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Formation, segmentation and deep crustal structure variations along the Algerian margin from the SPIRAL seismic experiment

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Abstract

The Algerian continental margin in the western Mediterranean formed as a back-arc basin and is today reactivated by the convergence between the African and Eurasian plates. It is one of the very rare examples of passive margins undergoing inversion expressed in a moderate seismicity of the margin and is possibly giving way for future subduction. With the objective to better know the deep structure of the margin and its associated basin, the origin of its seismicity and to study the mechanism of reactivation, five existing wide-angle seismic profiles along the margin are revisited. They were located offshore Mostaganem, Tipasa, Greater Kabylia, Jijel and Annaba. These profiles show that the basin is underlain by a 5km thick crust of oceanic magmatic origin, possibly created at non-continuous small accretionary ridge segments. The continent-ocean transition zone is narrow, except at the easternmost profile, possibly due to an opening including a shear movement. No high velocity zone in the lower crust corresponding to mantle rocks has been imaged at the Algerian margin. The continental crust is thinned in a narrow and strongly segmented manner. It is widest (70 km) in the central segment offshore Greater Kabylia where there is a wider zone of distal thinned continental crust than on the other margin segments. The thickest crust detected during this survey corresponds to the African continental crust and the Kabylides blocks and is about 22-25 km thick. This reduced thickness in comparison with unthinned continental crust might be due to the influence of earlier subduction at the margin, in form of erosion by the subducting slab.

Plain language summary

The tectonic plates moving on the Earth's surface will lead to the opening of oceans, with oceanic crust created at spreading centers located in the middle of the basins. Subsequently, these basins can get compressed, and the oceanic crust will be forced to move underneath the adjacent plate to form a new subduction zone. The precise mechanism of this transformation is still one of the unsolved problems in geosciences. Today the Algerian margin is undergoing such a transformation. This can be identified by the high amount of earthquakes created as the margin is undergoing compression. We studied the crustal structure of the Algerian margin to better know the origin of the seismicity, how this inversion is affecting the margin structure and what was the tectonic past of the region. Our results show how the crust is thinning from 25 km thickness at the margin to only 5 km in the Mediterranean Sea. We then compare this region with other basins in the Mediterranean to find similarities and differences in the mechanisms of creation of these basins.

1. Introduction

Reactivation of passive margins and initiation of subduction are two of the presently still highly discussed problems in geosciences (Lallemand and Arcay, 2021; Auzemery et al., 2021). Although the movements of plates can today be measured with high precision using geodetic instruments, the processes of this transformation remain poorly understood, because the traces of subduction margin reactivation and the initiation of a subduction zone will often be obscured by the subduction. Therefore, it is important to study examples of margin reactivation taking place at present times. The Algerian margin situated in the western Mediterranean is one of the few examples of a rifted margin being taken into compression and tectonically reactivated (Déverchère et al., 2005; Arab et al., 2016). The deformation resulting from the convergence between Africa and Eurasia induces a shortening of 2 to 3 mm/y at the margin toe inducing moderate seismicity, including larger earthquakes, such as the Boumerdes 2003 ($M_w = 6.9$; Delouis et al., 2004) earthquake. The Algerian margin thus presents unique opportunities to study passive margin inversion and subduction initiation.

The Algerian basin formed as a back-arc basin behind a northward directed subduction during the Late Oligocene to Lower Miocene (Réhault et al., 1984) ending after the collision of the Kabylia blocks, which are parts of the « AlKaPeCa » domain (Alboran-Kabyliques-Peloritani-Calabria) with the African continent (Bouillin et al., 1986; Frizon de Lamotte et al., 2000; Abassene et al., 2016). In the Tortonian, the marine gateway between the Atlantic ocean and the Mediterranean sea at the location of today's Strait of Gibraltar closed which led to the nearly complete desiccation of the

basin and the deposition of thick layers of evaporites during the Messinian salinity crisis (Auzende et al., 1971). The crisis ended when the Strait of Gibraltar opened and the Atlantic water filled the Mediterranean basin during the Zanclean flood. Tethyan slab breakoff (Maury et al., 2000) and delamination of the edges of the African and Kabylia continental lithospheres (e. g. Roure et al., 2012) generated an asthenospheric upwelling through the slab tear induced the thermal erosion of the Kabylia lithospheric mantle and post-collisional magmatism (Abassene et al., 2016). During the Plio-Quaternary, the ongoing convergence between the African and European plates led to an inversion of the north-Algerian margin (Frizon de Lamotte et al., 2000; Déverchère et al., 2005 and references therein).

Today, GPS measurements indicate a ~5 cm/yr shortening between the African and European plates, of which about 2-3 mm/yr occur offshore (Calais et al., 2003; Nocquet and Calais, 2004; Altamimi et al., 2017; Bougrine et al., 2019). Although nowadays, the Algerian Margin is characterized by a moderate seismicity on- and offshore (Buforn et al., 1995, Yelles-Chaouche et al., 2004) some larger earthquakes such as the Boumerdes 2003 (Mw = 6.9; Delouis et al., 2004) and the 1856 Jijel (Mercalli intensity IX; Harbi et al., 2011) earthquakes have happened in historic times. The reactivation leads to a downward bending of the oceanic plate against the continental plate (Hamai et al., 2015) and as proposed based on numerical modelling might lead to subduction in its central part (Hamai et al., 2018). This reactivation can also be recognized in seismic data imaging active faults, thrust faulting and ramps (Déverchère et al., 2005; Yelles-Chaouche et al., 2009; Arab et al., 2016; Leffondré et al., 2021).

Rifting and oceanisation in back-arc basins are similar to those of most oceanic basins, however, some differences can be observed especially for the oceanic crust generated in these basins. In back-arc basins the crust produced by spreading is affected by the hydrous melts from the subducting slab, therefore the crustal structure can depend from the distance to the slab (Martinez and Taylor, 2002). Oceanic crust emplaced close to a magmatic arc is proposed to show high lower crustal velocities (Arai and Dunn, 2014). In the Tyrrhenian back-arc basin opening was accompanied by volcanism but at a later phase mantle material was exhumed directly to the seafloor without formation of igneous oceanic crust (Prada et al., 2015). Furthermore, studies from the Parece Vela Basin and the Mariana Trough Basin show that oceanic crust in these two back-arc basins is fundamentally different in crustal thickness and lower crust velocities (Grevemeyer et al., 2021). The authors therefore conclude that in back-arc basins an originally highly heterogeneous mantle can cause a large diversity of oceanic-type crust.

The Algerian basin is bordered by the Alboran basin to the west and the Sardinia and Tunisia margins to the east, the Liguro-Provençal basin in the north and the north-African margin in the south. Our study area is located between -0.5 and 8.3°W along the Algerian margin from Mostaganem to Annaba. The North Tunisian Fracture Zone is located at the eastern boundary of the Algerian basin (Auzende et al., 1974; Mauffret et al., 2004). The central and eastern continental margin consist of the Kabylide basement, resulting from the Kabyle blocks collision with the African continent. A flexural basin filled with deep-water turbidites called Numidian flysch developed along the distal portion of the African margin (Wildi, 1983). The sedimentary cover of the eastern Algerian margin is interpreted to be composed by syn-rift and post-rift sediments which are interpreted to be Middle to Upper Miocene (Arab et al., 2016).

The steep slope of the eastern Algerian margin is proposed to result from transcurrent motions during back-arc opening (Mauffret et al., 2004; Schettino and Turco, 2006) followed by a strike-slip and thrust deformation (Auzende et al., 1975; Dewey et al., 1989; Kherroubi et al., 2009; Yelles-Chaouche et al., 2009).

From 30-35 Ma, northwards subduction of the Ligurian-Maghrebian Tethys between Eurasia and Africa started to retreat southward, forming the Liguro-Provençal basin (Jolivet and Faccenna, 2000; Leprêtre et al., 2018). This slab retreat resulted into the collision of the AlKaPeca block (from Alboran, Kabylies, Peloritani, Calabria) with the north African margin, while former mountain belts were dismantled and new orogens and arcs formed at the thrust front (Jolivet et al., 2021, and references therein). At 17-15 Ma, slab tearing enhanced a new slab retreat westwards, forming the Algero-Balearic basin in the overriding plate (Haidar et al., 2021). At the scale of the Algerian margin, this evolution explains the formation of the Tell thrust-Atlas belt on land by closure of the Maghrebian Tethys, collision of the Kabylid blocks with Africa and strain propagation within Africa (Bracene and Frizon de Lamotte, 2002; Leprêtre et al., 2018). Offshore, the first stage of slab retreat resulted into the formation of typical extensional structures with tilted continental blocks, i.e., from east to west: Lesser Kabylia (Bouyahiaoui et al., 2015), Greater Kabylia (Aïdi et al., 2018) and Khayr-Al-Din bank (off Tipaza: Yelles et al., 2009). The second stage of slab retreat by westward tearing has partly reworked the previous structures (Khayr-Al-Din bank: Leprêtre et al., 2013) and gave birth to (1) a transform-type margin (STEP-fault type) in the western part of Algeria (Govers and Wortel, 2005, Badji et al., 2015), and (2) large magmatic and volcanic intrusions linked to asthenospheric upwellings (Collo and Cap de Fer massif, Hannibal High, oceanic spreading centers) within the continental margin and the oceanic domain (Abbassene et al., 2016; Chazot et al., 2017; Aïdi et al., 2018; Medaouri et al., 2014) (for location see Figure 1).

In order to study questions about the geodynamic situation, the seismic hazard and hydrocarbon potential, five combined wide-angle (WAS) and multi-channel reflection (MCS) seismic profiles were acquired in 2009 onboard the R/V L'Atalante offshore Algeria. These profiles were modelled and published individually (Leprêtre et al., 2013; Mihoubi et al., 2014; Badji et al., 2015; Bouyahiaoui et al., 2015; Aïdi et al., 2018), and this study aims to give a regional synthesis trying to reconstruct the geodynamic history of the Algerian continental margin.

2. Seismic data acquisition

During the SPIRAL (Sismique Profonde et Investigation Regionale du Nord de l'ALgerie) wide-angle seismic cruise five profiles spanning the complete margin were acquired from east to west offshore Annaba (Profile GH), Jijel (Profile IJ), Greater Kabylia (Profile EF), Tipaza (Profile CD) and Mostaganem (Profile AB) (Figure 1). Between 40 and 45 marine seismometers (Auffret et al., 2005) were deployed along each transect and seismic shots were carried out using a 8909 in³ (ca. 146 l) tuned airgun array. WAS shots along Profiles IJ, EF and CD were recorded by a 4600 m 360 trace digital seismic streamer from Ifremer, in addition, to the reflection seismic data along all profiles which were acquired during a dedicated previous leg. The shot interval for the WAS profiles was 60 seconds, translating to a distance of about 150 m. All profiles were extended on land by seismic stations, however mostly the stations closest to the coast recorded usable signals. Magnetic data were acquired along all seismic profiles using a SeaSPY magnetometer towed either at the tailbuoy of the seismic streamer or at a distance of 150 m behind the ship. A Lockheed Martin BGM-5 gravimeter measured the gravity anomaly with a 25-m spacing at a vessel speed of 5 knots. All five wide-angle seismic profiles image the margin from the oceanic crust in the basin, the ocean-continent transition zone up to continental crust of the Algerian margin (Figures 1 and 2). To ensure an homogeneous interpretation, all five profiles were modeled using the « Rayinvr » software of Colin Zelt (Zelt and Smith, 1988). The software uses a combined forward and inversion approach to construct layered velocity models. While details of the modeling process are given by the local studies along each transect (Leprêtre et al., 2013; Mihoubi et al., 2014; Badji et al., 2015; Bouyahiaoui et al., 2015; Aïdi et al., 2018), this study focuses on the comparison between profiles and a synthesis of the lateral changes of the deep structure of the northern Algerian margin.

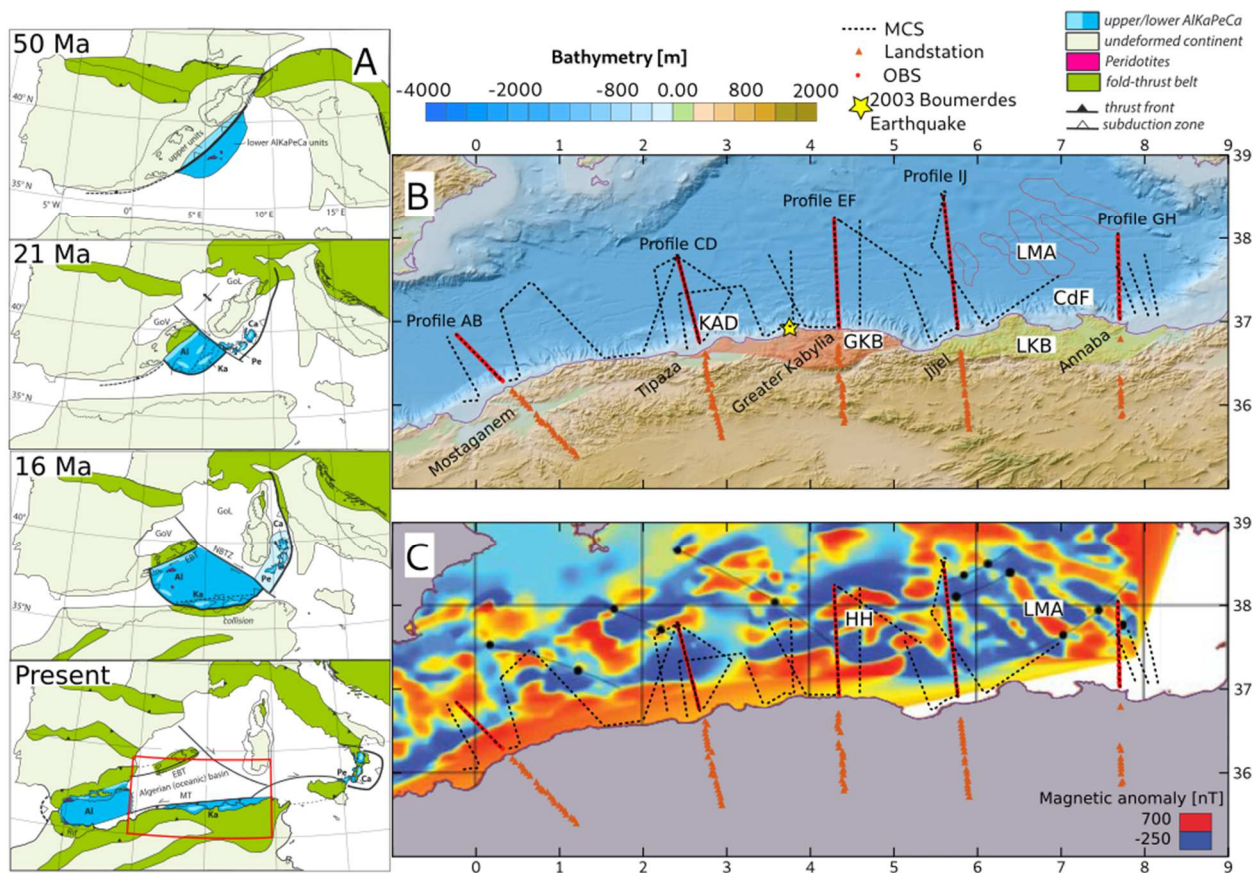


Figure 1 : (A) Tectonic history of the Mediterranean region. Simplified from Hinsbergen et al., 2013. Red frame shows extent of lower panels. (B) Location map of the wide-angle and reflection seismic profiles of the SPIRAL project. Dotted black lines mark the MCS profiles of the first leg and red lines WAS profiles from the second leg. Red dots represent positions of the marine seismometers and orange inverted triangles those of seismic landstations. (C) Magnetic anomaly from Schettino and Turco, 2006, with High = 700 and Low = -250 nT. HH = Hanibal High, LMA = Linear magnetic anomalies, GKB = Greater Kabylia block, LKB = Lesser Kabylia block, KAD = Khair-Al-Din bank, CdF = Cap de Fer massif.

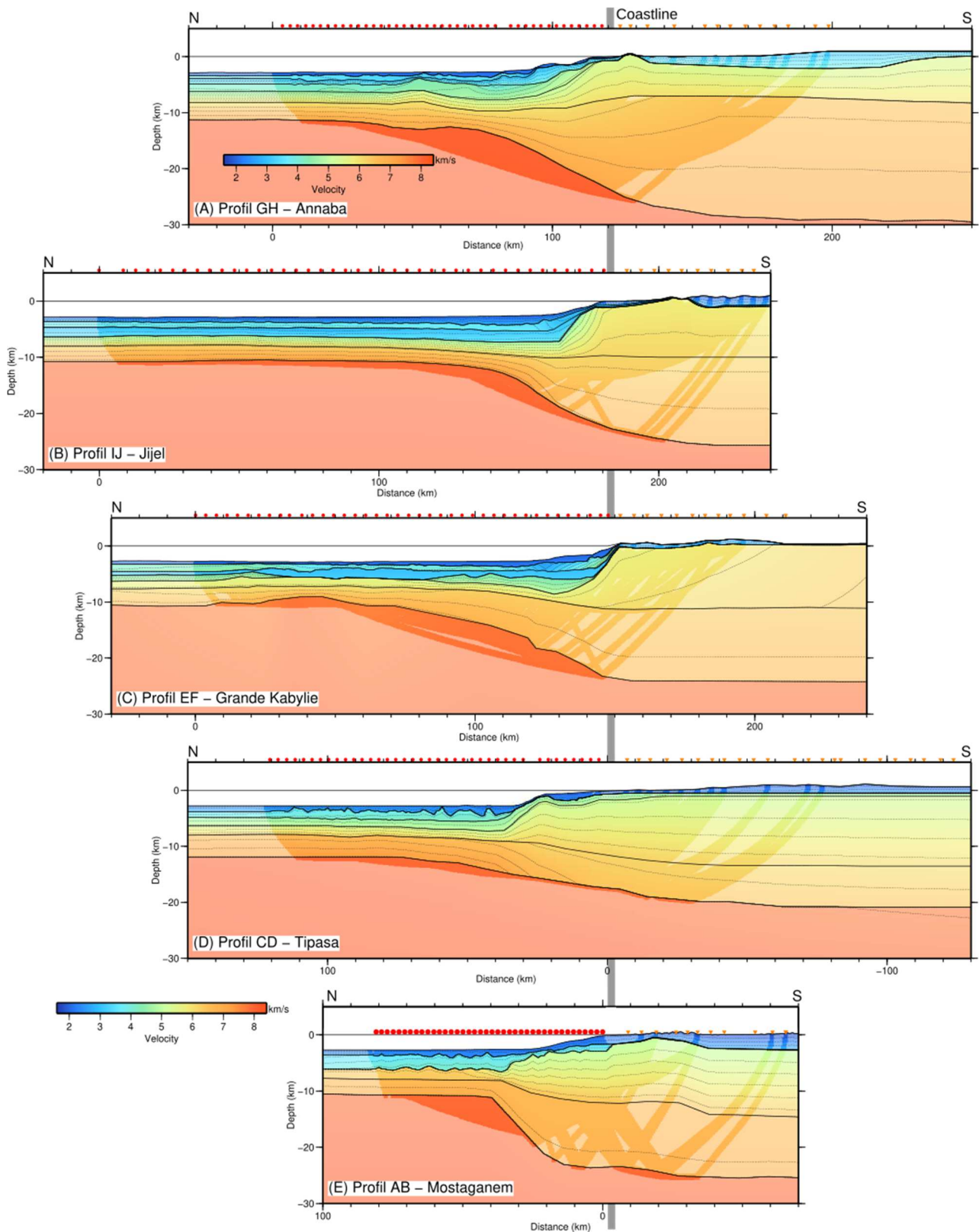


Figure 2 : Final velocity profiles from forward modelling of the five wide-angle seismic transects from west (top) to east (bottom)(location see Figure 1) (Leprêtre et al., 2013; Mihoubi et al., 2014; Badji et al., 2015; Bouyahiaoui et al., 2015; Aïdi et al., 2018). The velocities are contoured every 0.25 km/s and shaded zones are not constrained by seismic rays. Black lines mark the layer limits. (A) Profile AB offshore Mostaganem (B) Profile CD offshore Tipasa (C) Profile EF offshore Greater Kabylia (D) Profile IJ offshore Jijel (E) Profile GH offshore Annaba. Colour scale in (E) is

valid for all profiles.

3. Main Results from the Spiral published studies

Transect AB offshore Mostaganem

Situated at the western border of the Algerian margin offshore Mostaganem, close to the transition between the Algerian Basin and the Alboran Sea (Figure 1). The continental crust is imaged to be about 25 km thick, thinning to 5 km over a distance of only 20-30 km, leading to a slope of up to $45 \pm 3^\circ$ for the Moho interface (Figure 3) (Badji et al., 2015) and the continent-ocean transition zone (COT) is extremely narrow, less than the 10 km model resolution or non-existent. Both features, together with vertical faults observed in the corresponding MCS sections indicate that the margin here is marked by a major strike-slip fault (Badji et al., 2015). Therefore the authors propose that this part of the margin from Oran to Ténès was influenced by a fossil subduction-transform edge propagator fault at the edge of the Gibraltar subduction zone as proposed earlier by Govers and Wortel, 2005). This implies a movement of the Alboran block along this part of the margin (Badji et al., 2015).

For better comparison a wide-angle forward model using the identical methods as for the other profiles was constructed along this profile (for exact methodology see Leprêtre et al., 2013; Mihoubi et al., 2014; Bouyahiaoui et al., 2015; Aïdi et al., 2018 for details). The software "*rayinvr*" from Colin Zelt was used to construct the model (Zelt and Smith, 1088). It was then additionally constraint by synthetic modeling and gravity modelling. The resulting models are very comparable, and the use of the same modelling strategie allows the comparison of layer geometry and velocities between all five profiles. A full presentation of the modeling procedure however, would be out of the scope of this manuscript.

The oceanic crust bordering the margin is about 3-4 km thick, thinner than normal oceanic crust with a mean of 7.1 km (as defined by White et al., 1992) or 6.0 km (as defined by Grevenmeyer et al., 2018) and characterised by elevated velocities for oceanic crust (White et al., 1992), indicating that a moderate amount of serpentinised upper mantle material might have been included into the crust emplacement at slow spreading or at spreading located at a segment end (Badji et al., 2015).

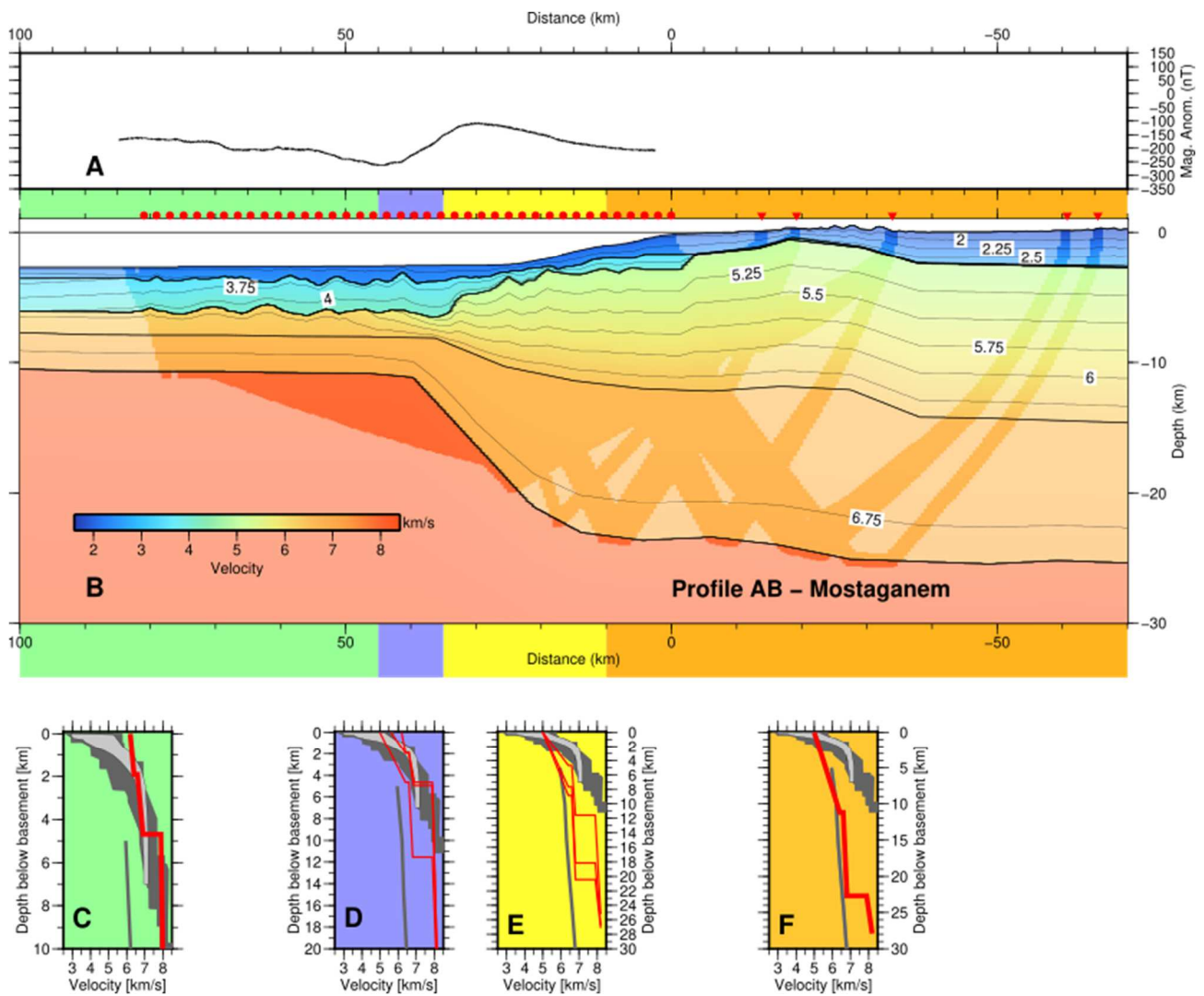


Figure 3 : Final forward velocity model of the Profile AB offshore Mostaganem (location on Figure 1). (A) Magnetic anomaly measured during the cruise (B) Final forward velocity model. Green region is interpreted to be of oceanic origin, the violet region the COT, the yellow region the thinned continental crust and orange unthinned continental crust. Bold red lines are for mean 1D velocity-depth (v_z) profiles and thin red lines for v_z -profiles every 10km along the model. (C) in the oceanic domain (D) in the COT (E) mean 1D velocity-depth profiles in the thinned continental crustal domain (F) in the continental domain. Grey line is mean velocity for thinned continental crust (Christensen and Mooney, 1995), grey area bounds of normal oceanic crust from White et al. (1992) and light grey areas oceanic crust from Grevemeyer et al. (2018).

Transect CD offshore Tipasa

The Profile CD is located offshore Tipasa (west of Algiers) (location on Figure 1) and spans from oceanic crust of the Algerian basin over the Khayr-Al-Din Bank, a 20-30 km wide bathymetric high, onto the North Algerian margin (Leprêtre et al., 2013; Figure 4). The oceanic crust here is ~5 km thick, about 1-2 km thicker than in the easternmost AB Mostaganem profile. The continental crust reaches 20-21 km thickness bordered oceanward by the Khayr-Al-Din Bank. The Khayr-al-

Din Bank is of continental nature and is proposed to be a syn-rift tilted block made of Internal Zones terranes remobilized on the margin during rifting (Leprêtre et al., 2013). The COT here is narrow (< 10 km) or absent indicating a highly oblique or shear movement during opening or that the oceanic accretion began just or shortly after the breakup of the continental crust. These two findings can be reconciled by a polyphased opening of the margin with a first phase corresponding to a N-S rifting and a second transcurrent episode during the westward migration of the Alboran block. The last phase then includes a compressional reactivation of the margin inducing a long-wavelength flexure of the basin basement and a partial uplift of the Khayr-Al-Din Bank (Leprêtre et al., 2013).

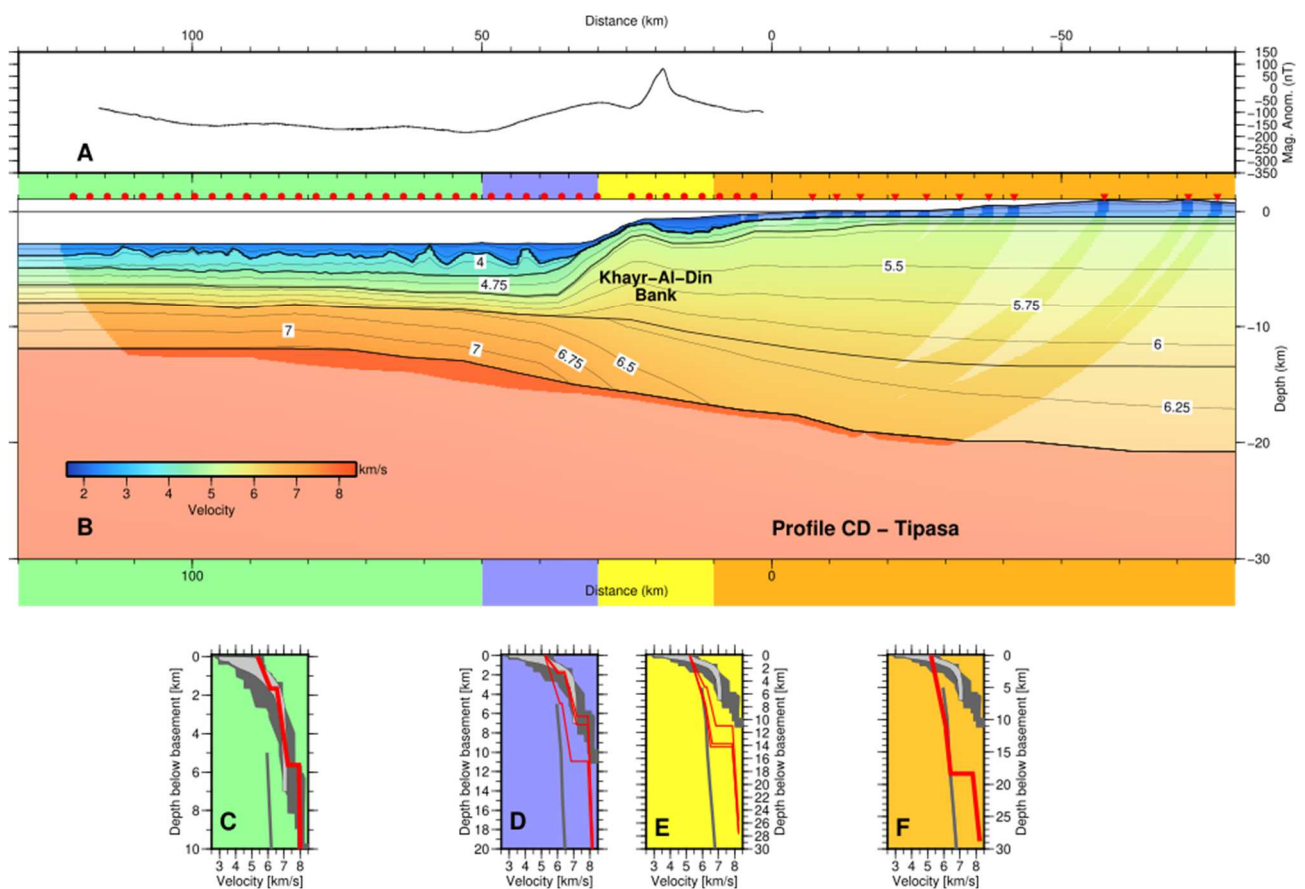


Figure 4 : Final forward velocity model of the Profile CD offshore Tipasa (Leprêtre et al., 2013). (A) Magnetic anomaly measured during the cruise (B) Final forward velocity model. Green region is interpreted to be of oceanic origin, the violet region the COT, the yellow region the thinned continental crust and orange unthinned continental crust. Bold red lines are for mean 1D velocity-depth (v_z) profiles and thin red lines for v_z -profiles every 10km along the model (C) in the oceanic domain (D) in the COT (E) in the thinned continental crustal domain (F) in the continental domain. Grey line is mean velocity for thinned continental crust (Christensen and Mooney, 1995), grey area bounds of normal oceanic crust from White et al. (1992) and light grey areas oceanic crust from Grevemeyer et al. (2018).

Transect EF offshore Greater Kabylia

The 210-km-long profile EF is located east of Algiers and reaches the Greater Kabylia region up to the southward limit of the internal zones on land (Aïdi et al., 2018), and situated close to the region of the Boumerdes 2003 earthquake and its aftershocks. Along this profile the continental margin is wider than in the east, thinning over a distance of 70 km from 23 km to 8 km thickness (Figures 1 and 5). The margin shows a peculiar asymmetrical shape of the crustal neck which has been proposed to result from an isostatic disequilibrium which might be characteristic for inverted rifted margins (Aïdi et al., 2018). At the foot of the margin a 4.5 km/s velocity body is imaged corresponding to either syn-rift sediments or fractured thin continental crust. The oceanic-type crust in the basin is of variable thickness between 4 km and 5.5 km and is characterized by high seismic velocities between 5.2 km/s and 6.8 km/s and can be divided into two domains, the Hannibal domain and a domain of very thin oceanic crust (Aïdi et al., 2018). In the northern Hannibal High zone, correlated to a sub-circular group of high amplitude magnetic anomalies (Figure 1 and Figure 5A in Schettino and Turco, 2006), the oceanic basement has an atypical three-layered structure interpreted to be volcanic products (lava flows, volcanoclastic and/or hyaloclastic products) overlying a thinner original oceanic crust and resulting from Miocene post-accretional magmatism. This rules thereby out the hypothesis that the Hannibal Ridge corresponds to a fossil N-S trending accretionary center as proposed earlier (Mauffret et al., 2004). The structure of the margin corresponds to a magma-poor rifted margin, reshaped by a later transcurrent phase and reactivated by compression expressed by a blind thrust system under the margin rising toward the surface at the slope toe (Aïdi et al., 2018).

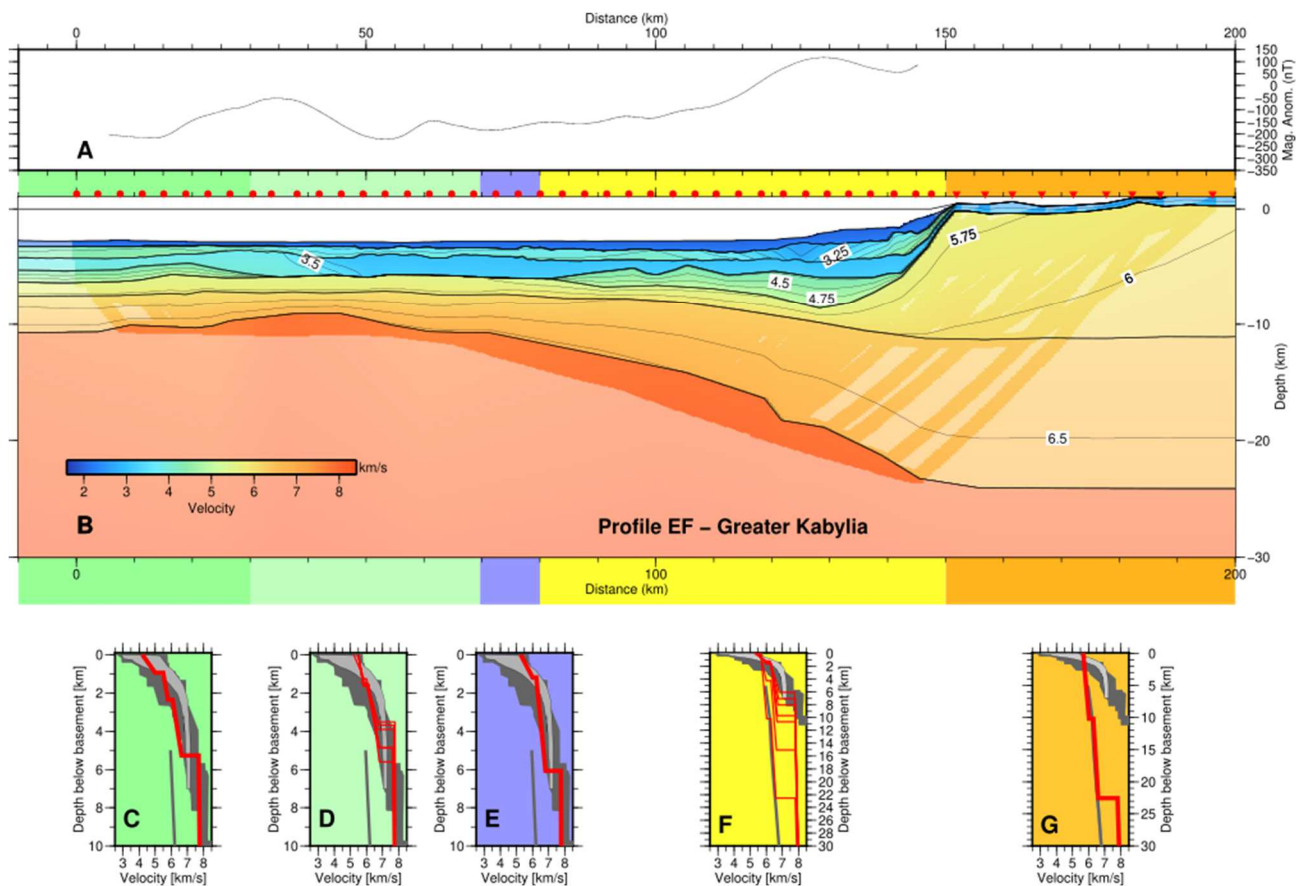


Figure 5 : Final forward velocity model of the Profile EF offshore Greater Kabylia (Aïdi et al., 2018). (A) Magnetic anomaly measured during the cruise (B) Final forward velocity model. Green region is interpreted to be of oceanic origin, the violet region the COT, the yellow region the thinned continental crust and orange unthinned continental crust. Bold red lines are for mean 1D velocity-depth (v_z) profiles and thin red lines for v_z -profiles every 10 km along the model (C) and (D) in the oceanic domain (E) in the COT (F) in the thinned continental crustal domain (G) in the continental domain. Grey line is mean velocity for thinned continental crust (Christensen and Mooney, 1995), grey area bounds of normal oceanic crust from White et al. (1992) and light grey areas oceanic crust from Grevemeyer et al. (2018).

Transect IJ offshore Jijel

This 250-km-long profile spans from the Algerian Basin over the internal zones of the lesser Kabylies (Jijel and Mila) to the Tellian thrustbelt (Setif and Batna) margin offshore Jijel (Mihoubi et al., 2014; Figures 1 and 6). The Lesser Kabylie continental crust reaches a thickness of 26 km thinning to about 5 km over a short distance of 70 km. Similar to the Greater Kabylie transect EF the necking zone is asymmetric with the upper crust thinning on a shorter distance than the lower crust. The authors propose that this could be explained by oceanward creep of ductile material in the lower crust (Mihoubi et al., 2014). The COT is existent but narrow, between 15 and 20 km. The oceanic crust northwards is homogeneous and has a thickness of ~5 km. It is located in a region

where linear magnetic anomalies, located parallel to the profile can be identified (Figure 1), indicating that the oceanic crust here results from accretion at an oceanic spreading center. Mass-wasting processes were probably active after rifting and before the accretion of the Lesser Kabylia to Africa. Since the Messinian salinity crisis the margin has been dominated by gravity driven salt tectonics (Mihoubi et al., 2014). Salt tectonics started during the Pliocene, the thickening of the sediments at the foot of the margin pressed the salt into the offshore basin, as the salt is less dense than sand or clay. During the Messinian erosion and deposition of silico-clastic sediments on the margin prevailed.

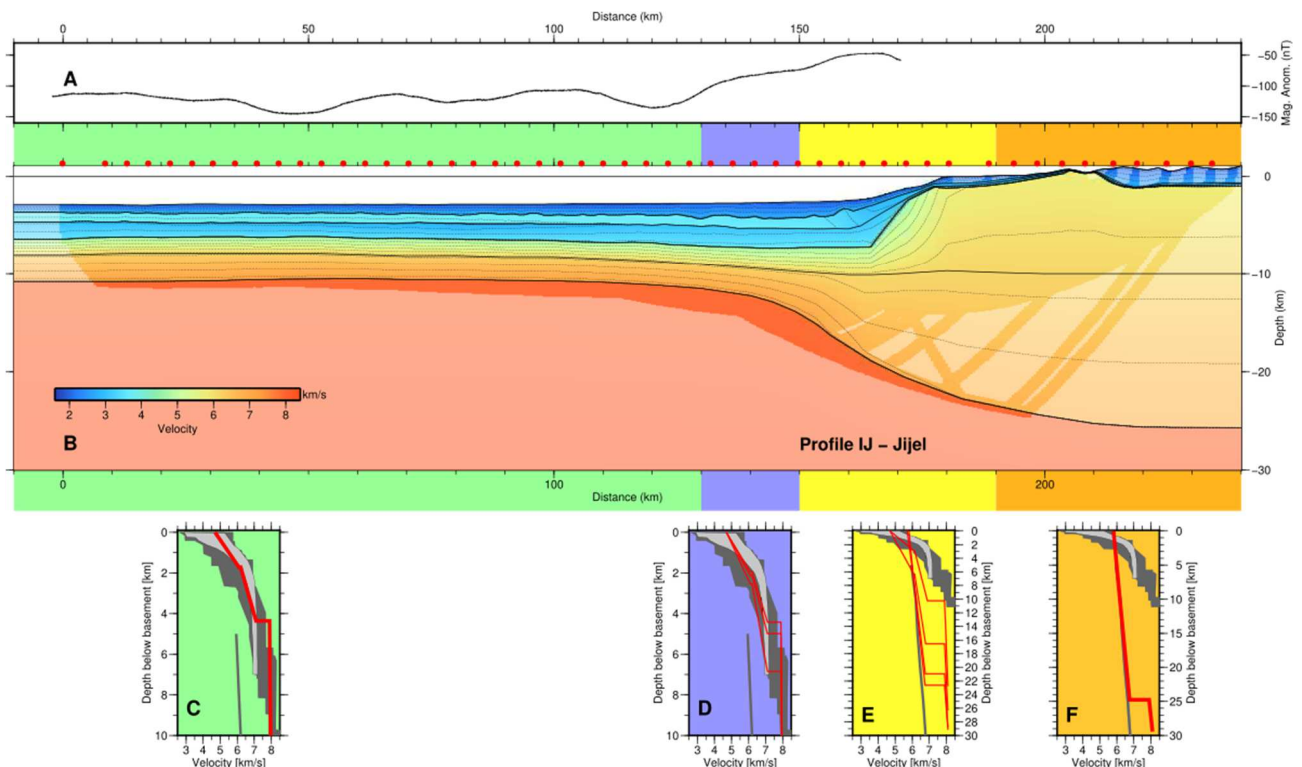


Figure 6 : Final forward velocity model of the Profile IJ offshore Jijel (Mihoubi et al., 2014). (A) Magnetic anomaly measured during the cruise (B) Final forward velocity model. Green region is interpreted to be of oceanic origin, the violet region the COT, the yellow region the thinned continental crust and orange unthinned continental crust. Bold red lines are for mean 1D velocity-depth (v_z) profiles and thin red lines for v_z -profiles every 10km along the model (C) in the oceanic domain (D) in the COT (E) in the thinned continental crustal domain (F) in the continental domain. Grey line is mean velocity for thinned continental crust (Christensen and Mooney, 1995), grey area bounds of normal oceanic crust from White et al. (1992) and light grey areas oceanic crust from Grevemeyer et al. (2018).

Transect GH offshore Annaba

The 240-km-long profile is located on the eastern edge of the Algerian basin near the Sardinia Channel (Figure 1 and 7) spanning over the Lesser Kabylia block close to Annaba up to the

Tellian thrustbelt (Bouyahiaoui et al., 2015) (Figure 1). Here the margin is wider than along the western profiles and the 27 km continental crust thins over a distance of about 50 km to about 15 km and symmetrically between the upper and lower crust. The COT is about 30 km wide, therefore about 10-20 km wider than in the West. The oceanic crust is about 5.5 km thick and thereby thinner than normal ocean crust. At model distance 50km in the oceanic domain a small ridge is imaged proposed to be of volcanic origin active during the Miocene (Bouyahiaoui et al., 2015) (Figure 7). S-wave modelling performed in the oceanic domain shows Poisson's coefficients more characteristic for gabbro than for peridotites, which confirms an oceanic origin of the crust rather than from upper mantle material exhumed and serpentinised at opening of the basin (Bouyahiaoui et al., 2015)(Figure 7). Based on the crustal structure of this profile the authors propose that the eastern Algerian basin opened during the southeastward migration of the European forearc before the collision, along a NW–SE trending spreading center. This geometry atypical for back-arc basins can be explained by the differing directions of the subduction rollback eastward for the Corsica–Sardinia block, and southward for the Kabylia blocks (Bouyahiaoui et al., 2015) (Figure 1).

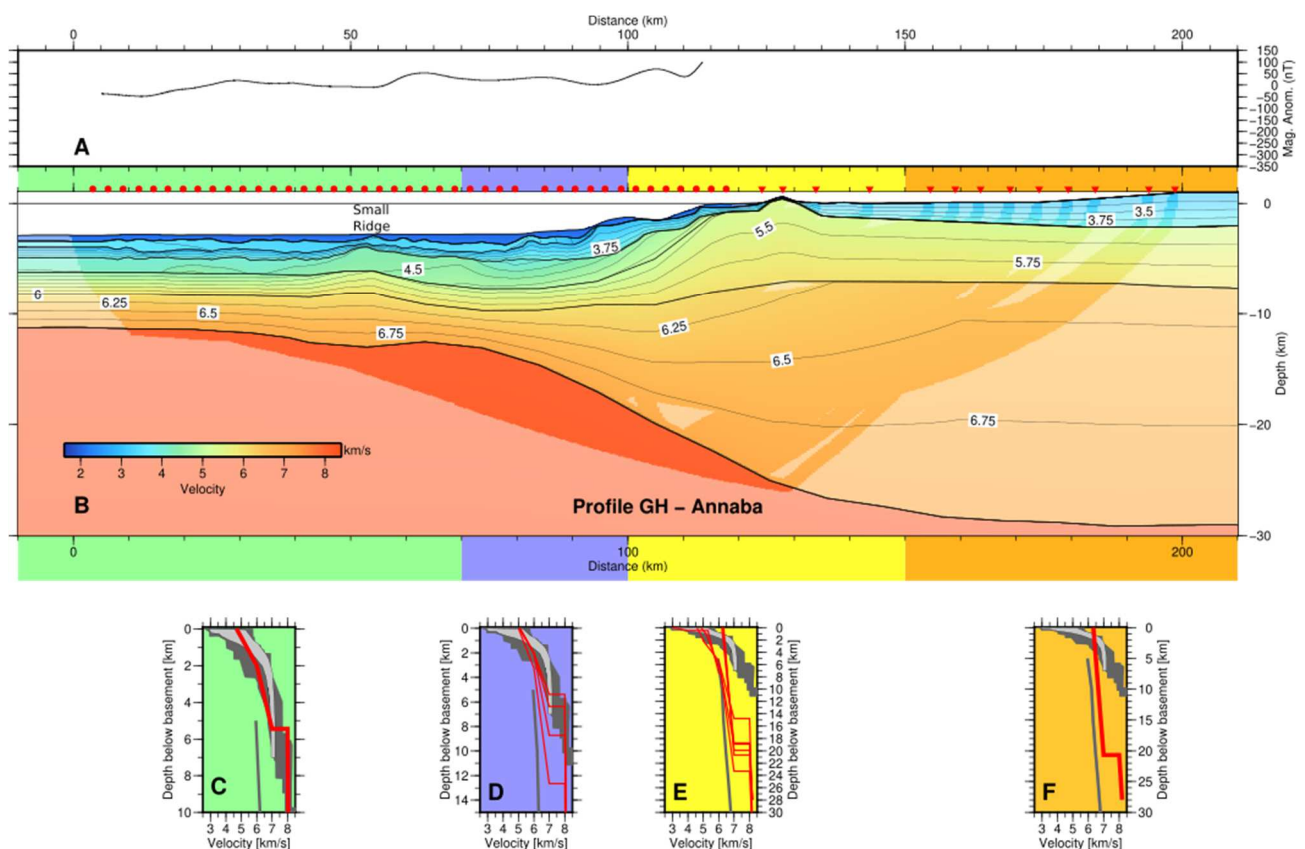


Figure 7 : Final forward velocity model of the Profile GH offshore Annaba (Bouyahiaoui et al., 2015). (A) Magnetic anomaly measured during the cruise (B) Final forward velocity model. Green region is interpreted to be of oceanic origin, the violet region the COT, the yellow region the thinned continental crust and orange unthinned continental crust. Bold red lines are for mean 1D velocity-depth (v_z) profiles and thin red lines for v_z -profiles every 10km along the model (C) mean 1D velocity-depth profiles in the oceanic domain (D) mean 1D velocity-depth profiles in the COT

(E) mean 1D velocity-depth profiles in the thinned continental crustal domain (E) mean 1D velocity-depth profiles in the continental domain. Grey line is mean velocity for thinned continental crust (Christensen and Mooney, 1995), grey area bounds of normal oceanic crust from White et al. (1992) and light grey areas oceanic crust from Grevemeyer et al. (2018).

4. Synthesis and discussion the SPIRAL wide angle seismic profiles

The comparison of the interpretation of the five wide-angle seismic profiles shows laterally varying differences in the structure of the oceanic crust, the width of the COT and the steepness of the continental slope (Figure 8).

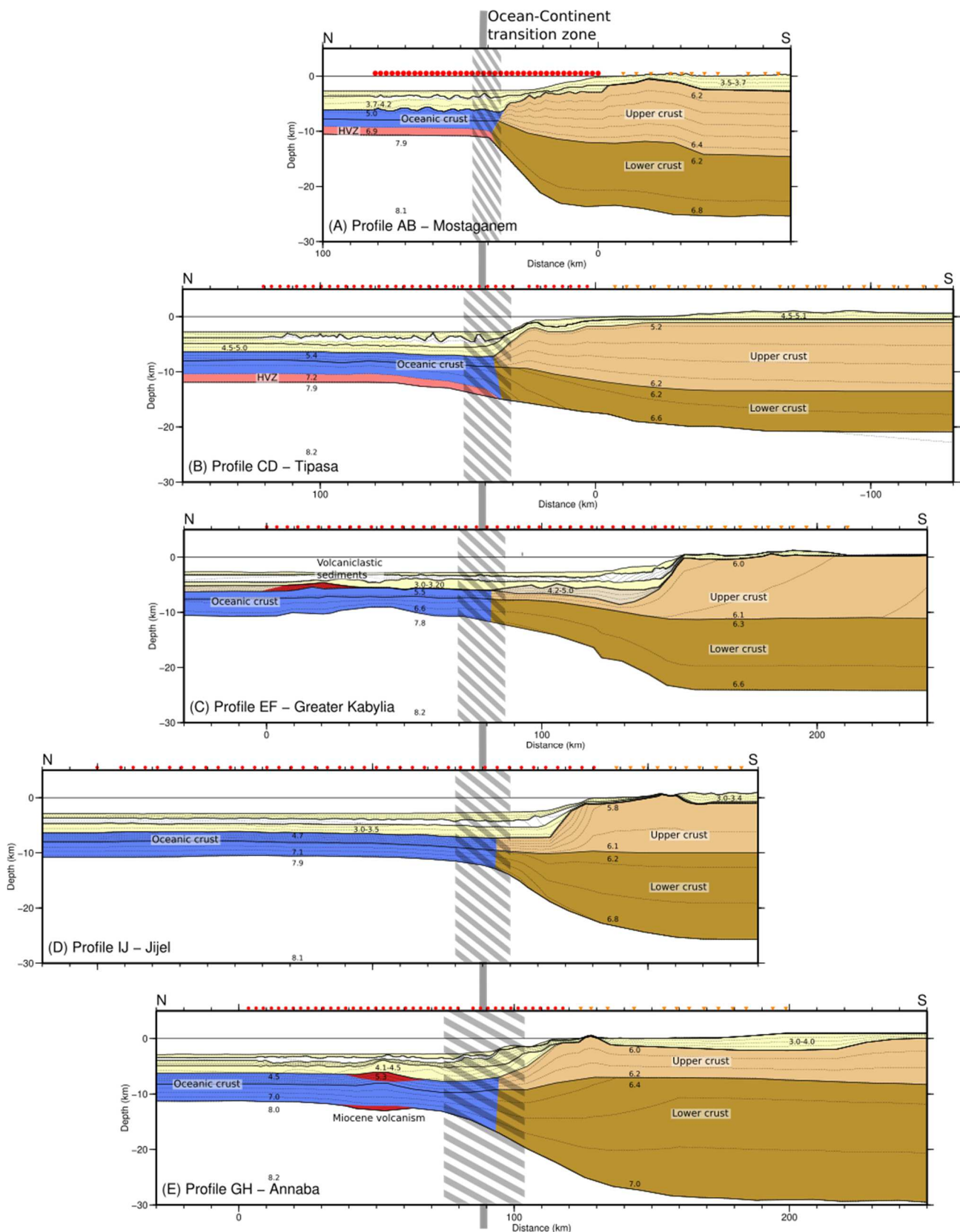


Figure 8 : Interpretation of the velocity profiles based on the original work . The velocities are contoured every 0.25 km/s. Brown areas depict continental crust and blue areas oceanic crust. High velocity zones in the lower crust are marked in pink and volcanic material in red. Approximate extent of the COT is shown by a transparent cross striped area. (A) Profile AB offshore Mostaganem (B) Profile CD offshore Tipasa (C) Profile EF offshore Greater Kabylia (D)

Profile IJ offshore Jijel (E) Profile GH offshore Annaba (Bouyahiaoui et al., 2015; Mihoubi et al., 2014; Aïdi et al., 2018; Leprêtre et al., 2013; Badji et al., 2015).

Synthesis and discussion of the structure of the oceanic crust in the Algerian basin.

Along the five transects the crust imaged in the ocean basin is between 3.5 km and 5.5 km thick and divided into two layers. Comparison of the 1D velocity-depth profiles of the 5 transects shows that the crust is not of thinned continental origin (Christensen and Mooney, 1995) but consistent with crust of oceanic origin, thinner than average oceanic crust of 7.2 km thickness (White et al., 1992) (Figures 9 and 10). However, a more recent compilation using modern wide-angle seismic data from 2D profiles finds that magmatic crust from fast- and intermediate spreading centers results in a crustal thickness of 6 ± 1 km (Grevemeyer et al., 2018) (Figure 9A). Compared to these data, the oceanic lower crustal velocities offshore Algeria remain lower than this magmatic crust compilation, a fact that can be explained by slow accretionary rates leading to lower crustal velocities (Grevemeyer et al., 2018) (Figure 9 B,C, and D). The mean v_z -profiles in our study region fit best with compilations of velocity data from segments ends, with only upper crustal velocities being higher than the corresponding bounds, with an increasing discrepancy from west to east. Only profile AB falls out of both the White et al., 1992 and the Grevemeyer et al., 2018 ranges for upper crustal velocities in oceanic crust (Figure 9A).

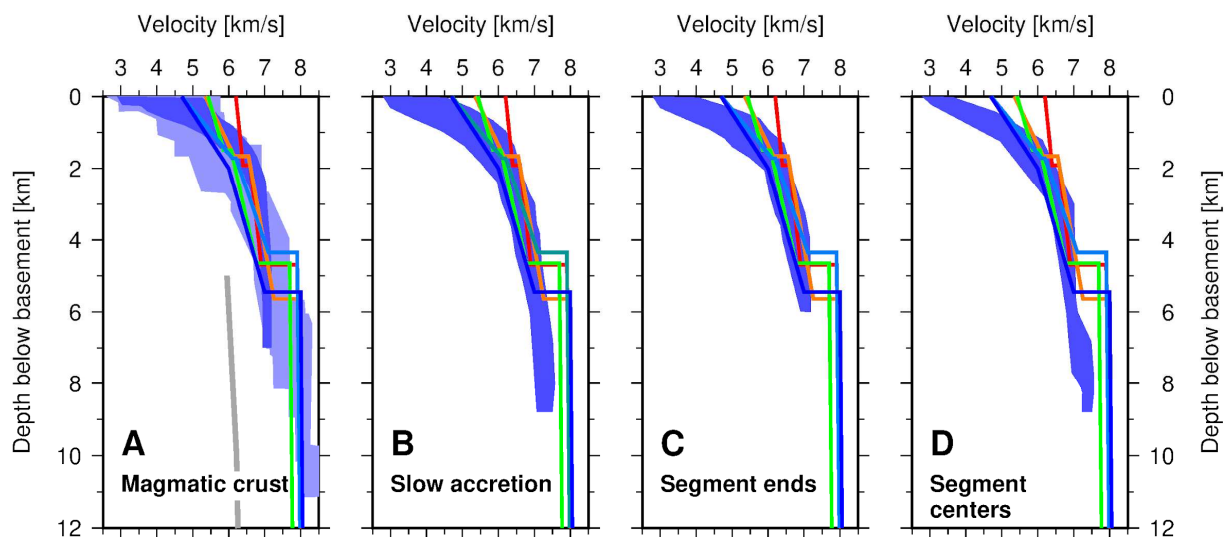


Figure 9 : Comparison of 1D velocity-depth profiles underneath the basement in the oceanic domain. Red line : profils AB Mostaganem, Orange line : profile CD Tipasa; Green line : profile EF Greater Kabylia; dark blue line : profile IJ Jijel, blue line : profile GH Annaba. (A) Light underlay is bound from normal oceanic crust (White et al., 1992), gray line is continental crust (Christensen and Mooney, 1995) and dark blue underlay is magmatic crust from Grevemeyer et al., 2018 (B) dark blue underlay is crust from slow accretion from Grevemeyer et al., 2018 (C) dark

blue underlay is crust from slow accretion segment ends from Grevemeyer et al., 2018 (D) dark blue underlay is crust from slow accretion in segment centers from Grevemeyer et al., 2018

Such thin oceanic crust is produced by slow to ultra-slow accretionary ridges (Bown and White, 1994) (Figure 10 B), such as the Southwest Indian Ridge (Muller et al. 1997), or the Mohns Ridge in the North Atlantic (Klingelhoefer et al., 2000 a and b) (Figure 10 A). Although the crust produced at Mohns Ridge appears to be divided into two layers corresponding to basalts (Layer 2) and gabbros (Layer 3), the accreted crust at the Southwest Indian Ridge consists of a basaltic layer directly overlying a layer of serpentinised upper mantle, due to a lack of melt production (Mueller et al., 2000) (Figure 10 B). Comparison with the Algerian Basin shows that the basaltic layer (Layer 2) in the Algerian Basin is characterized by higher velocities than those of very slow ridges. This can be explained by the decrease in porosity in the upper crustal layers due to the weight of the sedimentary layers along the Algerian margin leading to the closure of pore space.)

Although the velocity-depth profiles from offshore Algeria fit relatively well magmatic oceanic crust they might also fit exhumed and partly serpentinised mantle material, displaying velocities similar to those of oceanic crust. Such zones composed of mantle exhumed and serpentinized by seawater have been sampled and imaged along magma-poor passive continental margins (e.g. Boillot et al., 1995; Beslier et al., 1990; Dean et al., 2000; Funck et al., 2004; Van Avendonk et al., 2006; Afilhado et al., 2008) (Figure 10 C and D). These zones can be up to 100-150 km wide (e.g. Funck et al., 2004) and are characterized by thicknesses between 4-6 km. The Moho then corresponds to the serpentinization front in the mantle, and no or few reflections from this boundary are identified in the ocean-bottom seismometer data. The crust of the Algerian Basin shows a two-layer distribution that is generally not identified in these zones of exhumed and serpentinized mantle. After the phase of mantle exhumation during the opening of a margin and before the establishment of a stable oceanic accretion a thin proto-oceanic crust is often produced at spreading centers (Jagoutz et al., 2007 ; Klingelhoefer et al., 2014). The first embryonic crust may also be composed of a mixture of gabbros and serpentinites and in this case will be characterized by high crustal velocities that are higher than the velocities of the gabbros, a fact that is not observed off Algeria. However, s-wave modeling offshore Annaba indicates an absence or very low rate of serpentinisation in the basin's crust (Bouyahiaoui et al., 2015), and we propose therefore the oceanic crust offshore Algeria is mainly of magmatic origin, without large intrusions of upper mantle material.

In comparison between the profiles, the profile IJ offshore Jijel presents the most homogeneous

oceanic crust in terms of velocities and crustal thickness (Figure 8). While the eastern profiles, offshore AB offshore Annaba, IJ offshore Jijel and CD offshore Greater Kabylia have lower upper crustal velocities than the western profiles offshore GH offshore Mostaganem and CD offshore Tipasa. These slightly elevated velocities in the lower crust (Figure 8). This lateral variation might be due to the mantle temperature or position of the slab at the time of accretion or other local factors as it might also be explained by differences in age of several blocks in the Alboran Sea.

Other back-arc basins show thin oceanic crust probably due to low lithospheric temperatures due to the presence of a subducting slab leading to hydration of the mantle, e.g. the Philippine Sea Basin (Louden, 1980), the Tyrrhenian sea (Contrucci et al., 2005) (Figure 10 E) or the Liguro-Provencal Basin (Figure 10 F). These basins are entirely underlain by thin oceanic crust. The Liguro-Provencal Basin, a Mediterranean back-arc basin created from the rotation of the block Corso-Sardecia in the Oligocene, shows very similar thickness and velocities of the crust underlying the basin to those in this study. The fact that both basins are narrow implies that the slab was close to the accretionary spreading center. Therefore, we propose that the Algerian and Liguro-Provencal basin were created in similar circumstances of a cold mantle leading to reduced magma supply at the accretionary centre and most probably at slow spreading rates (van Hinsbergen et al., 2014), located close to the downgoing slab (Facenna et al., 2004) leading in both cases to thin but nevertheless oceanic crust.

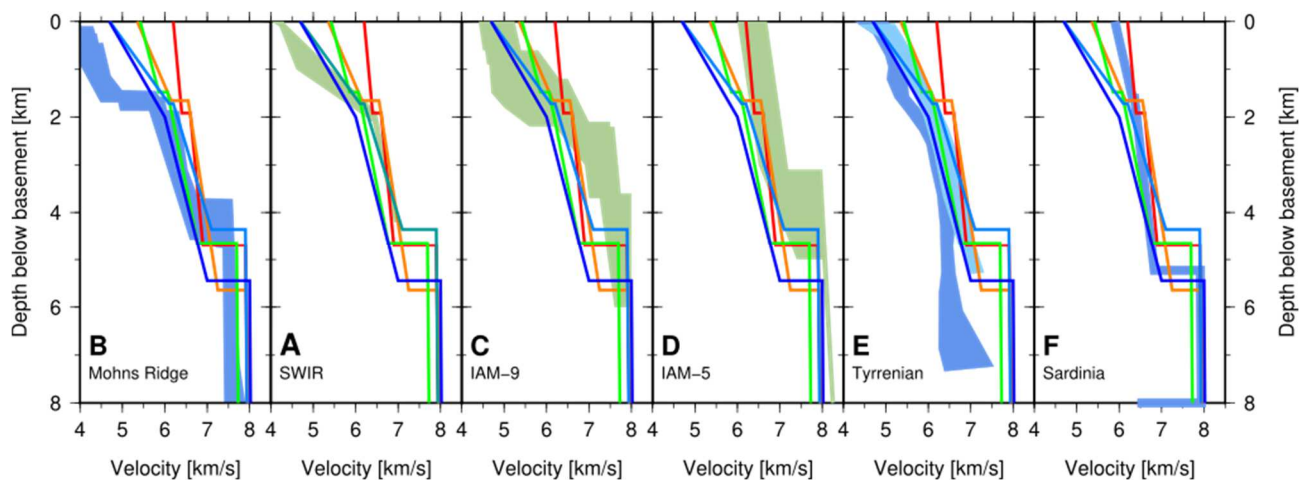


Figure 10 : Comparison of 1D velocity-depth profiles underneath the top of the basement in the oceanic domain. Red line : profile AB Mostaganem, Orange line : profile CD Tipasa; Green line : profile DE Greater Kabylia; dark blue line : profile IJ Jijel, blue line : profile GH Annaba. (A) Blue underlay is bound from Mohns Ridge (Klingelhoefer et al., 2000) (B) Green underlay is from South-West Indian Ridge (C) Green underlay is bound from southern Iberia Abyssal plain (Dean et al., 2000) (D) Green underlay is bound from west Iberia margin (Afilhado et al., 2008) (E) Blue underlays are bounds from Tyrrhenian back-arc basin (Contrucci et al., 2005) (F) Blue underlay is

bound from Liguro-Provencal back-arc basin. Blue underlays correspond to crust interpreted to be magmatic and green underlays to regions interpreted to result from serpentinisation of exhumed upper mantle material.

Synthesis and discussion of the ocean-continent transition zone

The ocean-continent transition zone (COT) of the north Algerian margin is extremely narrow, between < 10 km and 30 km wide (Figure 8). This is about 70 km more narrow than the COT at for example the the NW Moroccan margin, which opened during perpendicular rifting of the central Atlantic (Biari et al., 2015). To the west along the profiles AB offshore Mostaganem and CD offshore Tipasa the resolution of our dataset does not allow to rule out a complete absence of the COT locally. (Figure 8). This absence can be explained by the genesis of the margin as a STEP (Subduction-Transform Edge Propagator Fault) fault (Govers and Wortel, 2005, Gallais et al., 2013; Badji et al., 2015). A STEP fault is formed near the termination of a subduction related to slab rollback. Govers and Wortel (2005) proposed the existence of a STEP fault behind the subduction of the Gibraltar arc (Figure 12).

Along the profile CD offshore Tipasa the COT is also very narrow or absent (Figure 4) indicating shear opening. On the other hand, the continental nature of the Kayr-Al-Din Bank indicates a first phase of rifting in a North-South direction. In this region, the extremely reduced width of the transition zone implies a phase of transform movement setting in after the creation of the Khayr-Al-Din Bank. This phase might be linked to the passage of the Alboran block after the initial opening (Rosenbaum et al., 2002; Leprêtre et al., 2013; Medaouri et al., 2012).

The COT is located further from the coast in the Greater Kabylia region, and it is as narrow as along the Tipasa profile (Figure 5). It is close to the position of the Hannibal Ridge, proposed to be an extinct ridge producing an E-W accretion (Mauffret et al., 2004). This hypothesis was not confirmed by the wide-angle seismic profile EF, although the orientation of the profile, also N-S is not ideally situated to answer this question (Aïdi et al., 2018). The authors propose that it is composed of rounded magnetic anomalies from later volcanism. On the other hand, off Jijel the COT is very close to the coast, also with a very reduced width (Figure 6). In this region its width might be related to an E-W opening of the basin (Mauffret et al., 2004). In the east of the Algerian basin offshore Annaba the COT is 20-40 km wide (Figure 7). This profile is located in the transition between the Algerian Basin and the Sardinia Passage which itself is underlain by highly thinned continental crust (Peirce and Barton, 1992) and outside the zone of identified magnetic anomalies in

the southeast of the basin (Schettino and Turco, 2006) (Figure 11).

Synthesis and discussion of the zone of crustal thinning

The thinning zone of the continental crust of the Algerian margin is narrow compared to the Atlantic passive continental margins. To the west along the profile AB offshore Mostaganem it is 20-30 km wide and to the east along the profile GH offshore Annaba about 50 km wide. The largest width is off the coast of Greater Kabylia where it is about 60 km wide (See summary in Table 1). In comparison on the Moroccan Atlantic margin it has a width of about 100-120 km. This can be partly explained by the greater thickness of the pre-rift continental crust.

Profile	Moho slope	Width of necking zone (km)
AB (Mostaganem)	45°	25
CD (Tipasa)	5°	30
EF (Greater Kabylia)	22°	60
IJ (Jijel)	20°	40
GH (Annaba)	22°	50
Atlantic margin MI1	20°	180
Ionian sea DYP1	38°	25
Sardinia GH	23°	60
Gulf of Lions AB	18°	150

Table 1: Comparison of Moho slope and width of the necking zone along all profiles and comparison to the Gulf of Lions and Ionian sea.

Synthesis and discussion of the unthinned continental crust

The thickness of the unthinned Algerian continental crust is not entirely constrained along the margin, due to the lack of reverse shots along the wide-angle seismic profiles. However it seems to be reduced to a thickness of about at least 25 km (Figure 2), about 10 km thinner than the Atlantic unthinned continental crust in Morocco (Contrucci et al., 2004). This difference is in good agreement with recent gravimetric modeling (Fullea et al., 2010) indicating a Moho depth of about 25km at the Algerian Margin.

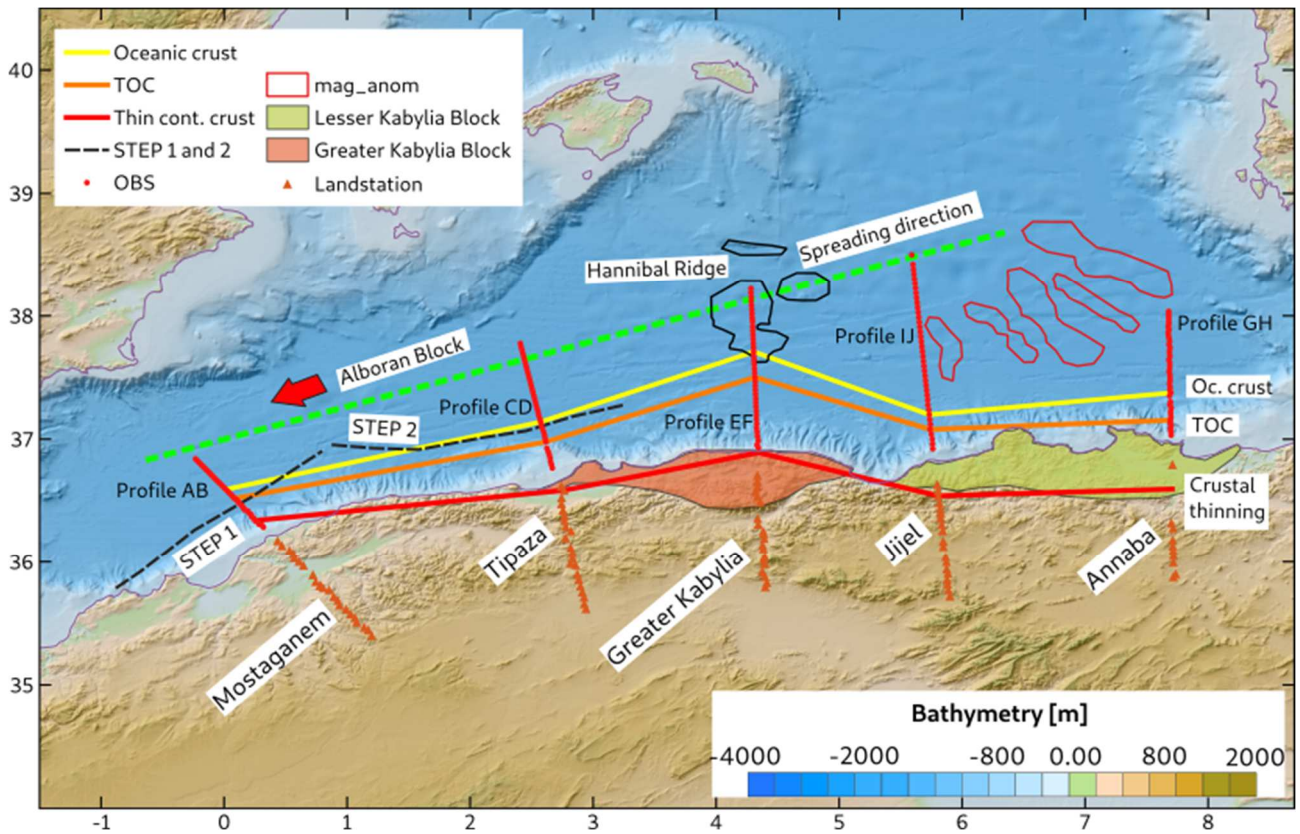


Figure 11 : Domain boundaries indicated by the five transects. The yellow line is interpreted as the southern limit of the oceanic crust, the orange as the southern limit of the COT and the red as the southern limit of the thinning zone. The Hannibal region is marked black outlines (Mauffret et al. 2004), in brown the Greater and yellow the Lesser Kabylia block and red outlines the correlated magnetic anomalies (Schettino and Turco, 2006). Dashed lines mark STEP 1 and STEP 2 faults from Medaouri et al., 2014.

5. Comparison to other narrow continental margins in the Mediterranean

Comparison to a STEP impacted margin in the Ionian sea

The existence of three STEP faults has been proposed in the Mediterranean basin, in association with the slab edges at the Gibraltar arc, the Calabria trench and the Hellenic trench (Govers and Wortel, 2005). Slab rollback can lead to the formation of slab tear faults which then leave STEP faults as a surface expression (Govers and Wortel, 2005). The Calabrian subduction zone is narrow (250 km wide) and characterized by a steep dipping slab (Selvaggi and Chiarabba, 1995). Slab rollback of more than 800km caused by lateral tearing of the slab led to the formation of a STEP fault in the upper plate (Gallais et al., 2013; Gutscher et al., 2016). Imaging the precise location of this major STEP fault in the Ionian sea was one of the objectives of the DYONISUS deep seismic cruise (Dellong et al., 2018; Dellong et al., 2020; Dannowski et al., 2019). One seismic profile crossing the basin shows an abrupt thinning margin at the Malta escarpment, probably the remnant of a transform margin from the Early Mesozoic (Dellong et al., 2018). The STEP fault is proposed to follow the trend of the Alpeo fault system rather than the Malta escarpment (Dellong et al., 2018) (Figure 12).

In a comparison, the deep structure of the Calabrian margin resembles the Algerian margin. The zone of crustal thinning is narrow, only 30-50 km as compared to several hundreds of kilometers e. g. along the Atlantic continental margins, leading to a steep Moho inclination and narrow continental shelf. The transition zone between continental and oceanic crust is narrow, in agreement with a transform opening rather than a purely orthogonally rifted margin. The oceanic basin of the Ionian basin is underlain by crust which is thinner than normal (5-6 km), but divided into two separate layers and likely of magmatic origin (Figure 13). This is similar to the structure imaged along the western zone of the Algerian oceanic basin. These similarities are in good agreement with our hypothesis that the northwestern Algerian margin formed under the influence of a STEP fault formed by a retreating slab.

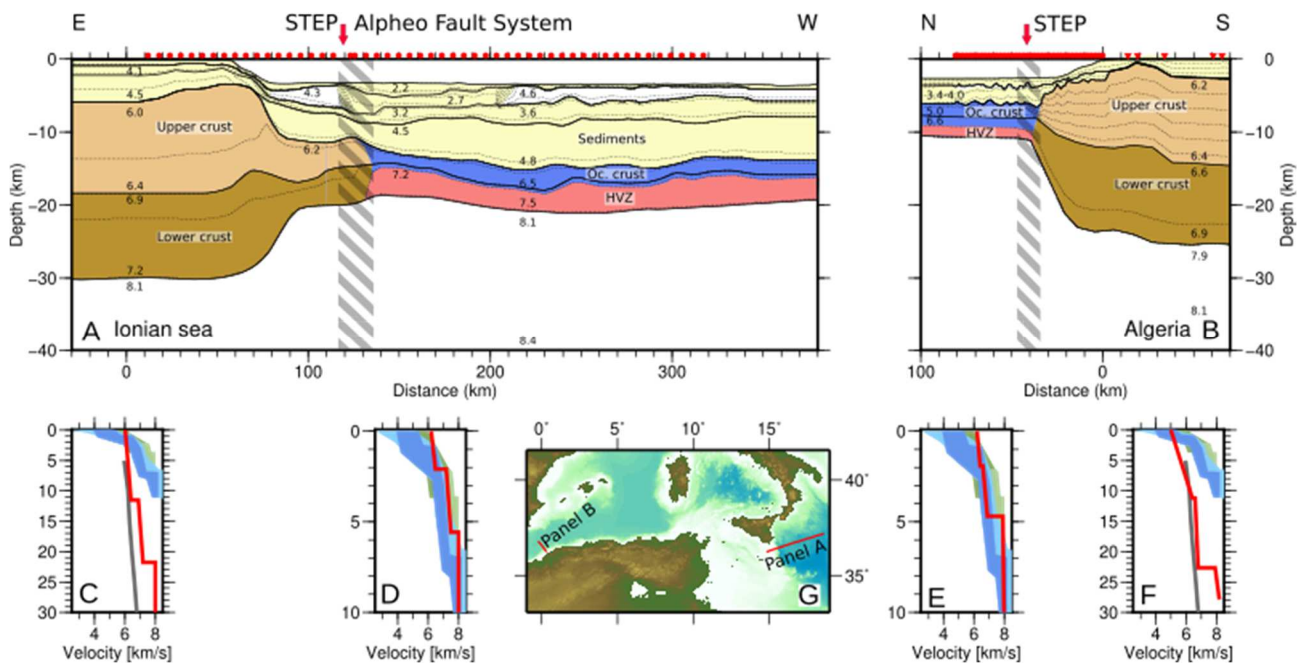


Figure 12 : Comparison of the Algerien margin offshore Mostaganem with the Dyonisus 1 profile located in the Ionian Sea. (A) Dyonisus profile 1 (Dellong et al., 2018) (B) SPIRAL AB (C) V_z -profiles extracted underneath the basement at the continental part of Ionian sea profile (D) V_z -profiles extracted underneath the basement at the oceanic part of Ionian sea profile (E) V_z -profiles extracted underneath the basement at the oceanic part of the Algerian profile (F) V_z -profiles extracted underneath the basement at the continental part of the Algerian profile.

Comparison to the Liguro-Provençal basin

The Liguro-Provençal basin formed by the rotation of the Corso-Sardinian block with respect to the Ibero-European plate from the Oligocene in a back-arc basin position (Le Pichon et al., 1971, Réhault et al., 1984). The basin was the focus of several deep seismic surveys. During the cruise CROC 2 in 1988 37 expanding spread profiles were acquired throughout the Liguro Provençal basin. These measurements helped to cartography oceanic and continental regions throughout the basin (Le Douaran et al., 1983; Pascal et al., 1993; Contrucci et al, 2001; Rollet et al., 2002). More modern wide-angle seismic data were acquired during the SARDINIA cruise (R/V L'Atalante, 2006) in the Provençal basin with the principal objective to determine the nature of the crust in the basin and along its margins. During the cruise six combined wide-angle and reflection seismic profiles were acquired. Two of the profiles were extended on land and present a conjugate pair of the Gulf of Lions-Sardinian margins (Figure 13) (Gailler et al., 2009; Moulin et al., 2015; Afilhado et al., 2015). Along these profiles, the margin at the Sardinia side is characterised by a thinner continental crust, probably due to the presence of the slab at this side eroding the margin crust during subduction. Tilted fault blocks present along the Gulf of Lions margin lead to a broader transition zone of 150 km as compared to only 70 km at the Sardinian side. The sediment layer in

the basin is up to 8 km thick marked by strong salt tectonics. High lower crustal velocities up to 7.6 km/s are observed at the COT along both margins and might be related to the presence of exhumed mantle material or volcanic underplate (Gailler et al., 2009). The asymmetry of the margin can be explained by its formation as a back-arc basin, as the Sardinia side which was close to the subducting slab during the rollback of the tethysian slab shows a more abrupt thinning and thinner continental crustal thickness. The oceanic crust flooring the basin has a thickness of 5 km (Moulin et al., 2015; Afilhado et al., 2015).

Eastward of these profiles a recent deep seismic study proposes the existence of hyper-extended continental crust thinned of only 2.5 km thickness (Dannowski et al., 2020). Alternatively, the velocities could be explained by a lateral isolated magmatic intrusion in the sediments (Dannowski et al., 2020). The crustal thickness increases toward the NE where stretching was less due to the rotational opening of the basin. Mantle velocities are slightly lower than normal (7.8 km/s) which is in good agreement with a serpentinisation of the mantle of about 20% (Carlson and Miller, 2003). The Ligurian basin margin north of this profile was studied during a 3D seismic experiment and no E-W change of crustal type is observed (Dessa et al., 2011)

A comparison of these profiles from the Liguro Provencal basin with the Algerian margin shows that the continental crustal thickness and width of the thinning zone of the Algerian margin are similar to the Sardinian margin (Figure 14). However, the Gulf of Lions side of the Liguro-Provencal basin is characterized by a 50-80 km wider thinning zone. The specific context of opening related to a continental block is similar for the margins of West-Sardinia and Algeria, as they both were located at the side of the slab rollback. This special geodynamic position might explain on one hand the thin continental crust and on the other hand the formation of an abrupt margin with a narrow COT.

The continent-ocean transition zone in the Liguro Provencal basin is characterised by the presence of a layer of unusual high (7.5 km/s) velocities in the lower crust. These velocities are proposed to correspond to serpentinised upper mantle material (Gailler et al., 2009), and are not imaged at the neighbouring Ligurian margin, probably due to the fact that full oceanisation has not been reached along these profiles (Dessa et al., 2011; Dannowski et al., 2020). Although some high lower crustal velocities were identified at the Algerian margins oceanic domain, these do not exceed 7.2 km/s and are not spatially related to the COT. So, while the Liguro-Provencal basin structure display characteristics highly similar to magma-poor Atlantic volcanic margins (eg. Iberia : Minshull et al., 2014; Goban Spur : Bullock and Minshull, 2005) the Algerian margin shows a more narrow

transition between continental and oceanic domains atypical for large ocean basins.

The oceanic crust in both basins is thin, between 4-5 km, with an irregular magnetic anomaly pattern, except a region of regular fan-shaped anomalies offshore Jijel in the Algerian basin (Schettino and Turco, 2006; Haidar et al., 2021). No structures corresponding to an extinct spreading center have been imaged in the Liguro Provençal basin and although the existence of an extinct spreading center has been suggested in the Algerian basin (Mauffret et al., 1995), later work proposes the magnetic anomalies to be associated with Miocene postrift volcanism (Aïdi et al., 2018). This thin oceanic crust without regular magnetic anomalies might be representative for back-arc spreading basins, where spreading might occur along short ridge widely spaced segments (Medaouri et al., 2014) or due to a partial melting during the second phase in a region of serpentinised mantle (Aïdi et al., 2018).

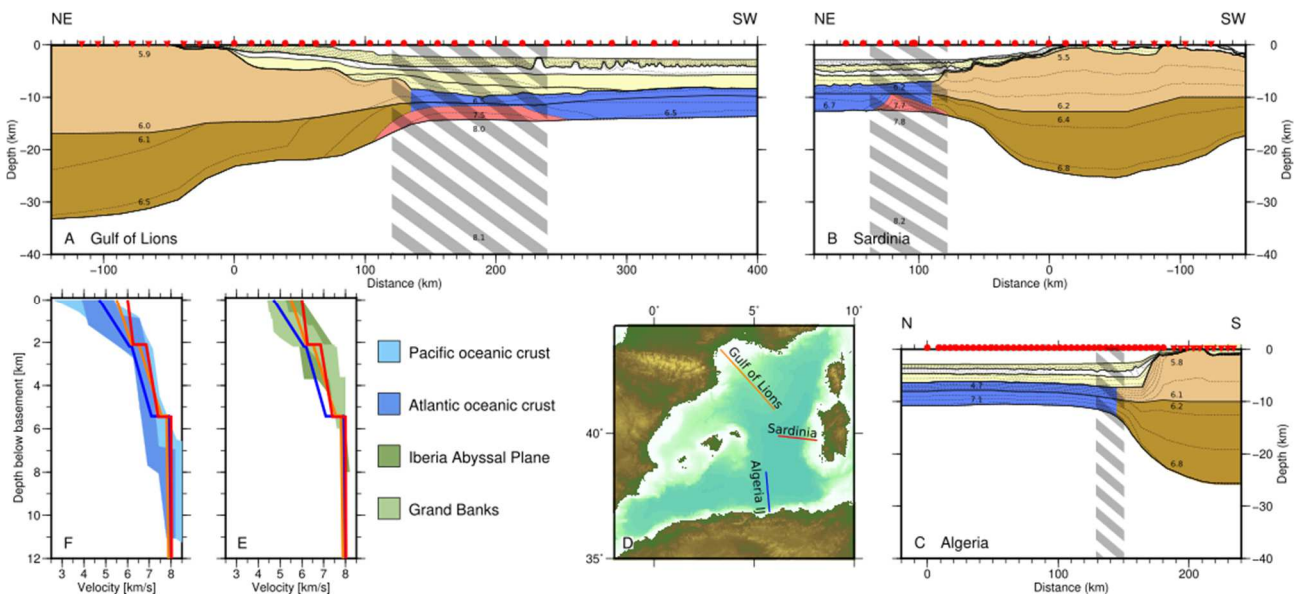


Figure 13 : Interpreted crustal structure from wide-angle seismic profiles from the Liguro-Provençal Basin and the Algerian Basin. (A) Gulf of Lions (Moulin et al., 2015) (B) Sardinia (Afilhado et al., 2015) (C) Profile GH offshore Anaba from the SPIRAL cruise (D) Location map (E) Mean v_z -profiles from the oceanic regions extracted underneath the basement underlain by velocity envelopes from serpentinized upper mantle (Grand Banks - Van Avendonk et al., 2006; Iberia Abyssal Plain - Dean et al., 2008) (F) Mean v_z -profiles from the oceanic regions extracted underneath the basement underlain by velocity envelopes from typical oceanic crust from the Atlantic and Pacific (White et al., 1992).

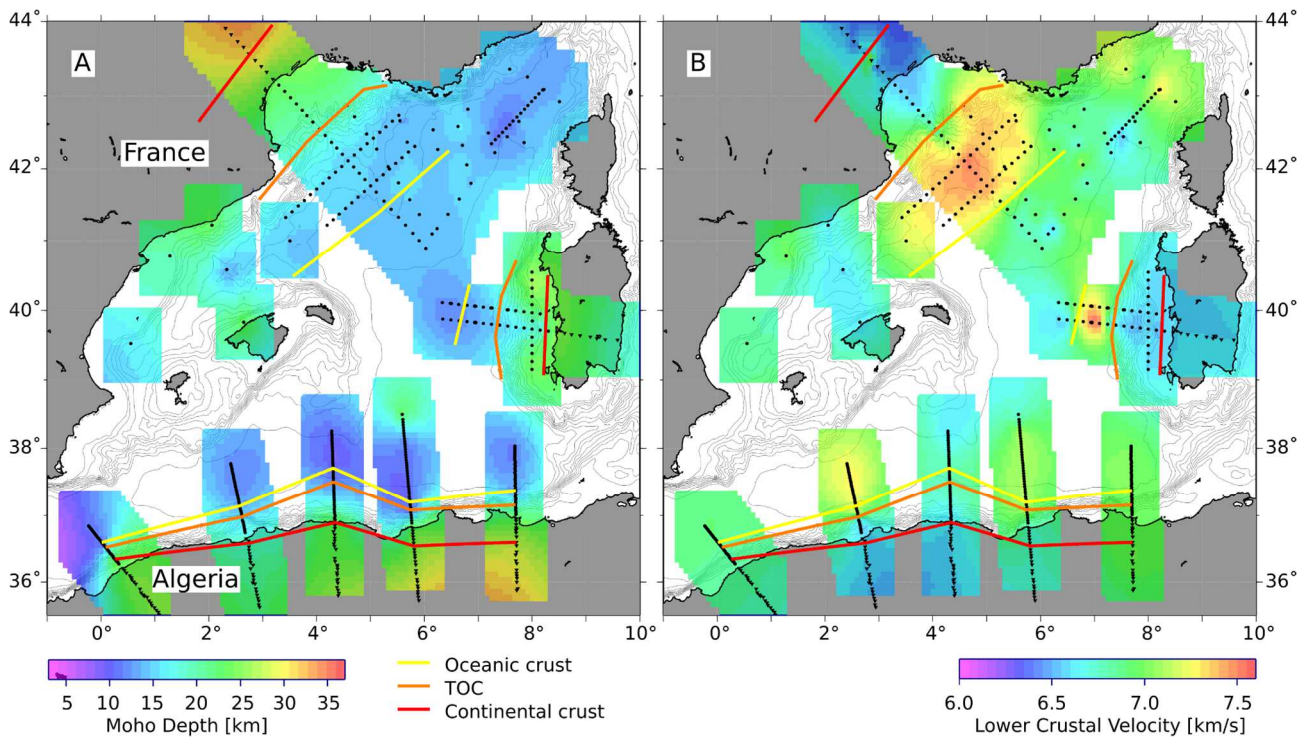


Figure 14 : (A) Moho depth in the Liguro Provencal and Algerian basins (B) Lower crustal velocity directly above the Moho in the Liguro Provencal and Algerian basins (Algerian Basin : Bouyahiaoui et al., 2015; Mihoubi et al., 2014; Aïdi et al., 2018; Leprêtre et al., 2013; Badji et al., 2013; Liguro Provencal Basin : Pascal et al., 1993; Contrucci et al, 2001; Gailler et al., 2009; Moulin et al., 2014; Afilhado et al., 2014; Dannowski et al., 2020).

Conclusions

Comparison of five onshore-offshore wide-angle seismic transects at the north Algerian margin allowed to constrain crustal structure variations and influence of the opening of the basin on its deep structure:

- 1) The Algerian Basin is underlain by a ~5 km thin oceanic crust. This kind of crust is typical for back-arc basins generated in an environment of reduced mantle temperature due to the closeness of the cold subducting slab. Upper crustal velocities increase from the East to the West along the Algerian offshore and the westernmost profiles show slightly elevated lower crustal velocities, probably linked to local varying parameters during accretion.
- 2) A very narrow or absent COT is observed along all the Spiral profiles with the exception of the easternmost Annaba (GH) profile. This might be due to a second phase of opening in an east-west direction, with the Alboran Block passing along the profile Tipasa (CD) and Mostaganem (AB). The Mostaganem profil (AB) shows the most narrow margin, steepest slope and Moho inclination bearing good resemblance with other STEP impacted margins. Offshore Tipasa (profile CD) the margin is impacted by two phases, an initial phase of rifting creating the Khayr-Al-Din bank and a second phase of transform deformation due to

the STEP fault.

- 3) The Hannibal ridge earlier proposed to be a N-S oriented spreading center in the middle of the Algerian basin (Mauffret et al., 2004) corresponds probably to several submarine volcanic centers formed after initial opening of the basin itself.
- 4) The thickest crust detected during the Spiral survey corresponds to the African continental crust or the Kabylides blocks and is about 22-25 km thick. This reduced thickness in comparison with unthinned continental crust might be due to the influence of subduction at the margin, similar to the reduced thickness of the Sardinian basement compared to the Gulf of Lions basement.
- 5) Comparison to the deep structure of a STEP fault impacted margin located in the Ionian Sea shows that the Algerian margin at Mostaganem is characterised by several features typically arising from the influence of a STEP fault such as a very narrow COT and a steep Moho inclination at the continental margin.
- 6) No high velocity zone in the lower crust corresponding to serpentinised mantle rocks has been imaged at the Algerian margin. This kind of high velocity zone has previously been detected in the Liguro-Provencal Basin. However, the oceanic crust underlying both basins is comparable in thickness and velocities. Spreading on both basins likely occurred along short segments of accretionary ridge segments in a more diffuse way than along steady mid-ocean ridges in full sized oceanic basins.

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