



HAL
open science

Gondwana breakup: messages from the North Natal Valley

M. Moulin, D. Aslanian, M. Evain, A. Leprêtre, P. Schnürle, F. Verrier, J. Thompson, P. de Clarens, Sylvie Leroy, N. Dias, et al.

► **To cite this version:**

M. Moulin, D. Aslanian, M. Evain, A. Leprêtre, P. Schnürle, et al.. Gondwana breakup: messages from the North Natal Valley. Terra Nova, 2020, 32 (3), pp.205-214. <10.1111/TER.12448>. <hal-02429986>

HAL Id: hal-02429986

<https://hal.science/hal-02429986v1>

Submitted on 20 Nov 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

DR MARYLINE MOULIN (Orcid ID : 0000-0002-5685-2451)

Article type : Paper

Title of manuscript: Gondwana breakup: messages from the North Natal Valley

M. Moulin^{1*}, D. Aslanian¹, M. Evain¹, A. Leprêtre^{1,2}, P. Schnurle¹, F. Verrier¹, J. Thompson¹, P. De Clarens³, S. Leroy⁴, N. Dias^{5,6} and the PAMELA-MOZ35 Team^{1,2,3,4,5,6,7,8,9,10,11,12,13}

¹ Ifremer, REM/GM/LGS, Centre de Brest, 29280 Plouzané, France, mmoulin@ifremer.fr

² LGO, Laboratoire Geosciences Ocean, IUEM, CNRS, 29280 Plouzané, France

³ Total, R&D, avenue Larribau, 64000 Pau, France

⁴ UPMC, Univ Paris 6, CNRS UMR 7193, ISTEP, 4 place Jussieu, 75005 Paris, France

⁵ ISEL - Instituto Superior de Engenharia de Lisboa, Lisboa, Portugal

⁶ IDL – Instituto Dom Luis, Lisboa, Faculdade das Ciências da Universidade de Lisboa, 1749-016
Lisboa, Portugal

⁷ AWI, Am Alten Hafen 26, D-27568 Bremerhaven, Germany

⁸ BGR, Geozentrum Hannover, Stilleweg 2, 30655 Hannover, Germany

⁹ INAMI, Praça 25 de Junho, n°380, P.O. Box. 217, Maputo, Mozambique

¹⁰ IFPEN, 1 & 4, avenue de Bois-Préau, 92852 Rueil-Malmaison Cedex, France

¹¹ INP – Instituto Nacional de Petróleo, Rua dos Desportistas, Parcela n° 259 E, Maputo,
Mozambique

¹² Nelson Mandela Metropolitan University, Port Elisabeth, South Africa

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1111/TER.12448](https://doi.org/10.1111/TER.12448)

This article is protected by copyright. All rights reserved

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

Accepted Article
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-Vz 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).

ACKNOWLEDGMENTS

We warmly thank Captain Thierry Alix, the crews and technicians of the Pourquoi Pas ? (IFREMER/GENAVIR). We are indebted to the French Embassies in Mozambique, Guillaume Thieriot and Sophie Jacquél and in South Africa, Jean-Paul Toutain. We thank all the onshore team from IGM/INAMI (especially Dr. Adriano Sênvano) and UeM who make the extension of the profiles on land possible. We acknowledge Francis Malcolm and Schlumberger London for their help in the preparation of the campaign by presenting their seismic data to position the MOZ3-5 profiles. The authors acknowledge the fruitful and constructive English editing advices and corrections by Alison Chalm. And finally, we thank the Editor, Jason Phipps Morgan, Wolfram Geissler and two other anonymous reviewers for their comments, which substantially improved the manuscript.

The oceanographic expedition and study PAMELA-MOZ3/5 is co-funded by TOTAL and IFREMER as part of the PAMELA (Passive Margins Exploration Laboratories) scientific project.

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.

Comparison of kinematic models was done by J. Thompson during his PhD, financed by the PAMELA Project. Forward Modeling of MZ1 profile was done by A. Leprêtre, M. Evain, P. Schnurle, C. Davy, A. Afilhado, A. Loureiro and F. Verrier. Processing of the deep sounding reflection seismic data was done by P. Schnurle, S. Leroy & E. D'Acremont and that of the high resolution seismic data by M. Picot, P. De Clarens, L. Droz, P. LeBoutellier. The overall geodynamic interpretation was made by M. Moulin & D. Aslanian with discussions on seismic and geological with A. Lepretre, P. Schnurle, M. Evain, F. Verrier, J. Thompson and P. De Clarens and on sedimentary process with L. Droz, S. Jorry, G. Jouet, M. Rabineau and S. Toucanne. J. Crozon, M. Roudaut, P. Fernagu, P. Pelleau, R. Apprioual, A. Ferrant, C. LeBihan were the OBS team who operated the seabed instruments during the cruise. SIG and bathymetry processing were done by D. Pierre and M. Pitel. C. Corela, J.L. Duarte, H. Inguane, A. Senkans were active members of the onshore team. Finally A. Bronner, R. Castilla, D. Moocroft, M. Fischer, D. Franke, C. Rombe, S. Mahanjane took part in data acquisition and contributed to the good spirit of the mission.

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].

REFERENCES CITED

- Afilhado, A., Moulin, M., Klingelhofer, F., Aslanian, D., Schnurle, P., Nouzé, H., Rabineau M. and Beslier, M. O., 2015, Deep crustal structure across an young passive margin from wide-angle and reflection seismic data (The SARDINIA Experiment) - II. Sardinia's margin, BSGF, ILP Special volume, 186, 331-351, doi:10.2113/gssgfbull.186.4-5.331.
- Aslanian, D., Moulin, M., Schnürle, P., Evain, M., Afilhado, A. & Rabineau, M., Passive margin and continental basin: towards a new paradigm, *Iere conference of the arabian journal of geosciences (CAJG)*, 12 -15 November 2018, Hammamet, Tunisia.
- Aslanian, D. and Moulin, M., 2012, Paleogeographic consequences of conservational models in the South Atlantic Ocean, In: Mohriak, W.U., Danforth, A., Post, P.J., Brown, D.E., Tari, G.C., Nemcok, M. & Sinha, S.T. (eds). *Conjugate Divergent Margins*. Geological Society of London, Special Publications, 369, <http://dx.doi.org/10.1144/SP369.5>.
- Aslanian, D., Moulin, M., Olivet, J.-L., Unternehr, P., Matias, L., Bache, F., Rabineau, M., Nouzé, H., Klingelhofer, F., Contrucci, I. and Labails, C., 2009, Brazilian and African passive margins of the Central Segment of the South Atlantic Ocean: kinematic constraints, *Tectonophysics*, 468, 98-112, doi:10.1016/j.tecto.2008.12.016
- Auffret, Y., Pelleau, P., Klingelhofer, F., Géli, L., Crozon, J., Lin, J.-Y. and Sibuet, J.-C., 2004, MicroOBS: a new generation of ocean bottom seismometer. *First Break*, 22, 41-47.
- Baird, D. J., Knapp, J. H., Steer, D. N., Brown, L. D. and Nelson, K. D., 1995, Upper-mantle reflectivity beneath the Williston Basin, phase-change Moho, and the origin of intracratonic basins, *Geology*, 23, 431–434
- Blaich, O.A., Faleide, J.I., Tsikalas, F., 2011. Crustal breakup and continent–ocean transition at South Atlantic conjugate margins. *Journal of Geophysical Research* 116, B01402, <http://dx.doi.org/10.1029/2010JB007686>.
- Brune, S., 2014. Evolution of stress and fault patterns in oblique rift systems: 3-D numerical lithospheric-scale experiments from rift to breakup. *Geochemistry, Geophysics, Geosystems* 15, 3392–3415. <http://dx.doi.org/10.1002/2014GC005446>.
- Brune S., Heine, C., Clift, P.D., Perez-Gussinyé, M., 2017. Rifted margin architecture and crustal rheology: Reviewing Iberia-Newfoundland, Central South Atlantic, and South China Sea, *Marine and Petroleum Geology* , 79, 257-281.

- Charvis, P., and Operto, S., 1999, Structure of the Cretaceous Kerguelen Volcanic Province (southern Indian Ocean) from wide-angle seismic data, *J. Geodyn.*, 28, 51–71, doi:10.1016/S0264-3707(98)00029-5.
- Clerc, C., Ringenbach, J.-C., Jolivet, L. and Ballard, J.F., 2018, Rifted margins : Ductile deformation, boudinage, continentward-dipping normal faults and the role of the weak lower crust, *Gondwana Research*, 53, 20-40.
- Cloetingh, S., Burov, E., Matenco, L., Beekman, F., Roure, F., Ziegler, P.A., 2013, The Moho in extensional tectonic setting: insights from thermo-mechanical models. *Tectonophysics*, 609, 558-604.
- Daly, M. C., Fuck, R. A., Julià, J., Macdonald, D. I. M. and Watts, A. B. 2018. Cratonic Basin Formation: A Case Study of the Parnaíba Basin of Brazil. Geological Society, London, Special Publications, 472, 1–15. <https://doi.org/10.1144/SP472.20>
- Davis, J.K., Lawver, L.A., Norton, I.O. and Gahagan, L.M., 2016, New Somali Basin magnetic anomalies and a plate model for the early Indian Ocean. *Gondwana Research*, 34, 16–28.
- DeRito, R. F., Cozzarelli, F. A. and Hodge, D. S., 1983, Mechanism of subsidence of ancient cratonic rift basins, *Tectonophysics*, 94, 141–168.
- Dingle, R.V. and Scrutton, R.A., 1974, Continental breakup and the development of post-Paleozoic sedimentary basins around southern Africa, *Geol. Soc. Am. Bull.*, 85 , 1467–1474.
- Domingues, A., Silveira, G., Ferreira, A.M.G., Chang, S.J., Custodio, S. and Fonseca, J.F.B.D., 2016, Ambient noise tomography of the East African Rift in Mozambique, *Geophysical Journal International*, 204, 1565–1578, doi: 10.1093/gji/ggv538.
- Dove, D., Coakley, B., Hopper, J., Kristoffersen, Y. and HLY0503 Geophysics Team, 2010, Bathymetry, controlled source seismic and gravity observations of the Mendellev ridge; implications for ridge structure, origin, and regional tectonics. *Geophysical Journal International*, 183, 481-502, doi:10.1111/j.1365-246X.2010.04746.x
- Gaina, C., Torsvik, T., Van Hinsbergen, D., Medvedev, S., Werner, S. and Labails, C., 2013, The African Plate: A history of oceanic crust accretion and subduction since the Jurassic. *Tectonophysics*, 604 Special Issue: SI doi: 10.1016/j.tecto.2013.05.037.

- Gaina, C., Van Hinsbergen, D. J.J. and Spakman, W., 2015, Tectonic interactions between India and Arabia since the Jurassic reconstructed from marine geophysics, ophiolite geology, and seismic tomography. *Tectonics*, 34, 875–906. doi:10.1002/2014TC003780.
- Gibbons, A. D., Whittaker, A. D. and Müller, R. D., 2013, The breakup of East Gondwana: Assimilating constraints from Cretaceous ocean basins around India into a best-fit tectonic model, *J. Geophys. Res. Solid Earth*, 118, 808–822, doi:10.1002/jgrb.50079.
- Goodlad, S.W., Martin, A.K. and Hartnady, C.J.H., 1982, Mesozoic magnetic anomalies in the southern Natal Valley. *Nature* 295, 686-688. <http://dx.doi.org/10.1038/295686a0>.
- Gohl, K. and Uenzelmann-Neben, G., 2001. The crustal role of the Agulhas Plateau, southwest Indian Ocean: evidence from seismic profiling, *Geophysical Journal International*, 144, 632–646.
- Gohl, K., Uenzelmann-Neben, G., Grobys, N., 2011, Growth and dispersal of a southeast african large igneous province. *South African Journal of Geology*, 114, 379-386, doi:10.2113/gssajg.114.3-4.379
- Green, A.G., 1972, Seafloor spreading in the Mozambique Channel. *Nature Phys. Sci.* 236, 19-21, 32.
- Hanyu, T., Nogi, Y. and Fujii, M., 2017, Crustal formation and evolution processes in the Natal Valley and Mozambique Ridge off South Africa, *Polar Science* 13, 66-81, <http://dx.doi.org/10.1016/j.polar.2017.06.002>.
- Haxby, W. F., Turcotte, D. L. and Bird, J. M., 1976, Thermal and mechanical evolution of the Michigan Basin, *Tectonophysics*, 36, 57–75
- Hubscher, C., Jokat, W. and Miller, H., 1996. Crustal Structure of the Antarctic continental margin in the eastern Weddell Sea. *From Storey, B. C., King, E. C. & Livermore, R. A. (eds), 1996, Weddell Sea Tectonics and Gondwana Break-up, Geological Society Special Publication, 108, 165-174*
- Kwadiba, M.T.O.G., Wright, C., Kgaswane, E.M., Simon, R.E. and Nguuri, T.K., 2003. Pn arrivals and lateral variations of Moho geometry beneath the Kaapvaal craton. *Lithos*, 71, 393-411.
- Kukla, P.A., Strozyk, F., Mohriak, W.U., 2018, South Atlantic salt basins – Witnesses of complex passive margin evolution, *Gondwana Research* 53, 41–57, <http://dx.doi.org/10.1016/j.gr.2017.03.012>

- Kumar, N., 2019, south Atlantic Continental Oceanic Boundary, South Atlantic conjugate Margins Workshop, ION FX Technology's, Rio de Janeiro, 11-12 November 2012.
- Lafourcade, P., 1984, Etude géologique et géophysique de la marge continentale du sud Mozambique (17°S à 28°S), Thesis, Université Pierre et Marie Curie, Paris VI, France.
- Lebedeva-Ivanova, N.N., Zamansky, Y.Y., Langinen, A.E., Sorokin, M.Y., 2006, Seismic profiling across the Mendeleev Ridge at 82°N: Evidence of continental crust. *Geophysical Journal International*, 165, 527-544.
- Leinweber, V. and Jokat, W., 2011, Is there continental crust underneath the northern Natal Valley and the Mozambique Coastal Plains? *Geophysical Research Letters*, 38, L14303.
- Leinweber, V. and Jokat, W., 2012, The Jurassic history of the Africa–Antarctica corridor — new constraints from magnetic data on the conjugate continental margins. *Tectonophysics* 530, 87–101.
- Leinweber, V., Klingelhoefer, F., Neben, S., Reichert, C., Aslanian, D., Matias, L., Heyde, I., Schreckenberger, B. and Jokat, W., 2013. The crustal structure of the central Mozambique continental margin - wide-angle seismic, gravity and magnetic study in the Mozambique Channel, Eastern Africa. *Tectonophysics*, 599, 170-196.
- Leprêtre, A., Verrier, F., Evain, M., Schnurle, P., Watremez, L., Aslanian, D., de Clarens, P., Dias, N., Afilhado, A., Leroy, S., d'Acremont, E., Castilla, R. and Moulin, M., 2017. First results on the crustal structure of the Natal Valley from combined wide-angle and reflection seismic data (MOZ3/5 cruise), South Mozambique Margin. *EGU 2017 - General Assembly 2017 of the European Geosciences Union, 23-28 April 2017, Vienne*.
- Lepretre, A., Verrier, F., Schnurle, P., Evain, M., Aslanian, D., Leroy, S., de Clarens, P., Dias, N., Afilhado, A., Gonçalves, S. and Moulin, M., 2018. Insights on the crustal structure of the Natal Valley from combined wide-angle and reflection seismic data (MOZ3/5 cruise), South Mozambique Margin. *Seismix2018*, 18-22 June 2018, Cracovia
- Leroux, E., Aslanian, D., Rabineau, M., Moulin, M., Granjeon, D., Gorini, C. and Droz, L., 2015, Sedimentary markers: a window into deep geodynamic processes, *Terra Nova*, 27, DOI: 10.1111/ter.12139.

- Ludwig, W. J., Nafe, J. E., Simpson, E. S. W. and Sacks, S., 1968, Seismic refraction measurements on the Southeast African Continental Margin, *J. Geophys. Res.*, 73, 3707–3719, doi:10.1029/JB073i012p03707.
- Mark, K.M. and Tikku, A.A., 2001, Cretaceous reconstructions of East Antarctica, Africa and Madagascar. *Earth and Planetary Science Letters* 186, 479-495.
- Martin, A.K., Hartnady, C.J.H. and Goodlad, S.W., 1981, A revised fit of South America and South Central Africa, *Earth Planet. Sci. Lett.*, 54 : 295-305.
- Miura, S., Nakamura, Y., Shinohara, M., Takahashi, N., Araki, E. and Taira, A., 2004, Seismological structure and implications of collision between the Ontong Java Plateau and Solomon Island Arc from ocean bottom seismometer – airgun data, *Tectonophysics*, 389, 191-220.
- Moulin, M. and Aslanian, D., 2016, PAMELA-MOZ03 cruise report, <http://dx.doi.org/10.17600/16001600>.
- Moulin, M. and Evain, M., 2016, PAMELA-MOZ05 cruise report, <http://dx.doi.org/10.17600/16009500>.
- Moulin, M. Aslanian, D. and Unternehr, P., 2010, A new starting point for the South and Equatorial Atlantic Ocean, *Earth Science Reviews*, 98, 1–37 doi:10.1016/j.earscirev.2009.08.001.
- Moulin, M., Klingelhoefer, F., Afilhado, A., Aslanian, D., Schnurle, P., Nouzé, H., Rabineau, M., Beslier, M.O. and Feld, A., 2015, Deep crustal structure across an young passive margin from wide-angle and reflection seismic data (The SARDINIA Experiment) - I. Gulf of Lion's margin, *BSGF, ILP Special volume*, 186, 309-330, doi:10.2113/gssgfbull.186.4-5.309.
- Mueller, C.O. and Jokat, W., 2019, The initial Gondwana break-up: A synthesis based on new potential field data of the Africa-Antarctica Corridor. *Tectonophysics*, 750, 301–328. DOI: 10.1016/j.tecto.2018.11.008.
- Mueller, C.O., Jokat, W. and Schreckenberger, B., 2016, The crustal structure of Beira High, central Mozambique—Combined investigation of wide-angle seismic and potential field data. *Tectonophysics*, 683, 233-254.
- Nguuri, T.K., Gore, J., James, D.E., Webb, S.J., Wright, C., Zengeni, T.G., Gwavava, O., Snoke, J.A., and Kaapvaal Seismic Group. 2001. Crustal structure beneath southern Africa and its

implications for the formation and evolution of the Kaapvaal and Zimbabwe cratons. *Geophysical Research Letters*, 28, 2501-2504.

Nguyen, L.C., Hall, S.A., Bird, D.E. and Ball, P.J., 2016, Reconstruction of the East Africa and Antarctica continental margins. *J. Geophys. Res. Solid Earth*, 121, 4156–4179. doi:10.1002/2015JB012776.

Nunn, J. A., and J. R. Aires, 1988, Gravity anomalies and flexure of the lithosphere at the middle Amazon Basin, Brazil, *J. Geophys. Res.*, 93, 415–428, doi:10.1029/JB093iB01p00415

Patriat, M., Klingelhoefer, F., Aslanian, D., Contrucci, C., Gutscher, M.-A., Talandier, J., Avedik, F., Francheteau, J. and Weigel, W., 2002, Deep crustal structure of the Tuamotu plateau and Tahiti (French Polynesia) based on seismic refraction data, *Geophys. R. Letters*, 29, 1–4, doi:10.1029/2001GL013913.

Quirk, D. G. and Rüpke, L.H., 2018, Melt-induced buoyancy may explain the elevated rift-rapid sag paradox during breakup of continental plates, *Scientific Reports*, 8:9985, doi:10.1038/s41598-018-27981-2.

Raillard, S., 1990, Les Marges de l'Afrique de l'Est et les Zones de Fracture associées: Chaîne Davie et Ride du Mozambique, Thesis, Laboratoire de Géodynamique sous-marine Villefranche-sur-mer et Département de Géologie Océanique Paris, France.

Reeves, C. and De Wit, M., 2000, Making ends meet in Gondwana: retracing the transforms of the Indian Ocean and reconnecting continental shear zones. *Terra Nova* 12, 272–280.

Reeves, C., Teasdale, J.P. and Mahanjane, E.S., 2015, Insight into the Eastern Margin of Africa from a new tectonic model of the Indian Ocean. In Nemcok, M., Rybar, S., Sinha, S. T., Hermeston, S. A. & Ledvényiova, L. (eds), *Transform Margins: Development, Controls and Petroleum Systems*. Geological Society, London, Special Publications, 431, <http://doi.org/10.1144/SP431.12>.

Sahabi, M., 1993, Modèle général de l'évolution de l'océan Indien, Thesis, Univ. de Bretagne Occidentale, Brest, France.

Sahabi, M., Aslanian, D. and Olivet, J.-L., 2004, Un nouveau point de départ pour l'histoire de l'Atlantique Central. *Compte Rendus de l'Académie des Sciences*, 33, 1041-1052.

- Salman, G. and Abdula, I., 1995, Development of the Mozambique and Rovuma sedimentary basins, offshore Mozambique. *Sedimentary Geology*, 96, 7-41.
- Sandwell, D. T. and Smith, W. H. F., 2009, Global marine gravity from retracked Geosat and ERS-1 altimetry: Ridge segmentation versus spreading rate, *Journal of Geophysical Research*, 114 (B1), B01411, doi:10.1029/2008JB006008.
- Schnurle, P., Leprêtre, A., Verrier, F., Evain, M., Aslanian, D., Leroy, S., de Clarens, P., Dias, N., Afilhado, A. and Moulin, M., 2018. Crustal structure of the Natal Valley from combined wide-angle and reflection seismic data (MOZ3/5 cruise), South Mozambique Margin. *Seismix2018*, 18-22 June 2018, Cracovia
- Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shepard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S. and Chandler, M., 2012, Global continental and ocean basin reconstructions since 200 Ma. *Earth-Science Reviews*, 113, 212-270.
- Shulgin, A., Mjelde, R., Faleide, J.I., Hoy, T., Flueh, E. and Thybo, H., 2018, The crustal structure in the transition zone between the western and eastern Barents Sea. *Geophys. J. Int.*, 214, 315–330.
- Thompson, J.O., Moulin, M., Aslanian, D., de Clarens, P., Guillocheau, F., New starting point for the Indian Ocean: Second phase of breakup for Gondwana, *Earth-Science Reviews*, in press, <https://doi.org/10.1016/j.earscirev.2019.01.018>
- Thybo, H. and Artemieva, I.M., 2013, Moho and magmatic underplating in continental lithosphere. *Tectonophysics*, 609, 605-619. <https://doi.org/10.1016/J.TECTO.2013.05.032>.
- Thybo, H. & Nielsen, C. A., 2009. Magma-compensated crustal thinning in continental rift zones. *Nature*, 457, 873-876, doi:10.1038/nature07688.
- Thybo, H., Janik, T., Omelchenko, V.D., Grad, M., Garetsky, R.G., Belinsky, A.A., Karatayev, G.I., Zlowski, G., Knudsen, M.E., Sand, R., et al., 2003, Upper lithospheric seismic velocity structure across the Pripyat Trough and the Ukrainian Shield along the EUROBRIDGE'97 profile. *Tectonophysics*, 371, 1-4, 41-79. [https://doi.org/10.1016/s0040-1951\(03\)00200-2](https://doi.org/10.1016/s0040-1951(03)00200-2).
- Tikku, A.A., Marks, K.M. and Kovacs, L.C., 2002, An Early Cretaceous extinct spreading center in the northern Natal valley. *Tectonophysics*, 347, 87–108.
- Torsvik, T., Müller, R.D., Van der Voo, R., Steinberger, B. and Gaina, C., 2008, Global plate motion frames: toward a unified model, *Reviews of Geophysics*, 46, RG3004, 1-44. Torsvik, T., Van der

Voo, R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P.V., Van Hinsbergen, D. J.J., Domeier, M., Gaina, C., Tohver, E., Meert, J.G., McCausland, P.J.A. and Cocks, L.R.M., 2012, Phanerozoic polar wander, palaeogeography and dynamics. *Earth-Science Reviews*, 114, 328-365.

Tozer, B., Watts, A.B. and Daly, M. C., 2017, Crustal structure, gravity anomalies, and subsidence history of the Parnaíba cratonic basin, Northeast Brazil, *J. Geophys. Res. Solid Earth*, 122, 5591–5621, doi:10.1002/2017JB014348.

Ulvrova, M. M., Brune, S., & Williams, S., 2019, Breakup without borders: How continents speed up and slow down during rifting. *Geophysical Research Letters*, 46, 1338–1347. <https://doi.org/10.1029/2018GL080387>

Verrier F., Leprêtre, A., Evain, M., Schnurle, P., Watremez, L., Aslanian, D., De Clarens, P., Dias, N., Afilhado, A., Leroy, S., d'Acremont, E., Castilla, R. & Moulin, M., 2017. Preliminary results from combined wide-angle and reflection seismic data in the Natal Valley, South Mozambique margin across the Almirante Leite volcanic ridge : MZ2 profile (MOZ3/5 cruise). *EGU 2017 - General Assembly 2017 of the European Geosciences Union, 23-28 April 2017, Vienne*.

Zelt, C.A. and Smith, R.B., 1992, Seismic traveltimes inversion for 2-D crustal velocity structure. *Geophys. J. Int.*, 108 (1), 16-34. <https://doi.org/10.1111/J.1365-246X.1992.TB00836.X>.

Zelt, C.A., 1999, Modeling strategies and model assessment for wide-angle seismic traveltimes data. *Geophys. J. Int.*, 139 (1), 183-204. <https://doi.org/10.1046/J.1365-246X.1999.00934.X>

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;

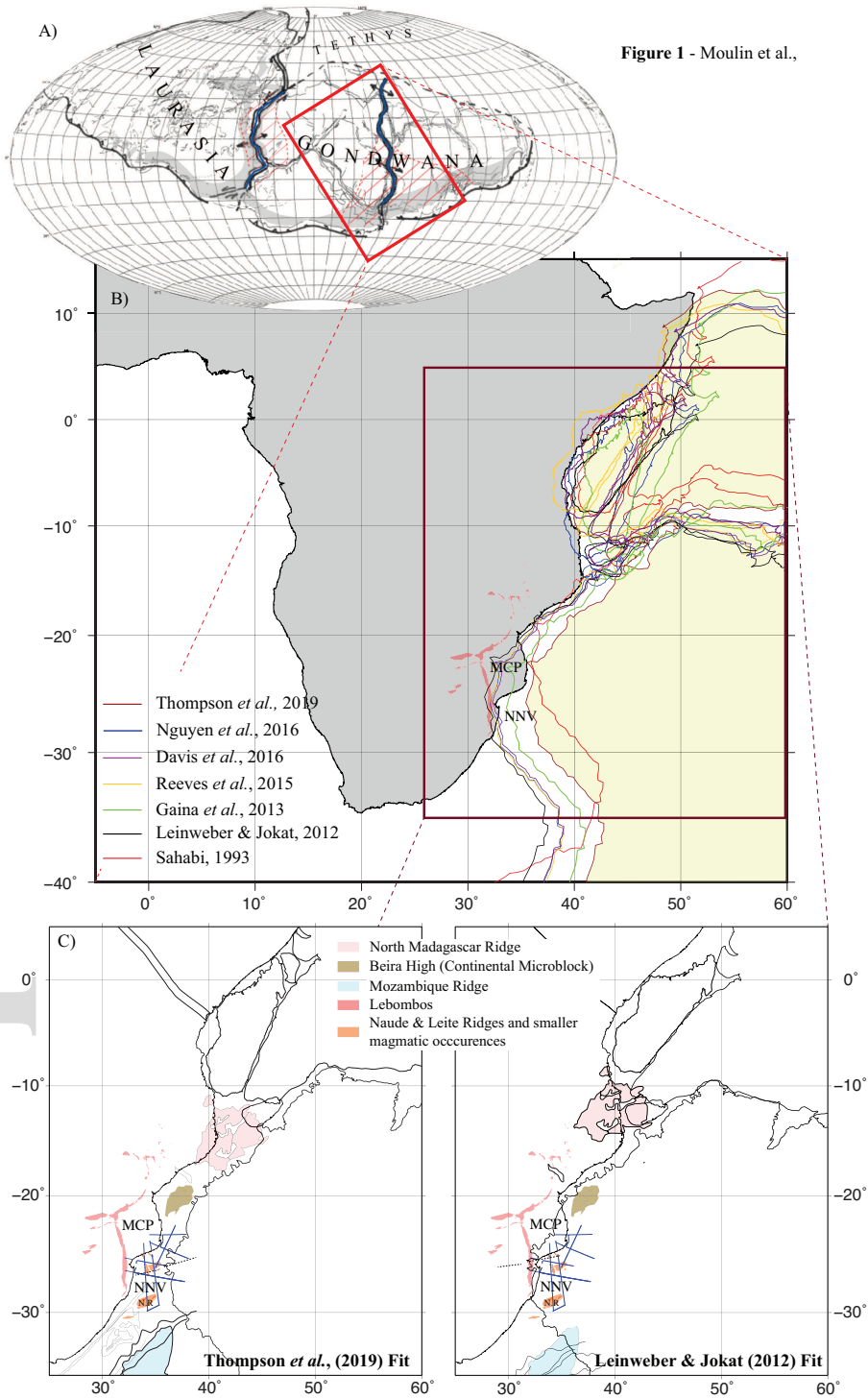
Thompson *et al.*, 2019). Africa is fixed. The figure was modified after Thompson *et al.*, (2019) C) & D) Consequences for two reconstructions models: C) Sahabi (1993) to the left, D) Leinweber and Jokat (2012) to the right, with the position of the main tectonic plates (black lines) Beira high (dark 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).



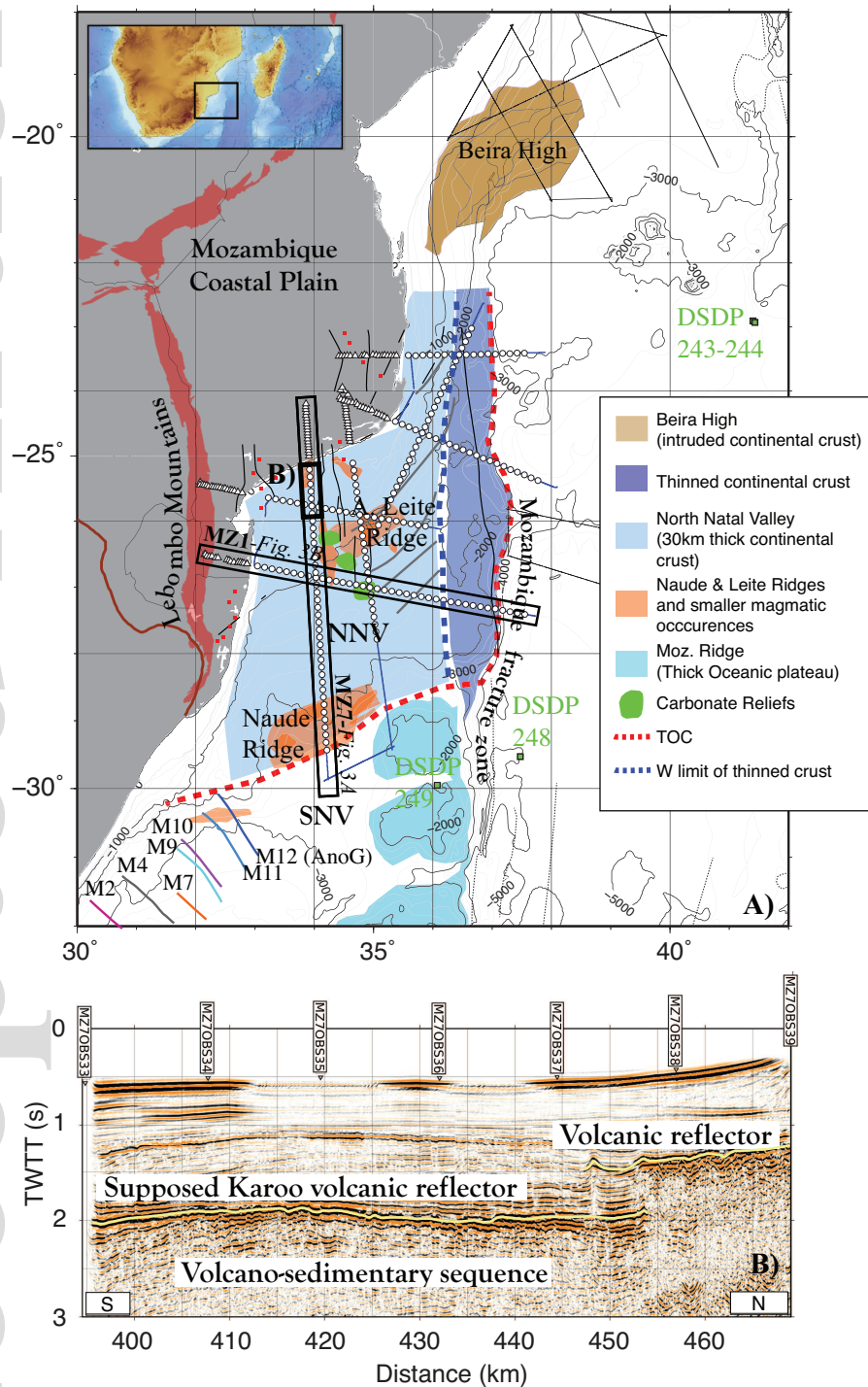


Figure 2 - Moulin et al.,

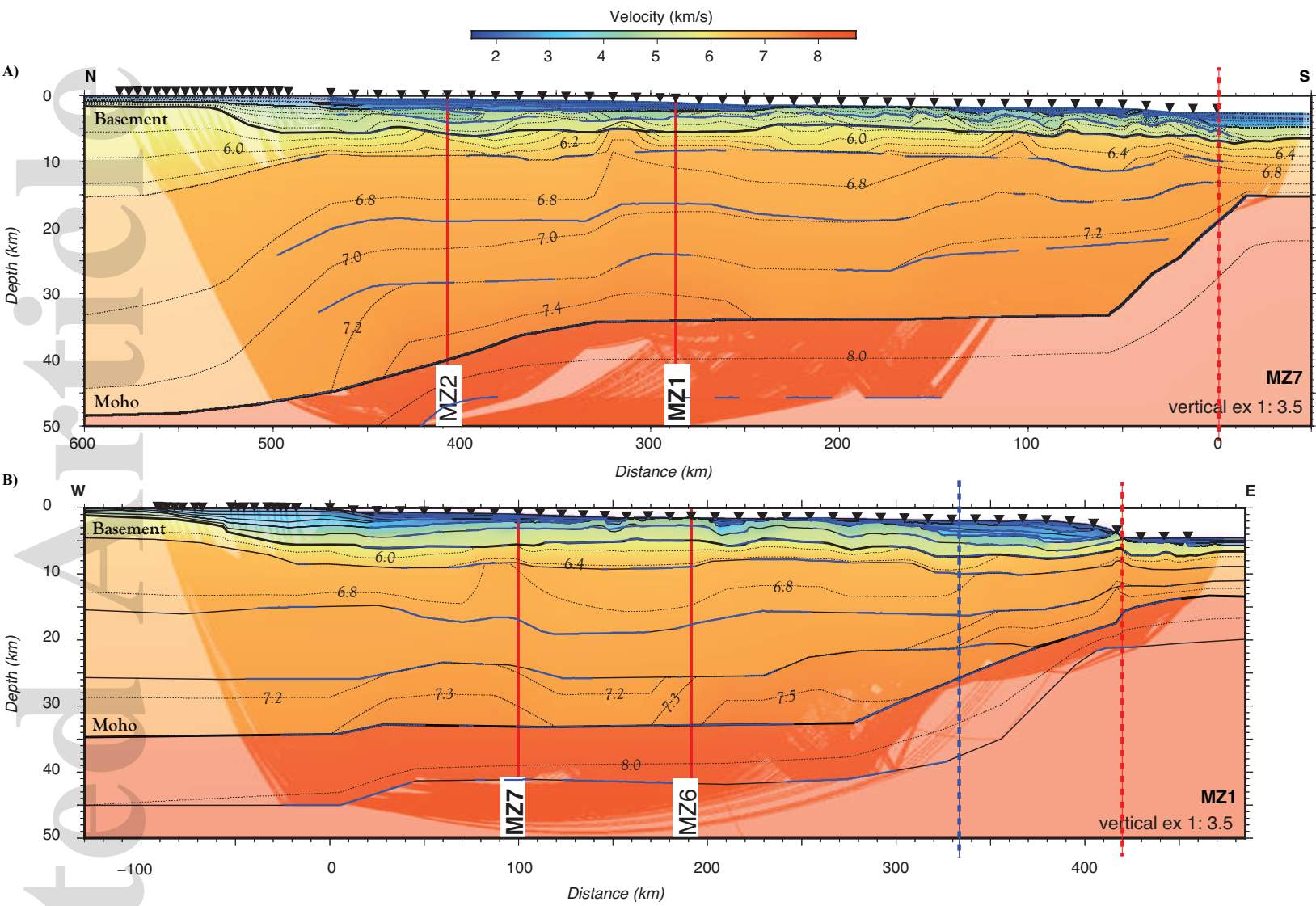


Figure 3 - Moulin et al.,
 ter_12448_f3.eps

Accepted Article

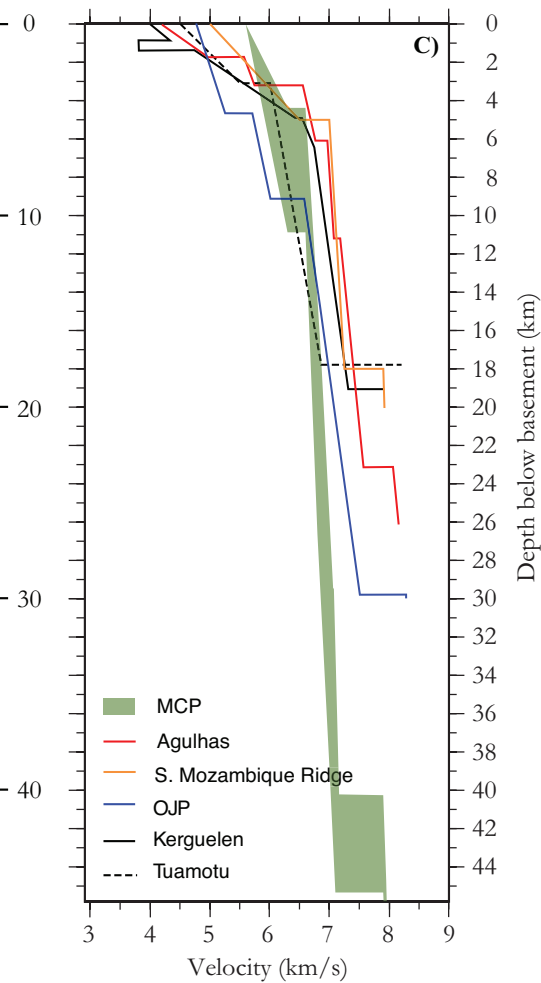
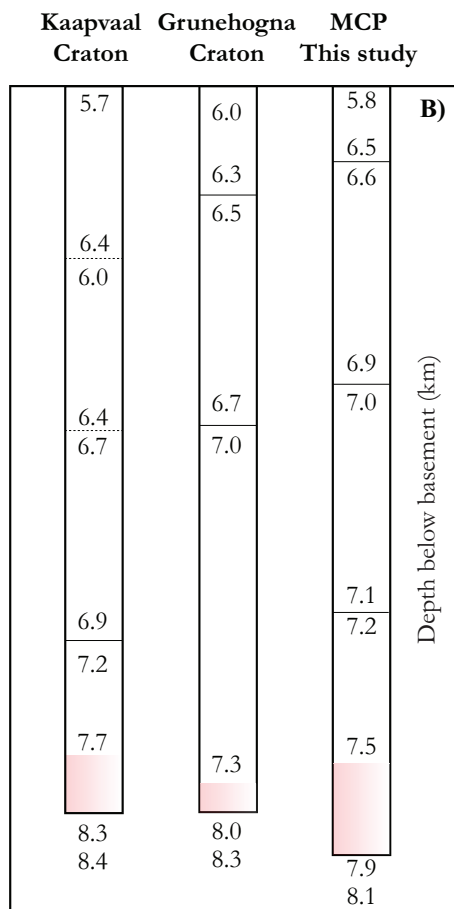
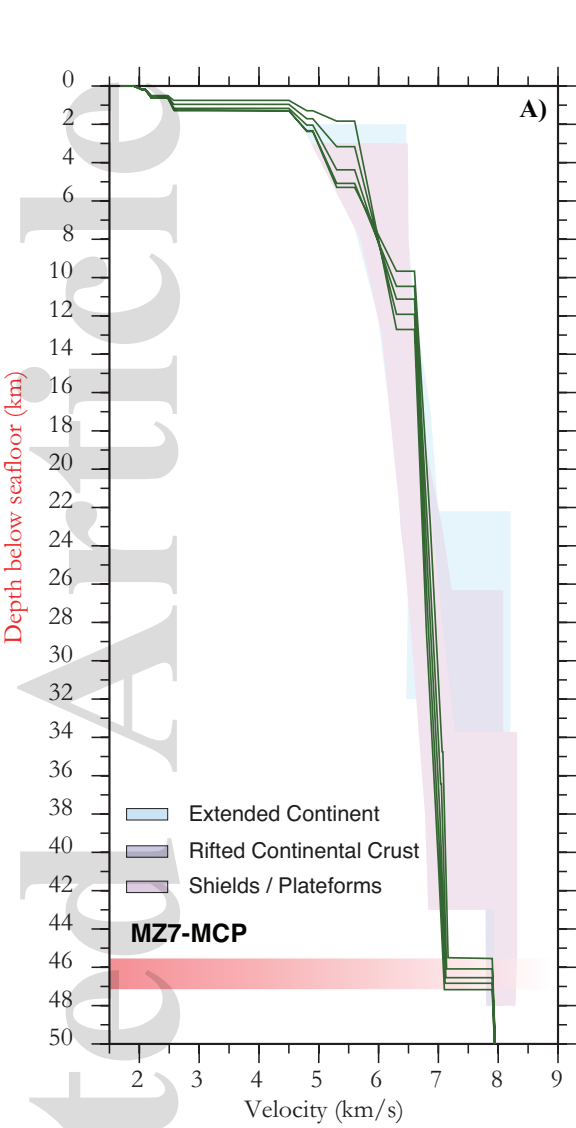


Figure 4 - Moulin et al.,

ter_12448_f4.eps

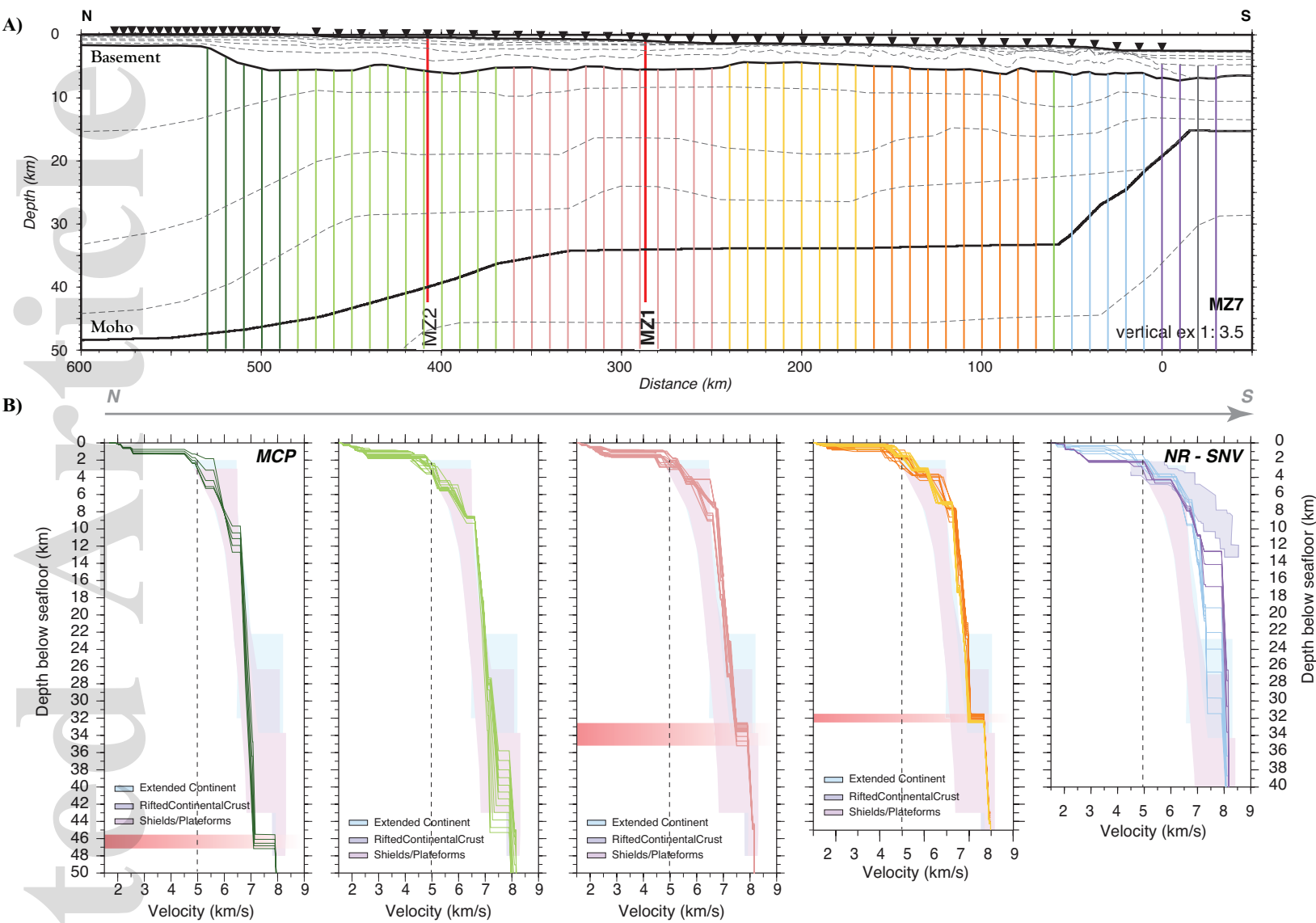


Figure 5 - Moulin et al.,
 ter_12448_f5.eps