Exhumed Lower Continental Crust and Proto-oceanic Crust Interactions? The BasAlg and ArcMal Deep Seismic Projects

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Abstract

The exhumed lower continental crust appears to be omnipresent in the intermediate domain of passive margins. However, the first oceanic crust seems to be essentially atypical in nature, herein called proto-oceanic, before the establishment of a homogeneous and stable oceanic crust. The interaction between these two domains suggested nearly 50 years ago (Bott in Tectonophysics 11:319–337, 1971) seems to be a crucial phenomenon in the genesis of passive margins; it has major consequences on the thermal and tectonic evolution of the margin, as well as on the geodynamic paleo-reconstructions of the system. In the Mediterranean, the Provençal Basin has already highlighted this relationship (Moulin et al. in BSGF 186:309–330, 2015; Afilhado et al. in BSGF, ILP Special volume 186:331–351, 2015) but some areas remain unresolved. We proposed two experiments, on either side of the Strait of Sicily: in the Algerian Basin (Western Mediterranean) and in the Levantine Basin (Eastern Mediterranean). In both places, the nature and geometry of the different segments of the Earth's crust, their boundaries and links are of crucial importance for a precise geodynamic evolution, which remains controversial.

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Keywords

Proto-oceanic crust • Lower continental crust • Passive margins • Wide-angle seismics • Levantin Basin • Algerian Basin • Mediterranean Sea

1 Introduction

The transition from the so-called intermediate domain of passive continental margins located between the continental necking and the first true oceanic crust is still under debate and the exact boundary of the first true oceanic crust may be difficult to define in many, if not all, passive margins. The nature of the intermediate domain, after a more or less rapid and narrow continental thinning zone, is also the subject of debate and exhibits lateral variations. Over twenty years, Ifremer with its academic and industrial partners have imaged this transition zone in the Mediterranean Sea (Provençal Basin), the Central Atlantic (Morocco margins), the Equatorial Atlantic (Berrenhinhas-Maranão-Ceara margins), the central segment of the South Atlantic (Angola Margin, Santos Basin, Jequitinhonha-Almada-Camamu-Sergipe-Alagoas margins) and the Indian (Mozambique margins) oceans. The forwarded modeling of the wide-angle seismic profiles acquired at sea and on land during these experiments reveals an evolution from the continental necking zone to the true (but usually thin) oceanic crust, with a domain of exhumed material, most generally exhumed lower continental crust, and the existence of a proto-oceanic crust. Lateral and longitudinal variations were also described. In the Santos Basin for instance, the central segment presents strong lateral variation, showing a passage of a thin exhumed lower continental crust to an anomalous and probably heterogeneous crust, which can be inferred as proto-oceanic crust on a failed rift (Moulin et al. 2012; Evain et al. 2015). On the Ceara-Maranhão Margin, the 4–5 km thick intermediate domain is interpreted as exhumed lower continental crust. Seawards and parallel to the coast, an

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about 50 km-wide band of proto-oceanic crust is described before reaching a more normal but only 5 km thick oceanic crust (Aslanian et al. 2016). Lastly, in the Provençal Basin, wide-angle data and seismic 3D-grid, drilling and numerical stratigraphic modeling allow identifying a segmentation in three domains of different crustal nature: continental crust, exhumed lower continental crust and proto-oceanic crust (Moulin et al. 2015; Afilhado et al. 2015; Leroux et al. 2018). However, the nature and the evolution of some domains in the Mediterranean sea, as the Algerian and the Levantine basins, remain subject of debate. Opposite hypotheses are proposed, implying opposite geodynamic evolutions.

2 BasAlg Project

The opening of the Algerian Basin remains controversial regarding its kinematic evolution (north–south vs. east–west extension—Fig. 1), crustal nature (oceanic vs. thinned continental) and geodynamic process (slab roll-back vs. continental delimination-driven). Recent evolution (Ethève et al. 2016; Leprêtre et al. 2018) favors a two-step opening scenario including a first westward migration and a second one toward the edges of the basin, which is accompanied by detachment or delamination. Last, while the roll-back process is the most widely accepted mechanism to explain the coincidence of compression and expansion in this region, other models such as the collapse of the previously thickened continental crust during the Alpine stage (Dewey 1989; Platt and Vissers 1989) or lithospheric delamination (Roure et al. 2012) are also proposed. This great variety of evolution hypotheses arises from the differences in study scale, chosen approach and type of data, in particular the geological and/or geophysical, onshore and/or offshore data.

This leads to very different positions of the same element when the Cenozoic evolution of the Western Mediterranean system proposed by different authors is compared. This is illustrated with the position of the AlKaPeCa metamorphic units at 33 Ma (Fig. 2) and even the proposal of the absence of the Alboran Terrane in its pre-drift position (Carminati et al. 2012).

At the same time, the kinematic and amount of displacement between the different segments of the AlKaPeCa terrane are key data to determine origin and role of the observed limit between each onshore and offshore domain developed during the opening of the Western Mediterranean.

This basin presents a strong E-W segmentation which may play an important geodynamic role and must be studied in detail.

3 ArcMal Project

In the Eastern Mediterranean, models involving the opening and closing of the Neo-Tethys still depend largely on determining the nature, age and deformation of the crust forming the Cyprus, Herodotus and Levant basins, and many questions remain to be discussed. Thus, according to different authors, the opening of the Eastern Mediterranean began at the end of the Paleozoic (Stampfli et al. 1991; Stampfli and Borel 2004) or even in the Cretaceous (Dercourt et al. 1993; Ricou 1994). Granot (2016) proposes that the floor of the Herodotus Basin is of oceanic nature and 340 Ma in age, based on magnetic anomalies. Nevertheless, was rifting facilitated by a mantelic plume in the Lower Cretaceous, and followed by the accretion of an ocean floor during the period of magnetic calm between CM10N (~122 Ma) and C34N (~84 Ma, Segev et al. 2018)? The opening direction of these basins is also debatable and one may face the following question: is the Levant Margin a transform margin in direct connection with Neo-Tethys (Stampfli et al. 1991; Keeley 1994; Stampfli and Borel 2004) or a combined normal margin of the micro-continental block of Eratosthenes and Cyprus (Garfunkel 1998; Barrier and Vrielynck 2008; Gardosh et al. 2010)?

Schattner and Ben-Avraham (2007, 2012) propose that the Carmel Structure south of the Galilean Graben separates a basin to the north (Phoenician) from the Levantine Basin to

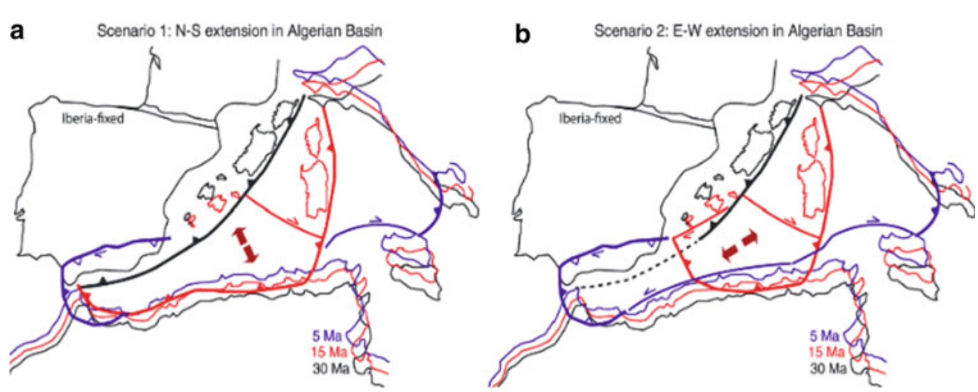

Fig. 1 Two types of scenarii for the opening of the Algerian Basin (Van Hinsbergen et al. 2014)

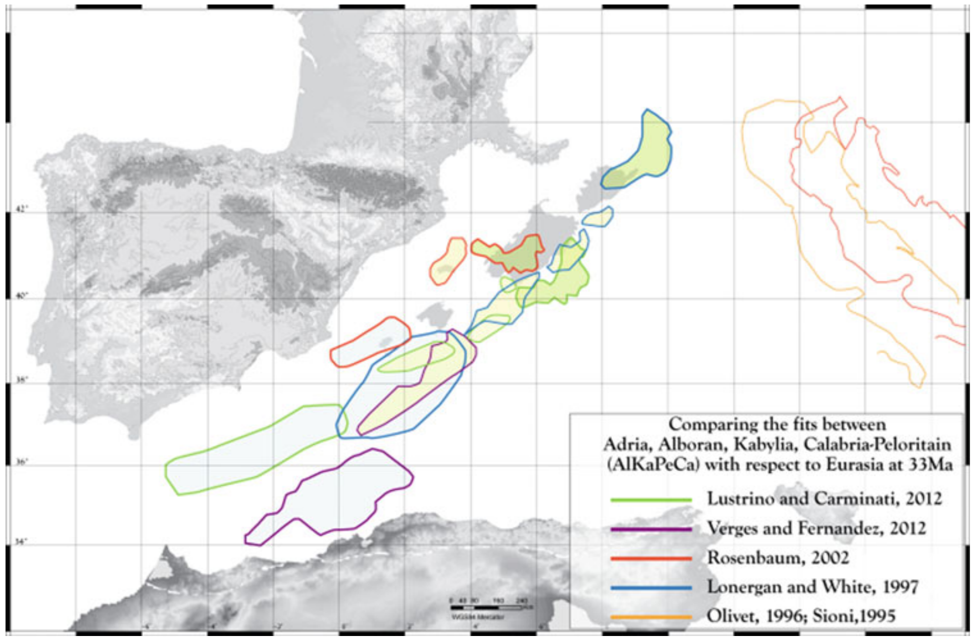

Fig. 2 Different positions of the AlKaPeKa blocks according to various author

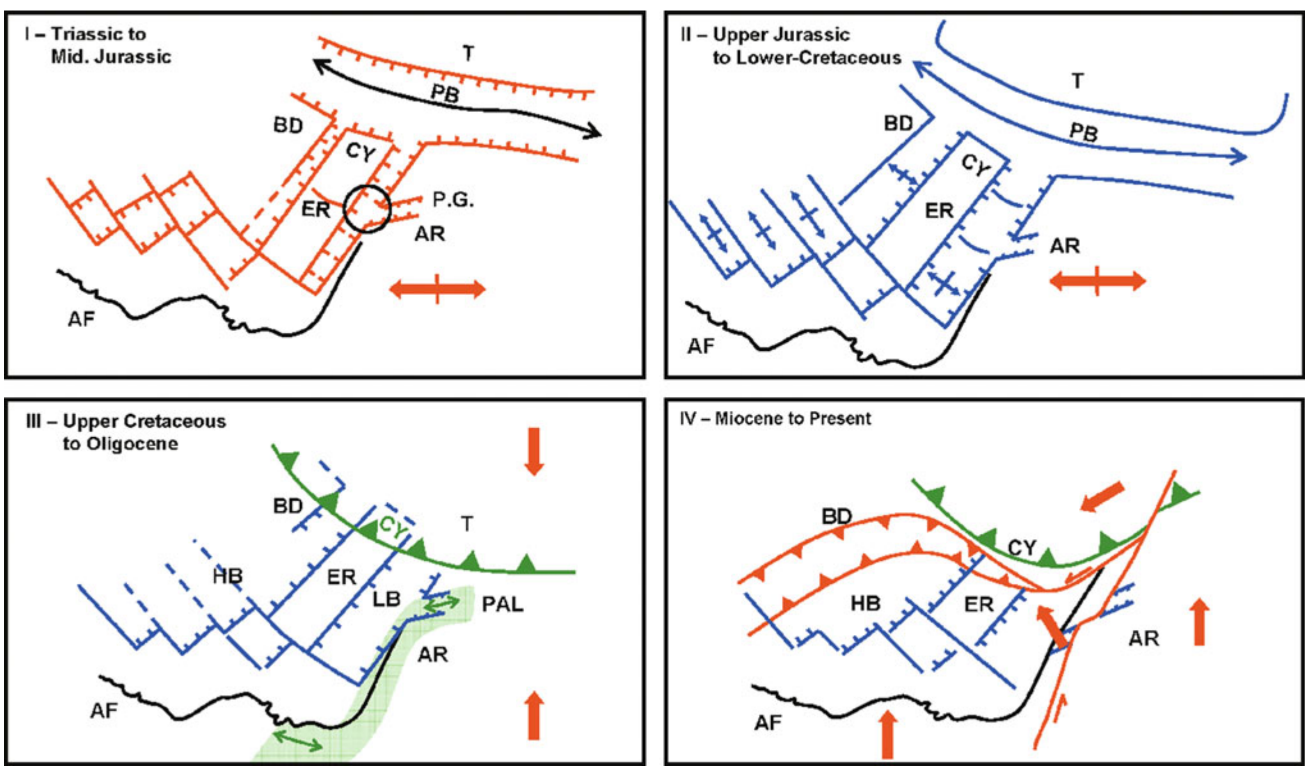

Fig. 3 Paleo-tectonic evolution of the Eastern Mediterranean from the Triassic (ER = Continental Block of Eratosthenes, CY = Cyprus, BD = Bey Daglari, HB = Herodot Basin, PB = Pamphyliein Basin, T = Taurus, AR = Arabia, AF = Africa: MR = Mediterranean Ride). (I) Rift from Triassic to Middle Jurassic. (II) Oceanic extension and accretion from the Upper Jurassic to the Cretaceous. (III) Upper Cretaceous: formation of the Cyprus Arc and its ophiolitic belt, subduction continues during the Paleogene. (IV) Miocene to the Present, activity of the Mediterranean Ridge, Latakia Ridge, and the transform fault of the Levant. According to Montadert et al. (2014)

the south. The northern basin would be rifted in Permian times from the Eratosthenes Block and followed by an oceanic N-S accretion, forming a sliding margin on its continental edge of north Levant (Galileo and Lebanese); the southern basin is derived from the NW migration of the Eratosthenes Block. Montadert et al. (2014) propose a paleo-tectonic scheme common to all basins in the Eastern Mediterranean, separated by transfer/transforming faults (Fig. 3).

Is the Levantine Basin rather a back-arc basin formed by the subduction of the Meso-Tethys (the Herodotus Basin) during the Senonian-Maastrichtian period (Segev and Rybakov 2010)? Has this extension been followed by a rift and accretion of oceanic crust (Frizon de Lamotte et al. 2011)? Active processes during rifting, such as crust thinning, exhumation of lower crust and/or upper mantle are poorly characterized, and the location of the ocean-continent transition in these basins also remains uncertain (Gardosh et al. 2010).

While the Levant Margin and Levantine Basin south of the Carmel Structure, the Eratosthenes Seamount, the Cypriot Arc and the Hecataeus Ridge have been the subject of several wide-angle seismic surveys, it is not the case of the Herodotus and North Levant basins, the Latakia Ridge and the Lebanese Margin. These structures identify areas where tectonic events are numerous and diverse, and structural boundaries are still poorly constrained.

4 Conclusions

We proposed to conduct two wide-angle and multi-channel reflection seismic surveys, which would allow determining the geometry, structure, and acoustic velocity of the different segments of the Algerian and Levantine basins, their bases and the underlying lithospheric mantle.

Characterizing the sequence of processes that lead from continental rifting to oceanic drifting during the genesis of passive margins is a key to our fundamental knowledge of the structure and history of the earth. Clarifying the nature and behavior of the first oceanic crust contributes to understanding the processes presently active at mid-oceanic ridges and transform faults. The respective role and behavior of the lower crust and upper mantle between rift and drift remain to be established.

Furthermore, the dynamic of the upper mantle is responsible for topography building, leading to consecutive erosion, subsidence and isostatic rebound, and is therefore connected to the quantification of global sedimentary mass transfer through time (Source to Sink). Finally, continental margins are the most populated and developed areas on earth. Deep Earth dynamics (topography, erosion, tectonics) are strongly related to naturals hazards such as earthquakes, slope instabilities, and tsunamis and mass transfers have important consequences on geo-resources and geothermal energy. The ability to read and understand the link between deep Earth dynamics and surface processes has therefore important societal impacts.

Thanks to these new cruises, this rather unique data set will cover most of the geological and geodynamical settings and hopefully establish the nature and geometry of the different segments, their limits and their connections, and to replace this new information in a geodynamic context in order to fully resolve the kinematic history of the Western and Eastern Mediterranean seas.

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