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ABSTRACT

The Natal Valley, offshore Mozambique, is a key area for understanding the evolution of East Gondwana. Within the scope of the integrated multidisciplinary PAMELA project, we present new wide-angle seismic data and interpretations, which considerably alter Geoscience paradigms. These data reveal the presence of a 30 km-thick crust that we argue to be of continental nature. This falsifies all the most recent paleo-reconstructions of the Gondwana. This 30 km-thick continental crust 1000 m below sea level implies a complex history with probable intrusions of mantle-derived melts in the lower crust, connected to several occurrences of magmatism, which seems to evidence the crucial role of the lower continental crust in passive margin genesis.

INTRODUCTION

Since Aslanian *et al.*, 2009 and Kumar *et al.*, 2009, very few works on passive margin formation modeling have analyzed the implications of inherent horizontal movement in terms of kinematic reconstruction and intraplate deformation (for instance: Blaich *et al.*, 2011; Brune *et al.*, 2017; Kukla *et al.*, 2018). Notwithstanding, to understand the genesis and evolution of continental passive margins we need to define their current and initial geometries, their crustal segmentation and its nature by combining high quality multi-channel (MCS) and wide-angle seismic data. We also need to determine the exact conjugate margin system and its tightest initial position and constrain horizontal and vertical motions (subsidence) by studying the overlying sedimentary sequences with a focus on paleo-environments and stratigraphic sequences (for instance Leroux *et al.*, 2015).

Therefore, all propositions, interpretations and conceptual models must be restored on precise paleo-geographic maps to test their consequences on the global view and be validated or falsified (Aslanian & Moulin, 2012). Symmetrically, paleo-geographic reconstructions should take into account all observations available on passive margins and continental deformation to avoid gaps and overlaps (Moulin *et al.*, 2010; Thompson *et al.*, 2019).

The disintegration of Pangea occurred on two parallel breakups, spaced 6000 km apart, in the Central Atlantic Ocean and the Indian Ocean (Figure 1A). Whilst the opening of the Central Atlantic Ocean is

now well dated at Sinemurian (195 Ma) (Sahabi *et al.*, 2004), the age of the Indian Ocean and the initial position of the different plates (Madagascar, India and Antarctica) with respect to Africa are still under debate (Sahabi, 1993; Leinweber and Jokat, 2012; Gaina *et al.*, 2013; Gibbons *et al.*, 2013; Gaina *et al.*, 2015; Reeves *et al.*, 2015; Nguyen *et al.*, 2016; Davis *et al.*, 2016; Mueller & Jokat, 2019; Thompson *et al.*, 2019) (Figure 1B). The Northern Natal Valley (NNV) holds a key position in the East Gondwana breakup. Whilst the Southern Natal Valley (SNV), separated from the NNV, by the Naude Ridge (NR), since Goodlad *et al.*, (1982) and Martin *et al.*, (1981), is commonly interpreted as an oceanic crust with Mesozoic magnetic anomalies (M12 to M0), the NNV is subject to controversy as the magnetic anomalies are very weak and the seismic images very poor: old wide-angle seismic data (Ludwig *et al.*, 1968) were interpreted as imaging either continental crust (Dingle and Scrutton, 1974; Lafourcade, 1984) or oceanic crust (Ludwig *et al.*, 1968). Green (1972) interpreted the northern Mozambique ridge as a N/S spreading centre, and Marks and Tikku (2001) proposed the recognition of magnetic anomalies from chron M11 to chron M2 as an evidence of an extinct E-W spreading center in the middle of the NNV. This debate leads to two tendencies for the Gondwana reconstruction (Figure 1C): an old hypothesis with a loose fit in the Mozambique area (Sahabi, 1993) and a set of recent models with a tighter fit implying a large overlap of plates. For instance, Mueller and Jokat, (2019), derived from the Leinweber and Jokat model (2012) proposed a 300 km-wide overlap of the Antarctic plate on the Mozambican Coastal Plain (MCP) and the NNV, implying an oceanic nature of substratum for both areas. However, new results based on both inversion and forward analysis of new sea surface vector geomagnetic data acquired in 2009 (Hanyu *et al.*, 2017) seem to rule out the existence of an extinct E-W spreading center and support instead the presence of stretched continental crust, with basaltic magma intrusion in the NNV. The MCP, East of the Lebombo monocline, exhibits low crustal velocities, from 1-D shear wave velocity profiles (Domingues *et al.*, 2016) inconsistent with the presence of an oceanic crust as suggested by most of the recent models of Gondwana reconstruction (Figure 1B). Finally, the new kinematic fit proposed by Thompson *et al.*, (2019) supports the same conclusions.

METHODS

During the PAMELA-MOZ3-5 cruise (2016) (Moulin & Aslanian, 2016; Moulin & Evain, 2016) on the R/V Pourquoi Pas?, new marine geophysical and geological data were acquired (bathymetry, coring, water column, sub-bottom profiler, gravity, magnetism, dredges, wide-angle and reflection seismic) with the aim of resolving this controversy. We conducted 193 deployments of Ocean Bottom Seismometers from the Ifremer pool (Auffret *et al.*, 2004) over seven profiles on the NNV and Limpopo margin (LM) (Figure 2A). Six profiles were extended onshore with 124 land stations from the FCUL pool. The seismic source was composed of an array of 15 airguns, providing a total volume of 6500-in³, with a shot interval every 60s. Method details regarding data processing and constraining a velocity model are available in the supplementary data (see also Lepretre *et al.*, 2017, 2018; Verrier *et al.*, 2017; Schnurle *et al.*, 2018).

RESULTS

The wide-angle data were modeled using the RAYINVR (Zelt & Smith 1992; Zelt, 1999) software package applying a layer-stripping approach and iterative damped least-squares travel-time inversion at later stages. Figure 3 presents two examples of the wide-angle results showing that the NNV exhibits a 30 km-thick crust, composed of four crustal layers, with a structure similar to the neighbouring onshore MCP. The propagation velocity in the crust varies from 5.6 km/s in the upper crust to 7.3 km/s in the lower crust. Whilst the Mohorovicic discontinuity is flat and at a depth of about 33-35 km, except at distal zones, the velocity structure inside the crustal layers presents, in some places, up to 0.5 km/s lateral variations (Figure 3). Above the basement, the sedimentary layer is about 5 km thick, and can be divided in two separated by a strong, probably volcanic reflector (Figure 2B), characterized by seismic velocities ranging from 4.05 to 4.5 km/s. This reflector was previously interpreted as a magmatic layer of Karoo age (183 Ma) (Salman & Abdula, 1995). Below it, the refraction data show the presence of 2 to 3 km of additional strata of probably volcano-sedimentary nature (Figure 3A). To the north, in the MCP, a similar 2-3 km thick sequence of deep reflectors is present below the strong reflector supposed to be related to the Karoo Magmatic event, arguing for a common origin and an onshore-offshore connection. In the center of the NNV, where the basement appears at a shallower depth (4.3-4.8 compared to 5-5.5 km) (Figure 3), reliefs were surveyed in bathymetry and seismic data, during the MOZ3-5 cruise. Carbonate dredges suggest several vertical

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motions during the evolution of the margin (Figure 2A).

Figure 4A shows the 1D velocity-depth below seafloor across the MCP at its southern extremity along the MZ7 profile. The 1D-V_z profiles below the seafloor fit perfectly with the velocity field of shields throughout the world (Christensen and Mooney, 1995) indicating that the crust in this region is of continental nature. Figure 4B also shows the resemblance between the MCP and the two conjugate cratons at the time of the Gondwana assemblage: both crustal structures estimated along the Lebombo monocline (35-38 km) (Nguuri *et al.*, 2001; Kwadiba *et al.*, 2003, etc) and below the Grunehogna craton in Antarctica (Hubscher *et al.*, 1996) are similar to the one described by our results. Figure 4C compares the same 1D velocity-depth profiles to the compilation of the « normal » Atlantic oceanic crust (White *et al.*, 1992) and the 1D velocity-depth profiles of some thickened oceanic structures like the Agulhas plateau (Gohl and Uenzelmann-Neben, 2001), the Ontong Java Plateau (Miura *et al.*, 2004), the South Mozambique ridge (Gohl *et al.*, 2011), the Kerguelen plateau (Charvis and Operto, 1999) or the Tuamotu plateau (Patriat *et al.*, 2002). Neither the velocity bounds of these 1D-velocity-depth profiles nor their thickness fit the velocity structure of the MCP.

Figure 5 shows the evolution of the 1D velocity-depth below basement profiles every 10 km along the N-S MZ7 profile. This evolution demonstrates the genetic link between the MCP and the NNV (Figure 5B). The NNV indeed presents a very similar velocity structure, except for the thickness, implying a southward step-by-step thinning of 10 km at the base of the continental crust, showing the crucial role of the lower crust (Aslanian *et al.*, 2009). South of Naude ridge, the Moho rises to a depth of 15 km below sea level and the velocity structure becomes increasingly similar to an oceanic or proto-oceanic type crust (Moulin *et al.*, 2015; Afilhado *et al.*, 2015; Evain *et al.*, 2015).

Our results show the evolution of the 35 km thick continental crust in the MCP to a thinner continental crust (25-31 km thick) in the NNV. These results are consistent with those proposed by Domingues *et al.*, (2016) in the MCP and Hanyu *et al.*, (2017) for the NNV.

The lateral velocity variations observed in the lower crust of the NNV (Figures 3 & 5) have already been imaged for other regions such as in the Paleoproterozoic block of the Ukrainian Shield (Thybo *et al.*, 2003; Thybo and Artemieva, 2013), the intracontinental lake Baikal rift (Thybo and Nielsen, 2009) or the intracontinental Parnaíba basin (Tozer *et al.*, 2017). Such variations are interpreted as a presence of mafic and ultramafic mantle materials in the lower or middle continental crust and as

magmatic intrusions (Nunn and Aires, 1988; DeRito *et al.*, 1983; Tozer *et al.*, 2018) or eclogitization of the lower crust (Haxby *et al.*, 1976; Baird *et al.*, 1995). As described for the Arctic Ocean (Shulgin *et al.*, 2018), this part of the Indian Ocean has also experienced several magmatic events at different periods (the Karoo volcanic event, the Turonian traps event, Eocene, Miocene...), which are observed on the reflection seismic profiles at different levels of the sedimentary layers and may imply the supposed intrusion/transformation of the lower crust.

DISCUSSION

The presence of 30 km-thick continental crust in the NNV, in continuation of the continental MCP (Domingues *et al.*, 2016), together with the presence of the Beira Continental block in the Zambezi Basin (Mueller *et al.*, 2016) exclude the possibility of an overlap between the Antarctica and Africa plates in that area, as inferred by the most recent kinematic models (Leinweber & Jokat, 2012; Gaina *et al.*, 2013, 2015; Gibbons *et al.*, 2013; Reeves *et al.*, 2015; Tikku *et al.*, 2002; Torsvik *et al.*, 2008, 2012; Seton *et al.*, 2012; Reeves & De Wit, 2000; Nguyen *et al.*, 2016; Davis *et al.*, 2016). These results definitely impose a looser fit model confirming kinematic results proposed recently by Thompson *et al.* (2019).

All these results induce the location of the continental ocean boundary at the limit between the NNV and the SNV, south of the NR (Figure 2A) as inferred by the sea surface vector geomagnetic analysis (Hanyu *et al.*, 2017), and timing at around 135 Ma, when the Patagonia plate moved to the west, during the opening of the Austral segment of the South Atlantic ocean.

A 30 km thick supposed continental crust, similar to the MCP but below more than 1000 m of the sea level is unexpected. This anomalous topography must be related to the presence of lateral variations in the velocity structure of the crust and the presence of multiple magmatic events recorded in the sedimentary layers. In the Parnaíba basin, Tozer *et al.* (2017) proposed that the lower part of the continental crust is overloaded by mafic intrusions, inducing subsidence and the formation of the sedimentary basin. Shulgin *et al.*, 2018 equally proposed a deep originating process with emplacement of intrusive mafic bodies at the transition crust/upper mantle. In line with these authors, we propose that several magmatic events (from Karoo to Miocene events) have played a role in the

transformation of the lower crust (intrusion, underplating, metamorphism, etc.), overloading the NNV crust.

The crustal geometry obtained in the NNV evidences the lack of extensive features, arguing against any extensional or a conservational thinning model, like simple shear, pure shear or polyphase models, which exclude exchanges between the lower continental crust and upper mantle (Aslanian & Moulin, 2012). The small thinning (about 10 km) from the MCP to the NNV as well as the presence of a 30 km continental crust below sea level implies an overloading of the lower part of the crust as proposed in the Parnaíba intracontinental basin (Daly *et al.*, 2018). Our results confirm the complexity of the thinning processes, with several mechanisms such as surface processes, reactivation of inherited structures, melting, thermo-mechanical structure and dyke dynamics providing additional complexity for the tectonic evolution of individual rift systems (Cloetingh *et al.*, 2013; Brune, 2014; Ulvrova *et al.*, 2018; etc...). Other basin forming mechanisms are entailed (Aslanian *et al.*, 2019) and must involve the crucial role of the lower continental crust, which can be affected by mafic intrusions and sometimes flow into the so-called intermediate domain, as was proposed for the South Atlantic Margins (Aslanian *et al.*, 2009; Clerc *et al.*, 2018; Quirk and Rüpke, 2018) and the Provençal Basin (Moulin *et al.*, 2015; Afilhado *et al.*, 2015).

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AUTHORS CONTRIBUTIONS

The MOZ3/5 Project was led by M. Moulin, D. Aslanian and M. Evain from Ifremer. N. Dias was the coordinator of the MOZ3/5 on-shore experiment and S. Leroy was the coordinator of the Limpopo Margin study. The PAMELA-MOZ35 Team is composed by A. Afilhado⁴, R. Appriou¹, A. Bronner¹, R. Castilla³, C. Corela⁵, J. Crozon¹, C. Davy¹, E. D'acremont⁶, L. Droz², J.L. Duarte⁵, P. Fernagu¹, A. Ferrant¹, M. Fischer⁷, D. Franke⁸, H. Inguane⁹, S. Jorry¹, G. Jouet¹, A. Loureiro⁵, P. Le Bouteiller¹⁰, C. Le Bihan¹, S. Mahanjane¹¹, D. Moocroft¹², P. Pelleau¹, M. Picot², D. Pierre¹, M. Pitel¹, M. Rabineau², C. Rombe¹³, M. Roudaut¹, A. Senkans⁶ and S. Toucanne¹.

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Data availability statement

The data that support the findings of this study are available from [third party]. Restrictions apply to the availability of these data, which were used under license for this study. Data are available [from the authors / at URL] with the permission of [third party].

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FIGURE CAPTIONS

Figure 1. A) Reconstruction of the super-continent Pangea at Permo-trias time (250 Ma) (Olivet & Aslanian, pers. comm.). Position of the Pangea has been chosen to highlight the parallelism of the two breakups (blue lines) and the meridian circles during the first phase of distension which give birth to the future central Atlantic Ocean and part of the future Indian Ocean. Grey areas correspond to Paleozoic mountains, the red dotted line and hatched red areas to volcanism in relation to distensive events. B) Comparison of several initial reconstructions of the system: Africa / Antarctica / India / Madagascar / Sri Lanka. Each color corresponds to different authors (Sahabi, 1993; Leinweber and Jokat, 2012; Gaina et al., 2013; Reeves et al., 2015; Davis et al., 2016; Nguyen et al., 2016;

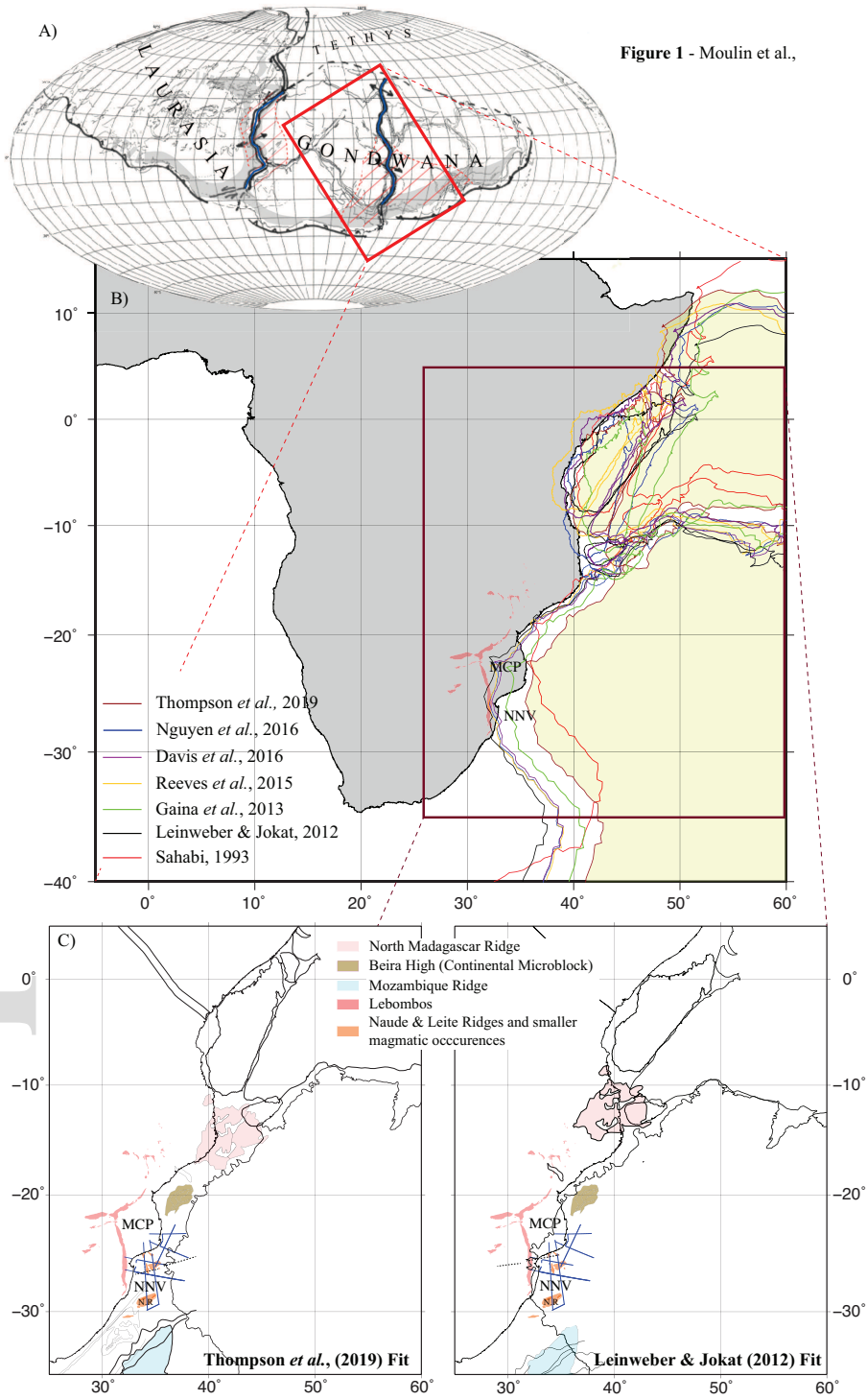
Thompson *et al.*, 2019). Africa is fixed. The figure was modified after Thompson *et al.*, (2019) C) & D) Consequences for two reconstructions models: C) Sahabi (1993) to the left, D) Leinweber and Jokat (2012) to the right, with the position of the main tectonic plates (black lines) Beira high (dark purple), the Mozambique aseismic ridges (light purple) and North Madagascar aseismic ridge (light red). Austral Africa is fixed. In the Sahabi model (1993), the position of main tectonic plates takes into account the directions of opening, the fit of the magnetic anomalies and homologous structures like the aseismic Ridges of Mozambique, Madagascar, Astrid, Gunnerus, etc. The Leinweber and Jokat model (2012) mainly focuses on the adjustment between Antarctica and Africa, on the base of fracture zones (Sandwell & Smith, 2009) and magnetic anomaly studies. NNV signifies North Natal Valley, NR Naude Ridge and MCP Mozambique Coastal Plain.

Figure 2. A) Location map showing the PAMELA-MOZ-3-5 cruises. White circles: OBSs; white triangles: Land stations; Blue lines: seismic acquisition. Black lines: seismic profiles related to the publications of Leinweber *et al.*, 2013 and Mueller & Jokat, 2016. NNV and SNV for North and South Natal Valley. Magnetic anomalies are identified by Goodlad *et al.*, (1982) and Martin *et al.*, (1981). Black squares indicate the position of the two profiles shown in Figure 3. B) Zoom of the multichannel seismic profile MZ7, highlighting different magmatic episodes on the NNV

Figure 3. Final P-wave velocity models for two of the MOZ3-5 profiles including the model boundaries used during inversion (solid black lines) and iso-velocity contours every 0.20 km/s (thin black dotted lines), OBS locations and land seismic stations are indicated by black inverted triangles. Areas constrained by ray-tracing modeling are the shaded areas. The top (acoustic basement) and bottom (Moho) of the substratum are marked in thick black lines. Red vertical lines: crossing point with other MOZ3-5 profiles. A) N/S profile MZ7, with thirty-eight OBS and sixteen land stations (LSS), from the MCP to the north, to the Naude Ridge (NR) to the south. B) E-W profile MZ1, with thirty-eight OBS and sixteen land stations (LSS), from the Lebombo Monocline in the west, to the Mozambique aseismic ridge in the east.

Figure 4. A) 1D-Vz profiles **below seafloor** extracted every 10 km, in the MCP, from MZ7 (in green) compared to the compilations of Extended Continental crust, Rifted Continental crust and Shields/Platforms (Christensen & Mooney, 1995); B) Comparison of crustal thickness between the MCP and neighbouring cratons: Kaapval Craton in Africa (Nguuri *et al.*, 2001; Kwadiba *et al.*, 2003) and the Grunehogna Craton in Antarctica (Hubscher *et al.*, 1996); C) the same 1D velocity-depth profiles of the MZ7-MCP profile (in shaded green area) compared to thickened oceanic structures, like the Agulhas plateau (Gohl and Uenzelmann-Neben, 2001), the South Mozambique Ridge (Gohl *et al.*, 2011) the Ontong Java Plateau (Miura *et al.*, 2004), the Kerguelen plateau (Charvis and Operto, 1999) and the Tuamotu plateau (Patriat *et al.*, 2002).

Figure 5. A) P-wave final modeling of the N-S profile MZ7, with the exact position of the extracted Vz-profiles, illustrated on profile MZ7 with the same colors. B) Evolution of the 1-D velocity versus depth **below seafloor** spaced every 10 km along the MZ7 profile showing the N/S evolution, marked by a thinning reducing the crustal thickness to a range of 26 to 31 km, and no major change until the NR. This compilation is compared to the one of Extended Continental crust, Rifted Continental crust and Shields/Platforms (Christensen & Mooney, 1995) and the last domain and also to that of the Atlantic oceanic crust (blue shaded area) (White *et al.*, 1992).



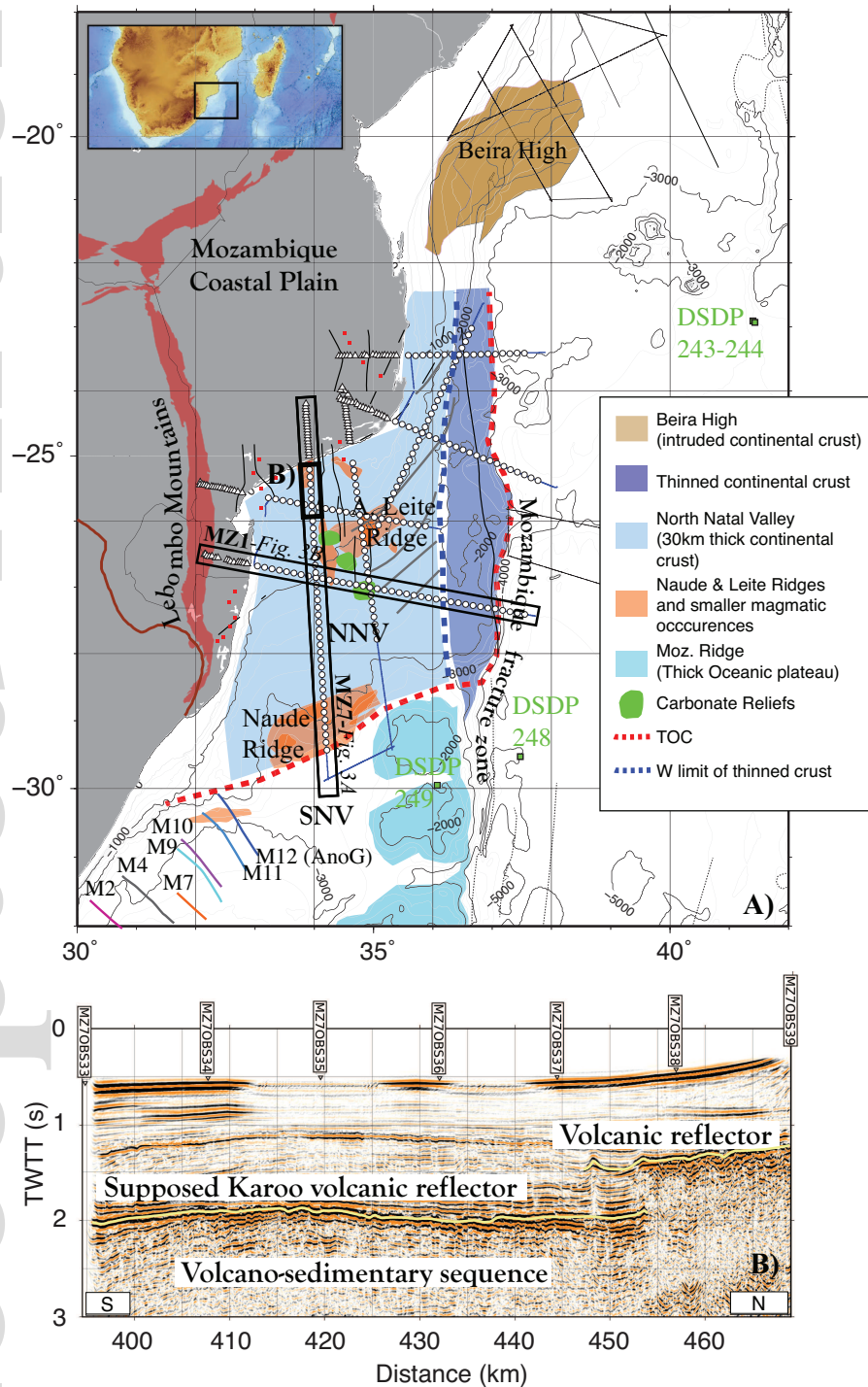


Figure 2 - Moulin et al.,

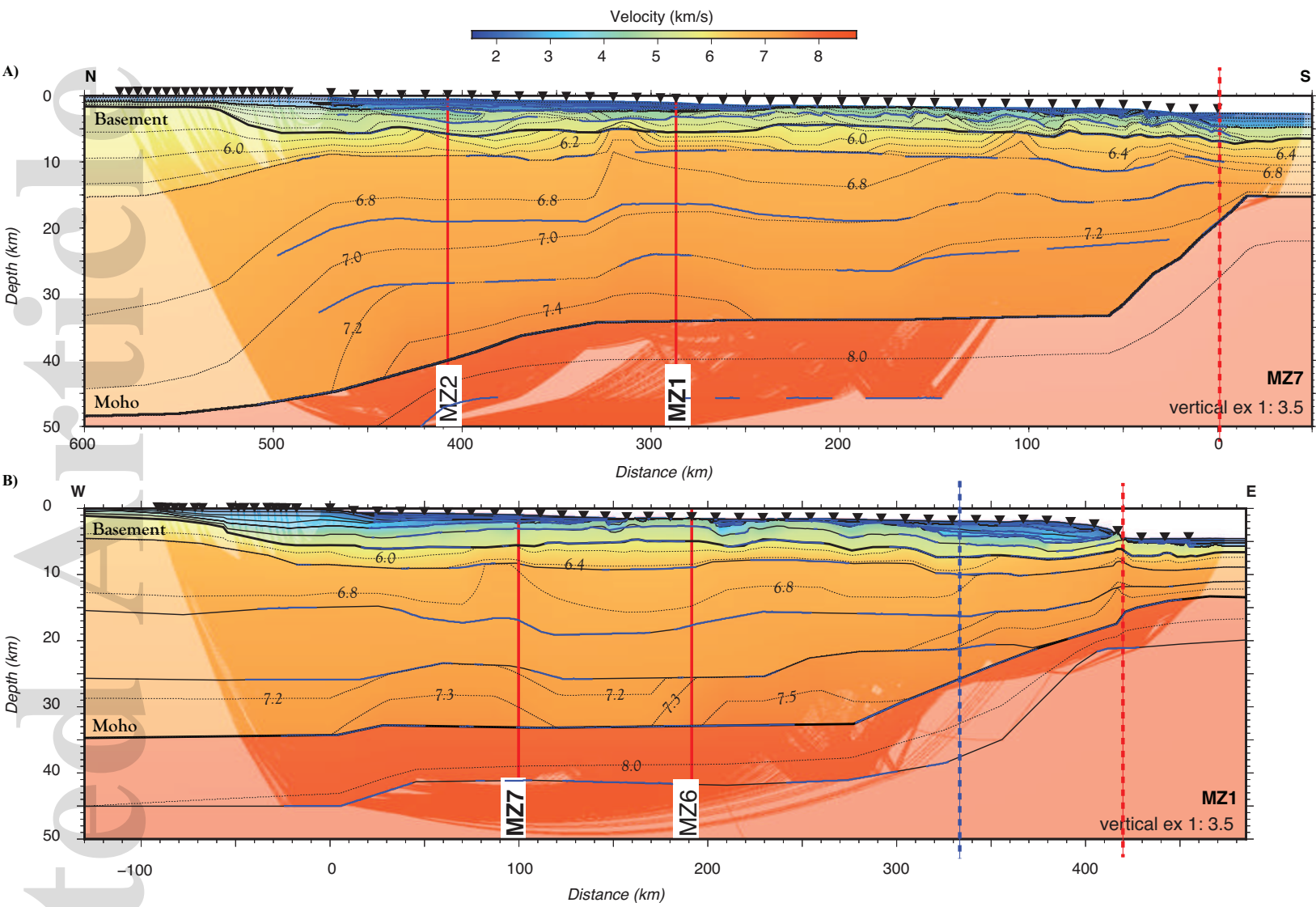


Figure 3 - Moulin et al.,
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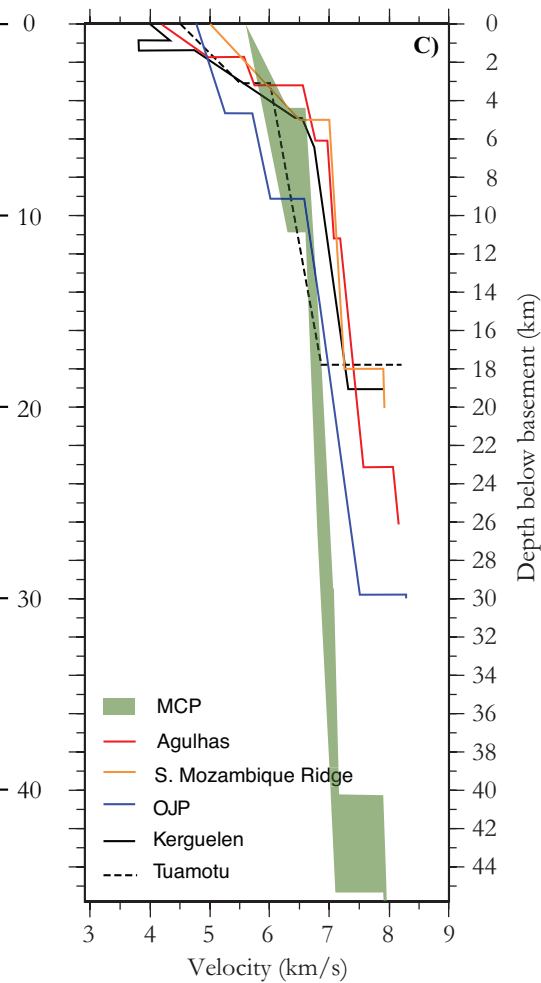
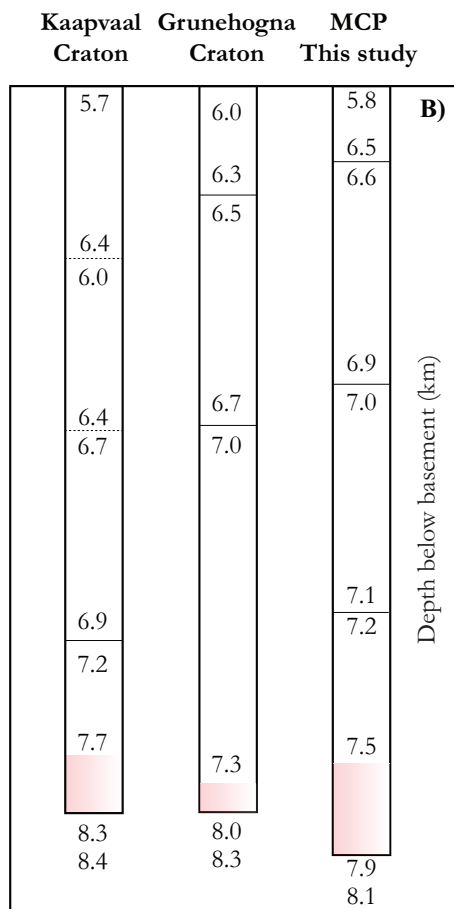
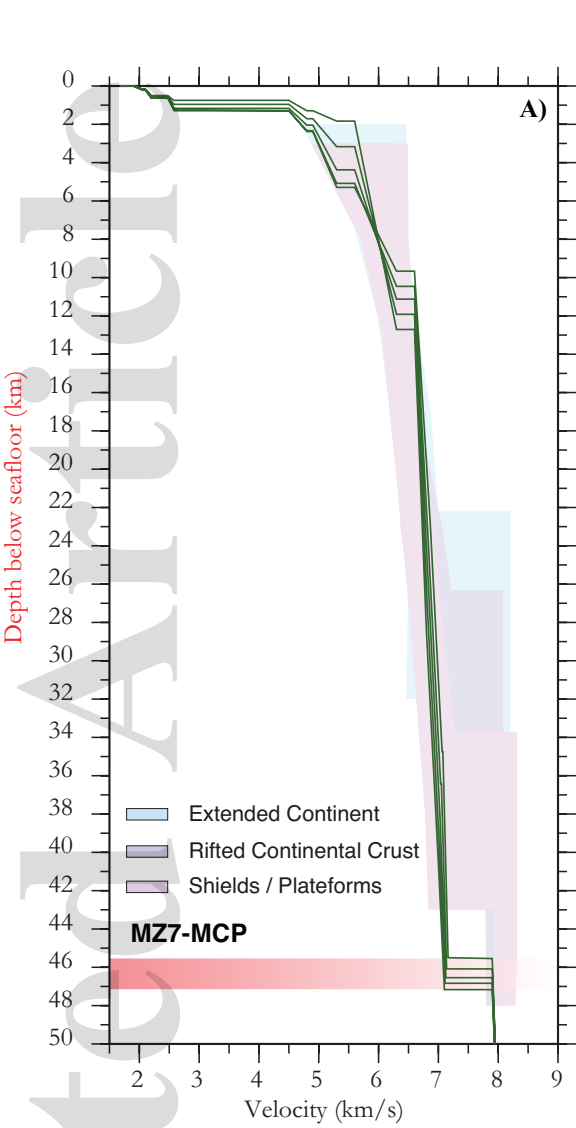


Figure 4 - Moulin et al.,

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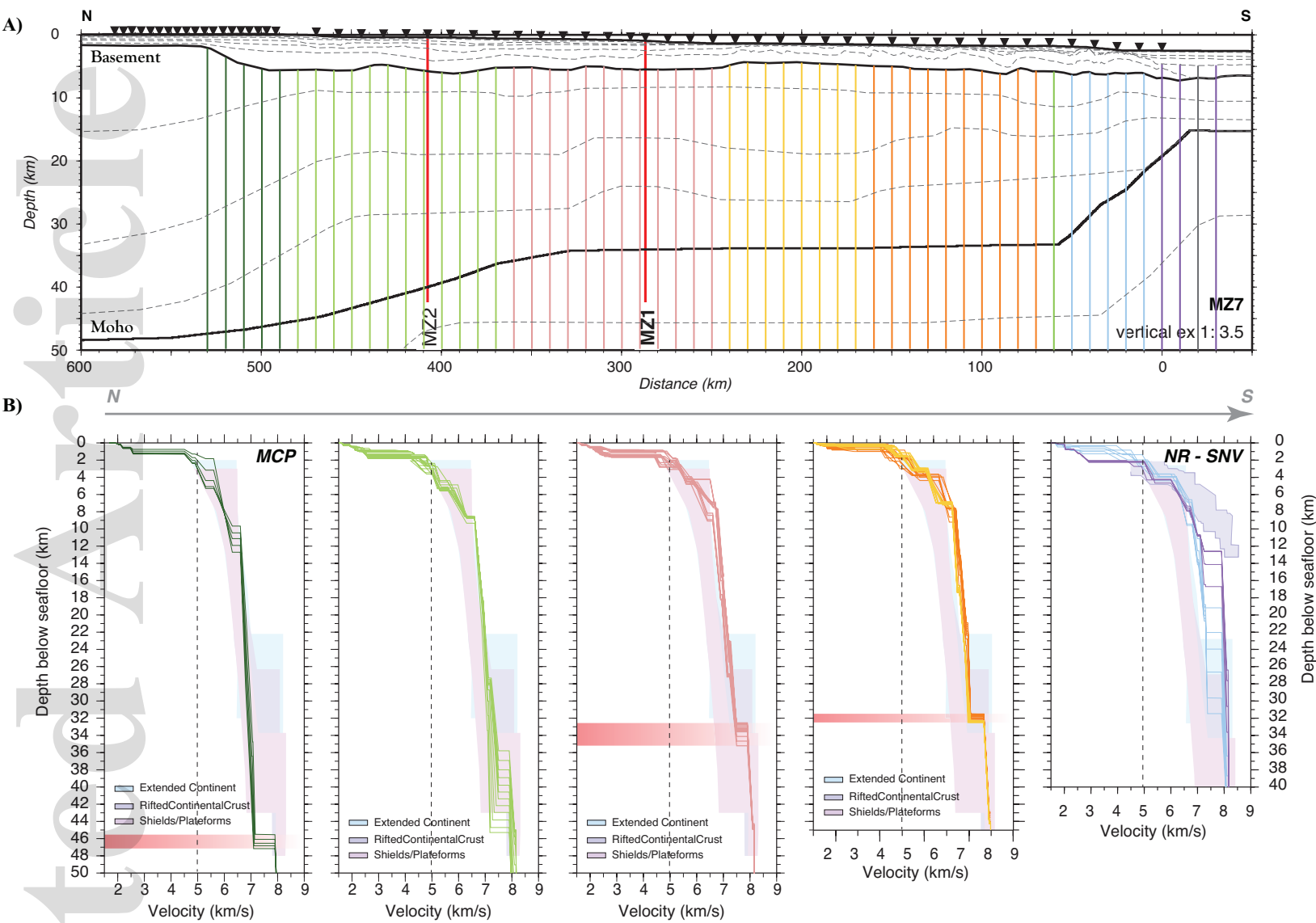


Figure 5 - Moulin et al.,
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