and some thin (*e.g.*, the Laxmi Basin) because of pre-magmatic extensional thinning and/or lower magma budget. Both crustal types (oceanic or VPMs) have high densities and similar seismic structure. Both also host linear magnetic anomalies, like this is observed in the Laxmi Basin above inner- and outer-SDRs (Fig. 3a; Bhattacharya et al., 1994). Because of their

extrusive nature and seaward development with time (Geoffroy, 2005) (Fig. 2), SDRs are associated with linear but segmented magnetic anomalies (Stica et al., 2014; Larsen and Jakobsdottir, 1988; Behn and Lin, 2000; Franke et al., 2019). Pairs of magnetic anomalies are also found in Afar where magmatic continental break-up is underway (Bridges et al., 2012). Therefore, linear magnetic anomalies are not unique to oceanic crust (Geoffroy et al., 2020);

8. Our model has implications for the structure of shallow oceanic plateaus some of which may be continental (Sager, 2014; Foulger et al., 2020). Many such plateaus worldwide are near VPMs (Stica et al., 2014; Sager, 2014; König and Jokat, 2010). These plateaus may contain more continental material, including magma-injected continental lower crust and C-Blocks, than hitherto assumed. Targeted oceanic drilling programs and strategic dredging could test these ideas at specific locations.

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