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A new tomographic-petrological model for the Ligurian-Provence back-arc basin (North-Western Mediterranean Sea)

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ABSTRACT

The nature of the crystalline basement of the Ligurian-Provence back-arc (LPB) basin is a matter debate as it remains unexplored by direct drilling methods. Several models have been proposed for the lower crustal structure comprising hyperextended continental crust or serpentinized mantle. In this paper, a new Vp-Vs geophysical dataset and corresponding tomography are used to propose a new petrological model for the LPB basin and for the formation of the crust of this back-arc domain. By crossing values of Vp, Vs and Vp/Vs ratios, the Messinian salt layer can be clearly identified down to 5 km depth, which highlights salt diapir structures into its overlying sedimentary cover. The 7.5 km depth corresponds to the transition with a heterogeneous basaltic oceanic crust about 4.5–5 km thick, intruded by rounded felsic gabbro plutons and underplated by a more mafic/ultramafic gabbro. This latter results from fractional crystallization of a hydrous magma inherited from the melting of a supra-subduction mantle which interacted with fluids originating from the subducting Adria slab. These magmas can be traced at the surface by magnetic anomalies punctuating the studied profile. Those new data and observations lead to conclude that the crust of the LPB basin resulted from a fast oceanic accretion during the opening of the back-arc. Its nature remains comparable to an immature oceanic crust with an overall basaltic and gabbroic composition and appears devoid of any serpentinized exhumed mantle.

1. Introduction

The precise description of the petrological nature of deep lithologies in oceanic domains is not straightforward it requires laboratory measurements (geochemical, rheological, petrophysical) on rocks extracted by drilling (e.g., Bonatti et al., 1990; Wilson et al., 2006; Larsen et al., 2018). Therefore, indirect geophysical methods designed to probe deep structures, such as seismic tomography, are needed (e.g., White et al., 1992; Grevemeyer et al., 2018). This is the case of the Ligurian-Provence basin (LPB) in the northwestern Mediterranean Sea where the crust still remains unexplored due to its thick sediment cover (5–8 km thick) (e.g., Gailler et al., 2009; Leprêtre et al., 2013).

Since the Late Cretaceous times, the geodynamic evolution of the western part of the Mediterranean domain has been controlled by the northward African plate motion relative to Europe (~1 cm/y, e.g., Macchiavelli et al., 2017; Rosenbaum et al., 2002). This movement has led to several compressive and collisional events between Europe and micro-plates as Adria and Iberia (Fig. 1). These events resulted into the formation of mountain ranges all around the western Mediterranean Sea: the Alps, Apennines, Pyrenees, Betics and Dinarides (e.g., Romagny et al., 2020; Van Hinsbergen et al., 2020; Angrand and Mouthereau, 2021). Part of this convergence was also associated with the opening of several back-arc basins as the LPB, the Tyrrhenian, the Algerian and the Alboran basins, formed in response of slab retreat processes (e.g., Jolivet and Faccenna, 2000; Jolivet and Faccenna, 2000). The characterization of the oldest one, the LPB, is complicated as it includes a thick sedimentary cover highlighted by seismic refraction and reflection, preventing any drilling down to the crust (e.g., Egger et al., 1988; Rollet et al., 2002; Dannowski et al., 2020). If the geological structure and the geodynamic of the basin have been well constrained (e.g., Chamot-Rooke et al., 1999; Séranne, 1999; Rollet et al., 2002), the petrological and lithological nature of the crustal basement is still debated and several hypotheses have been proposed: (1) a hyper extended margin that led to a very thin continental crust (e.g., Pascal et al., 1993;

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Dannowski et al., 2020); (2) a thin oceanic crust composed of tholeiitic volcanic rocks that cover directly the mantle, as it has been observed in several domains of the Tyrrhenian basin (e.g., Mascle and Rehault, 1990; Bonatti et al., 1990); (3) partly serpentinized peridotites of exhumed upper mantle, mostly devoid of volcanic crust (e.g., Gailler et al., 2009; Rollet et al., 2002; Moulin et al., 2015; Jolivet et al., 2020) also observed in the Tyrrhenian basin (e.g., Prada et al., 2014, 2015); (4) Lower crust partly intruded with magmatic material (Moulin et al., 2015).

Taking advantage of the availability of recent high-resolution Vp and Vs models (Dannowski et al., 2020; Nouibat et al., 2023), the purpose of the present paper is to further contribute in the description of the lithological and petrological nature of the crust beneath the oceanic domain of the LPB. Before the deployment of the Ocean-Bottom-Seismometers (OBS) (Fig. 2a) in the Ligurian Sea in 2017, the LPB was poorly described (e.g., Wolf et al., 2021; Nouibat et al., 2022a, 2022b). A unique opportunity is thus provided by the availability of these two new Vp and Vs seismological models to provide further insights into basin crust nature and structure. Indeed, the joint interpretation of Vp and Vs is crucial to discriminate the petrological nature of lithologies, since two lithologies of different petrological natures may have similar Vp and/or Vs signatures (e.g., Carlson and Miller, 1997; Christensen, 2004; Reynard, 2013; Grevemeyer et al., 2018; Malusà et al., 2021).

Thus, in this paper, we first describe the different geological layers and lithologies that compose the crust and the upper mantle of the LPB oceanic domain. Then, we discuss the significance of data within the LPB context for the evolution of western Mediterranean crust that finally allow us to propose a new petrological model for the LPB crust.

2. Geological setting of the Ligurian-Provence basin

The opening of the LPB was initiated 30 Ma ago by a rifting phase between European and Corsica-Sardinia domains, following the back-arc extension above the north-westward subduction of Adria micro-plate oceanic crust (e.g., Gattacceca et al., 2007; Jolivet and Faccenna, 2000). The progressive south-eastward roll-back and retreat of the Adria slab below the Corsica-Sardinia domain led to continental crust stretching followed by continental break-up during Early Miocene, and to the genesis of an oceanic crust domain between 20 and 15 Ma (Pascal et al., 1993; Contrucci et al., 2001; Rollet et al., 2002). As a result, the LPB comprises two conjugated thinned continental passive margins separated by an oceanic domain in its central part (Fig. 2a). The entire basin is characterized by magnetic anomalies interpreted as magmatic bodies identified from acoustic facies in seismic reflection profiles (Rollet et al., 2002). The area between margins and the oceanic domain corresponds to a transition zone likely made up of a very thin continental crust overlying a thick rift-related magmatic underplating corner (e.g., Séranne, 1999; Rollet et al., 2002). This limit is marked by an abrupt change in the amplitude of magnetic anomalies featured by the passage from mostly positive values in the deep (i.e., oceanic) basin, to negative values at the Continent-Ocean Transition and by a change in acoustic facies seen on seismic reflection data (e.g., Rehault et al., 1984; Rollet et al., 2002). The nature of magmatic bodies from sampled rocks occurring in the margins has been shown to have a tholeiitic nature, with a back-arc affinity as shown by a strong subduction component (e.g., Réhault et al., 2012 and references therein). However, the nature of magmatism observed in this oceanic domain could not be studied from direct petro-geochemical analyses unlike contexts where the crust is accessible by dragging or drilling (e.g., Falloon et al., 1992; Wilson et al.,

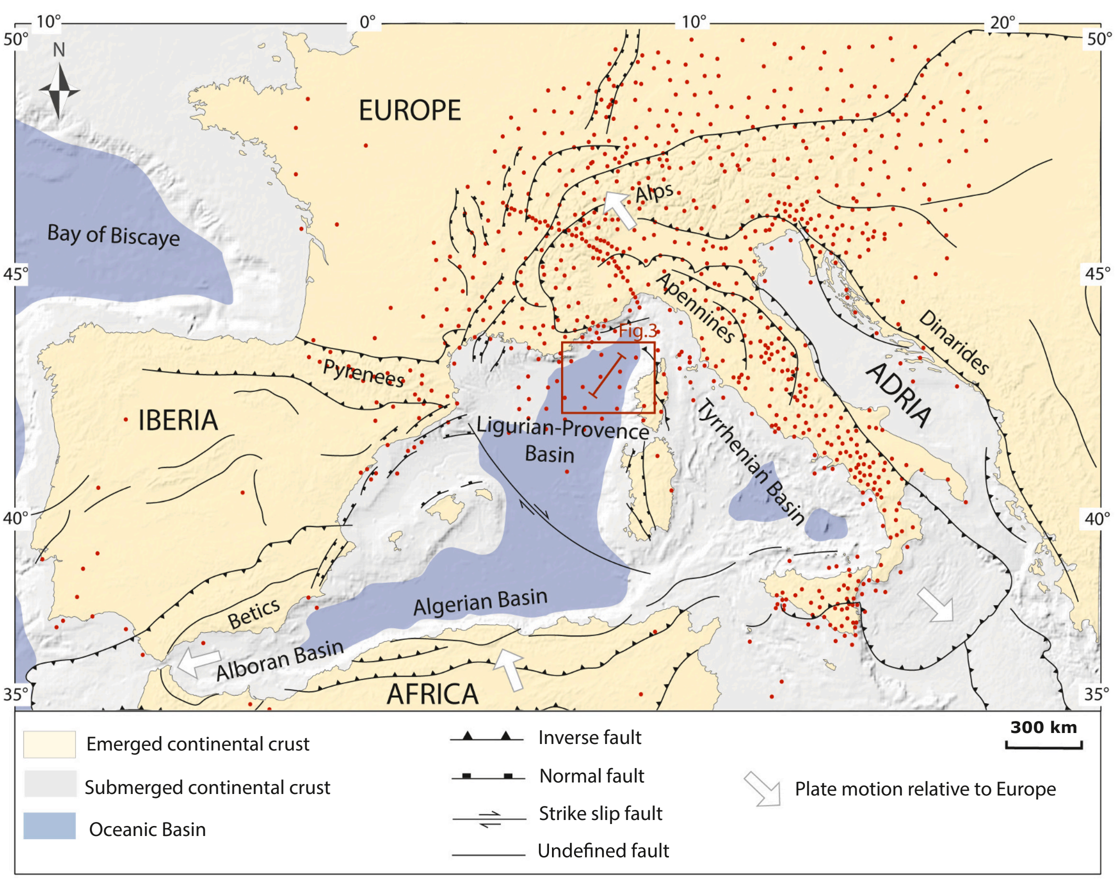

Fig. 1. : Geodynamic map of the western Mediterranean with location of study area (red frame). Geodynamic context from Jolivet et al. (2020) and Faccenna et al. (2004). Seismic stations from Nouibat et al. (2022a).

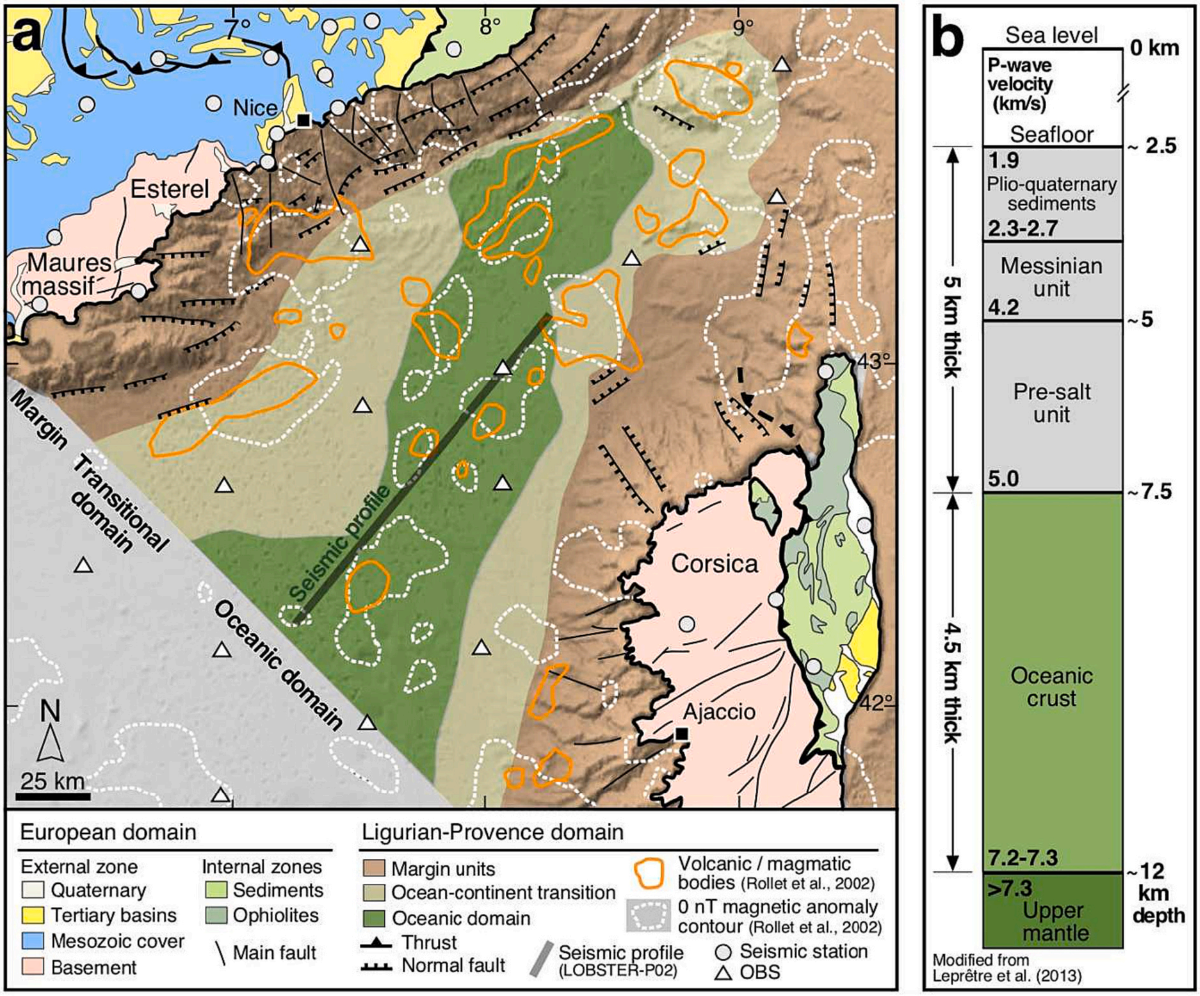

Fig. 2. a) Geological map of the Ligurian-Provencal basin modified from Nouibat et al. (2022a). Magnetic anomalies are taken from Rollet et al. (2002). (b) stratigraphic log showing P-wave velocities and thicknesses of geological units observed in Western Mediterranean basin (after Klingelhoefer et al., 2008; Gailler et al., 2008; Leprêtre et al., 2013; Dannowski et al., 2020).

2006) and is thus still debated.

A stratigraphic log representative of the Ligurian Basin has been built (Fig. 2b) based on units identified from combined wide angle and reflection seismic data (Klingelhoefer et al., 2008; Gailler et al., 2008; Leprêtre et al., 2013; Dannowski et al., 2020). These data reveal a sedimentary layer of 5 km average thickness and P-waves velocities ranging between 1.9 and 5 km/s. This layer is made up of Plio-Quaternary sediments, Messinian and pre-salt units. The Plio-Quaternary to Messinian unit transition is marked by a velocity of ~2.5 km/s. The Messinian sequence exhibits strong variations in thickness ascribed to salt diapirism and is separated from a pre-salt unit by the 4.2 km/s contour. Lower sediments overly an oceanic basement, marked by the 5 km/s contour. The crust is relatively thin and exhibits an average thickness of 4.5 km. Crustal P-wave velocities range from 5 to 7.2–7.3 km/s at ~12 km depth, which corresponds to the transition with the Upper Mantle (Vp > 7.3 km/s). Although these data allow to constrain the thicknesses of main layers and location of major interfaces (intra-sedimentary, sediment-crust and Moho), they only rely on P-waves velocities. Consequently, in the absence of available S-wave velocities, they did not allow to reliably constrain the petrological nature of crust, which remains a matter of debate as a typical or atypical oceanic crust with the presence of domains of exhumed serpentinized mantle (Rollet et al., 2002; Klingelhoefer et al., 2008; Gailler et al., 2008; Leprêtre et al., 2013) or as a hyperextended continental crust (Dannowski et al., 2020).

3. Seismic cross section of the central oceanic domain

The 3D Vs model by Nouibat et al. (2023) covers the Ligurian-Provence basin and goes down to 100 km depth. This model has been derived using wave-equation tomography of ambient noise data recorded by the OBSs of the AlpArray temporary network (Hetényi et al., 2018) and land stations from European permanent networks available in the period 2015–2019 (Nouibat et al., 2023 and reference therein) (Fig. 1). This model is an improved version of the Nouibat et al. (2022b) model and this is the most consistent available Vs model of the LPB since it accounts for the 3D effects of the water layer on the wave propagation of ambient-noise surface waves. Indeed, Nouibat et al. (2023) have considered the 3D fluid/solid coupling in the Ligurian sea for their wave equation tomography. The Vp model by Dannowski et al. (2020) has been derived using high-resolution P-wave travel time tomography of active-seismic refraction data recorded by OBSs and ocean-bottom hydrophones (OBHs) along a 127.5 km profile in the axis of LPB (LOBTSER-P02; Fig. 2). This model goes down to ~15 km as a maximum depth, with a high-resolution coverage of the crust at the illuminated part of the uppermost mantle. Additionally, we use the probabilistic model of Nouibat et al. (2022b) to estimate depths and geometries of limits between geological layers. This model is obtained by 1D Bayesian inversion in depth that allow to estimate the probability to have lithological interfaces at each location and each depth. Those interfaces probabilities cannot be estimated with the model of Nouibat et al.

(2023) as the inversion method used is not the same.

This discussion focuses on the portion of LPB following the LOBTSER-P02 profile where Vp is defined. Figs. 3a-b show the 2D cross-sections of the probability of interfaces and Vs computed along the same profile, and the Vp section from Dannowski et al., 2020. We are aware that these Vp and Vs models have different resolutions and different sensitivities as they are obtained from different datasets, with different imaging techniques. In both imaging techniques, uncertainties are not well constrained as they are not processed during inversions. For this reason, we cannot give estimates. However, we do have an estimate of the lateral and vertical resolutions of the two models: ~ 5 to 10 km laterally / ~ 1 to 3 km vertically for the Vs model (Nouibat et al., 2023), and ~ 2.5 to 5 km laterally / ~ 0.5 to 1.5 km vertically for Vp (Dannowski et al., 2020). The Vs model is smoother since it is derived from surface waves. However, it remains pertinent in recovering first-order 3D velocity structures of the crust given the high-sensitivity of ambient-noise surface waves to the 3D lateral variations (e.g., Shapiro et al., 2005; Stehly et al., 2009; Molinari et al., 2015). For the above-mentioned point, the interpretation of the crust petrological nature and its different lithologies, relies on joint point-by-point division of the two models, Vs and Vp absolute values and comparisons with Vp and Vs ranges of different rock type fiels deduced from Grevemeyer et al. (2018) study. Then a Vp/Vs ratio imaging of the section is used to illustrate our results.

This method allows us to identify four main layers presented above (Fig. 3):

(1) The deepest interface probability, located at 12 km marks the crust-mantle transition and matches the depth of the velocity contour with Vs = 4.1 km/s and Vp = 7.2 km/s. Those values correspond to an oceanic crust as defined by Grevemeyer et al. (2018) from Vp and Vs acquisition along off-axis profiles of older oceanic lithosphere at Mid-Cayman Spreading Centre.

(2) The intermediate interface occurs near 7.5 km depth, which coincides quite well with the velocity contour Vs = 3.2 km/s and corresponds to a Vp contour of 4–4.1 km/s. This contour is also observed with multichannel seismic data (MCS) and defined as a crystalline basement (Dannowski et al. (2020). Thus, it can be considered as the sediment-oceanic crust transition.

(3) A shallower and relatively pronounced interface, with rather high interface probabilities, occurs at about 5 km depth. This interface is in good correspondence with the depth of the velocity contour Vs = 2.3 km/s and Vp = 4.2 km/s. Theses values are coherent with salt velocities from Yan et al. (2016). Moreover, through MCS data, Dannowski et al. (2020) interpreted a salt layer with diapiric structues between 4 and 6 km. The same interpretation is proposed by Contrucci et al. (2001) in our study area with a diapir layer base at a depth of 5.7 km and thikness around 1.7 km. Those observations are coherent with our data.

(4) In the Vp section, toward the base of oceanic crust on both sides of transect, we note the presence of discontinuous domains with high velocity anomalies (Vp = 6–7.2 km/s, in green on Fig. 3c) with respect to the rest of the oceanic crust, which exhibit a weaker Vp gradient at the Moho. These anomalies correspond to Vs between 4 and 4.4 km/s.

These first order observations allow defining a first layer of Messinian salt deposit of about 2.5 km exhibiting significant variations in thickness (locally up to 5 km), then a sediment layer of about 2.5 km (between 5 and 7.5 km) and finally between sediments and the mantle,

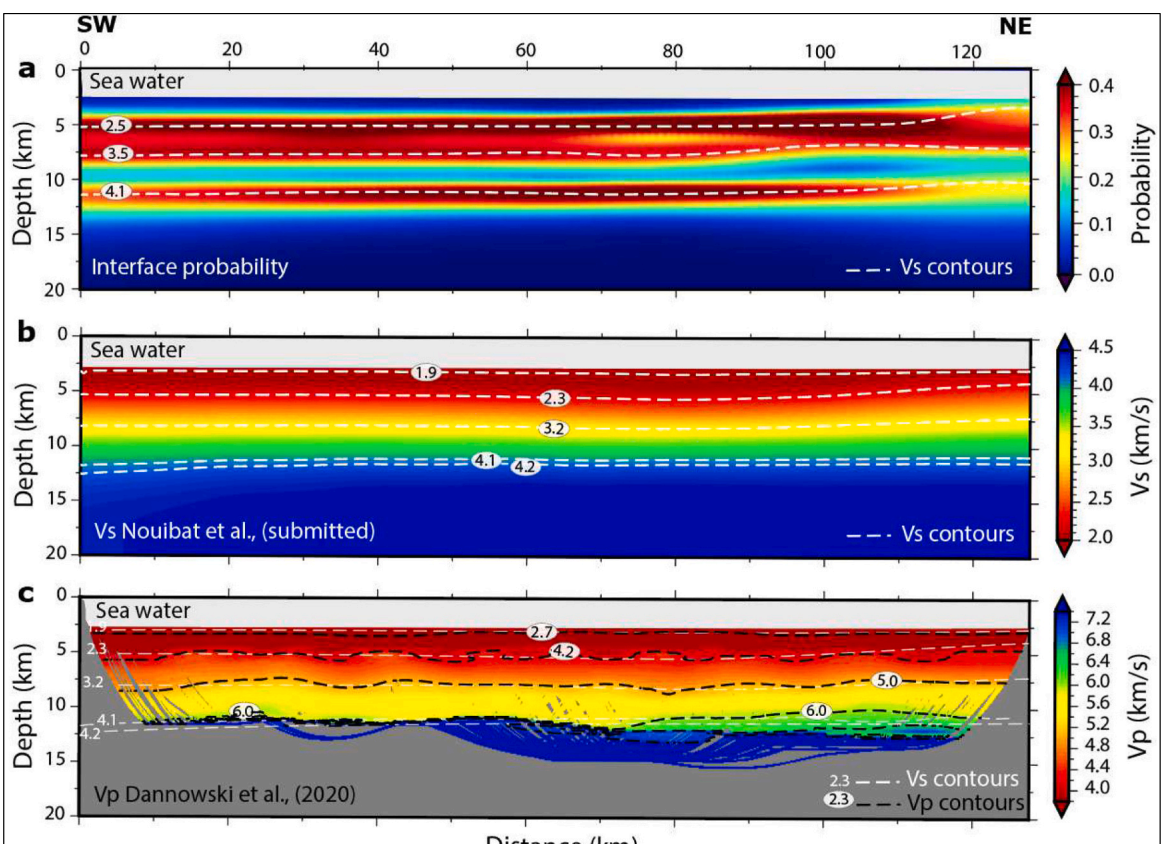

Fig. 3. Depth sections along the LOBSTER-P02 transect (location in Fig. 2); (a) Posterior probability densities of presence of a layer obtained from the Bayesian inversion. White dashed lines indicate Vs contours from (b). (b) Shear wave velocities from our final model. (c) P-wave velocities from Dannowski et al. (2020). Black dashed lines indicate Vp contours and white dashed lines as in (a).

an oceanic crust with a thickness ranging from 4.5 to 5 km (between 7.5 and 12 km depth). The mantle could also be considered in the model as a layer with Vp higher than 7.2 km/s and Vs higher than 4.1 km/s.

4. Insights for the petrological nature of the oceanic domain

In this section, we further discuss the petrological nature of the crust and upper mantle of the LPB (Fig. 4). This discussion is based on the seismic data (Vp, Vs) available along a reference cross section in the oceanic LPB domain (Dannowski et al., 2020; Nouibat et al., 2023). These data are discussed in the light of the Vp vs Vs diagram which defined different lithology filed for the oceanic crust (Grevemeyer et al., 2018). These fields are deduced from studies using different seismic profiles crossing the well-known Mid-Cayman Spreading Centre, where the estimated RMS error ranges from ~0.02 km/s to ~0.5 km/s on the Vp and Vs data of one of the seismic line used, and with RMS error roughly ranging from 0.005 to 0.17 on the Vp/Vs ratio along the same profile (P05 in Grevemeyer et al., 2018). We first note that the oceanic crust is dominated by rocks with a seismic signature of basalts with low hydrothermal alteration. This is confirmed by the value of Vp/Vs ratio ranging from 1.5 to 1.6 km/s (Fig. 4c). Thus, we suggest that the oceanic crust is mainly formed by basaltic lava flows (BLF) (Fig. 4a, b). At both section extremities, we identified bodies with distinct Vp values (Fig. 4c). These bodies exhibit the same Vp/Vs ratio as the crust, but absolute value data from Vs and Vp are largely higher. These values correspond to those of gabbros with a crustal affinity (IGc) due to their position at the transition between basalt and gabbro fields (Fig. 4a).

The mantle also exhibits a heterogeneous seismic signature. In the area where the Vp/Vs ratio range between 1.7 and 1.9, these values are similar to an anhydrous peridotite mantle (M in Fig. 4a). Further, an elongate shape domain with values at the upper boundary of gabbros ("mantle affinity" gabbroic bodies or IGm), with higher Vp/Vs ratio than IGc is also observed (Fig. 4b). The difference between IGc and IGm can be explained by fractional crystallization of a hydrous magma formed in the back-arc with a strong metasomatic influence from the subducting slab. Such magmas show a differentiation during fractional crystallization in hydrous conditions leading to a first phase of crystallization of olivine and pyroxene instead of plagioclase (e.g., Gaetani et al., 1994; Arai and Dunn, 2014). This can form IGm plutonic bodies with a mafic/ultramafic composition resulting in olivine and pyroxene accumulation at the base of the pluton (olivine-rich cumulate layer in Fig. 4b; e.g., Müntener et al., 2001; Arai and Dunn, 2014). As a result of this first

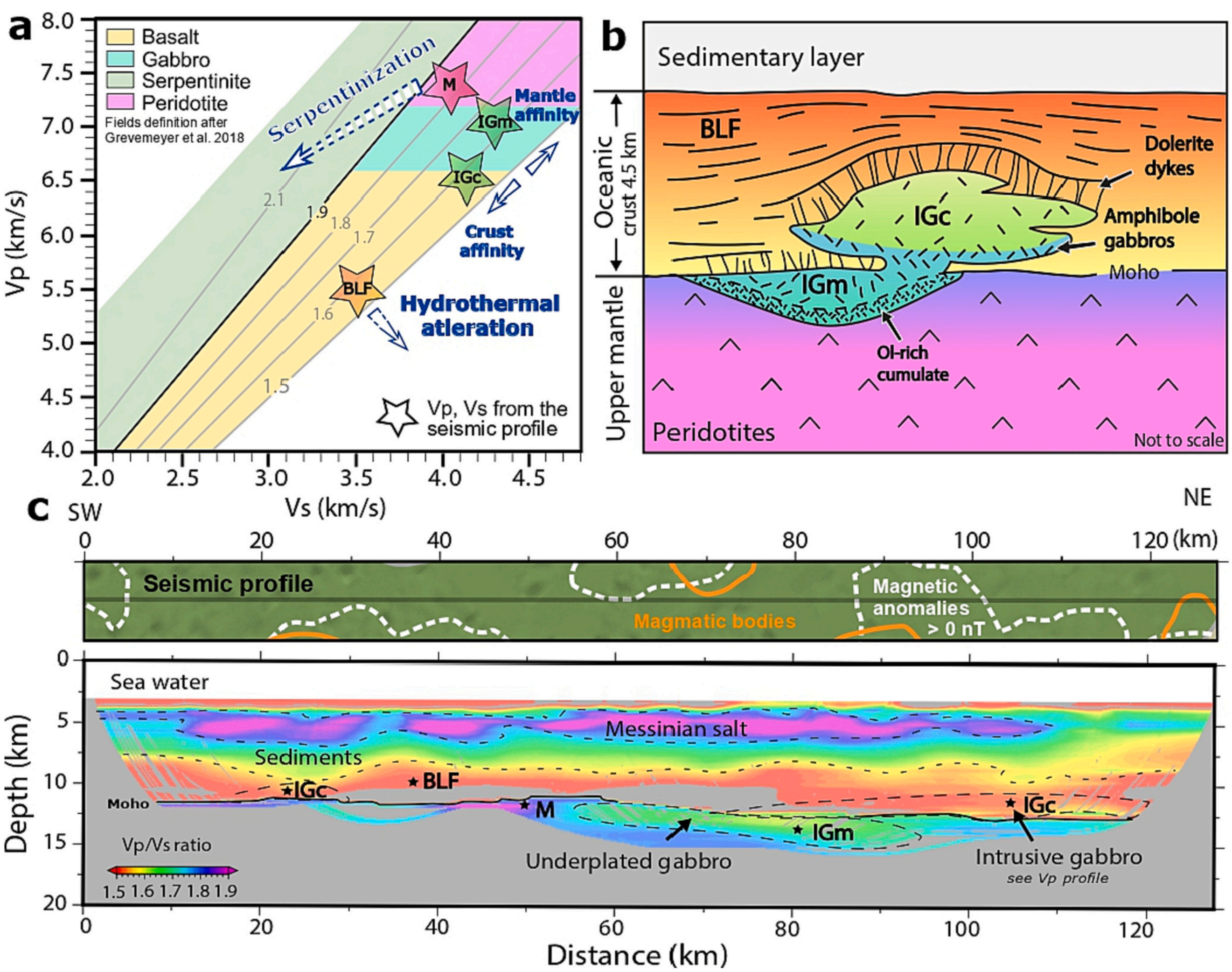

Fig. 4. Vp/Vs diagram modified from Grevemeyer et al. (2018). Stars represent domains where signals in Vp, Vs and Vp/Vs ratio are observed for each lithology. BFL: Basaltic Lava Flows; IGc; igneous gabbro with a crustal affinity; IGm: igneous gabbro with a mantle affinity; M: upper mantle. Blue arrows present possible evolution of the lithology. (b) Schematic interpretation based on results from (a). (c) Magnetic anomalies of LOBSTER-P02 transect from Rollet et al., 2002 (location Fig. 2) superimposed to the Vp/Vs ratio. Grey domains into the crust represent velocity values below 1.49, which are not coherent with crustal values. This local incoherence could result from discrepancies between the two different models with distinct resolutions. Black dashed lines represent possible contacts between lithologies. Back stars represent the lithologies defined in the diagram (a) above.

differentiation phase in the pluton upper part, the fractional crystallization leads to a marked “crustal affinity” (IGc) of the gabbroic pluton that can present amphibole cumulates instead of pyroxene (e.g., Müntener et al., 2001; Claeson and Meurer, 2004). These gabbroic bodies are located at the base of the crust and are interpreted as having a more felsic (plagioclase-rich) mineralogical composition (e.g., Nicholls and Ringwood, 1973; Arai and Dunn, 2014). Their formation could be associated with dolerite dykes and sills located at the upper part of the gabbroic pluton, and may correspond to the central emission of the BLFs as is commonly observed in relatively immature-spreading ridges (Fig. 4b) (e.g., Saunders et al., 1982; Janoušek et al., 2014; Terrinha et al., 2018). This kind of magmatism is consistent with the back-arc volcanism observed in both margins with dolerite dykes of K-calc-alkaline basalts formed during Miocene times in Corsica and Sardinia and alkaline basalts found in Southern France (Toulon area; Réhault et al., 2012 and references therein). Further, several magnetic anomalies have been described in the LPB (Rollet et al., 2002). Their superimposition with volcanic/magmatic bodies localisation determined by seismic facies allowed Rollet et al. (2002) to propose a correlation between both anomalies and volcanic/magmatic bodies. After superimposition of our seismic Vs/Vp transect on the magnetic map of Rollet et al. (2002), we suggest that in our domain, magnetic anomalies could correspond to gabbroic bodies as they appear to be correlated with their emplacement in the geophysical tomography (Fig. 4c). This observation could appear counter-intuitive with an oceanic crust interpretation because gabbros generally present a lower magnetisation than basalts. Further, in our case, there are no linear magnetic anomalies in the BLF as it is normally seen in a mature oceanic crust (Bayer et al., 1973; Sandwell et al., 1995; Rollet et al., 2002). However, we explain this peculiar magnetic signal of oceanic crust as (i) due to the fluid-rich fractionation of the gabbros producing crystallization of large amounts of magnetite and thus to a higher magnetic signal (e.g., Claeson and Meurer, 2004). Furthermore (ii), the lack of linear anomalies in BLFs suggests a rather immature stage of ridge magmatism with a rather radial dispersion of lavas emitted from IGc bodies, and possible slight alteration of the lavas, especially during the Messinian phase, which may have altered the magnetic minerals and led to a demagnetization of basalts. Moreover, recent studies show that even in a mature oceanic crust, magnetisation of gabbro layers cannot be ignored with an impact to the magnetic anomalies of up to 10%–30% (Hu et al., 2023). It means that magnetic anomalies seen in the LPB could have a gabbroic origin instead of a serpentinite one, as it has been discussed previously (e.g., Gailler et al., 2009; Moulin et al., 2015; Jolivet et al., 2020). Moreover, our seismic observations show no evidence of any serpentinized mantle, which would rather show Vp/Vs ratios higher than 1.9 (Fig. 4a). In the same way, no hydration of the crust is observed, as its Vp/Vs ratio is higher than 1.5. Finally, the presence of a minimum 4.5 km basaltic crust thickness excludes the hypothesis of a hyperextended continental crust basement (Dannowski et al., 2020) for the Ligurian-Provence central domain.

Here, we propose a new petrological model for the LPB crust (Fig. 4b) for a transect of the central part of the LPB where Vp and Vs are available, which is ideally chosen to decipher the structure of the oceanic crust far from the ‘transition zones’ to the continental crust. This petrological model shows:

(1) a relatively thin (4.5 km) oceanic crust formed by basaltic lava flows, cross-cut by bodies of intrusive gabbros emplaced at different levels: (i) below the base of the crust as large underplated mafic/utlramafic gabbroic bodies, (ii) within the lower part of the BLF crust as more felsic gabbroic bodies (IGc).
(2) The underlying mantle appears devoid of any serpentinization, indicating that is has never undergone significant hydrothermal alteration and was therefore never exposed to the seafloor surface. This observation is coherent with the geodynamic context, as the Ligurian-Provence basin appears to have formed at relatively fast accretion, associated with a back-arc extension rate estimated superior to 3 cm/yr (Faccenna et al., 1997; Séranne, 1999; Chamot-Rooke et al., 1999).

More evolved back-arc basins as the Grenada basin present the same kind of crust as the LPB with a 6–8 km thick basaltic crust superimposed on a mantle devoid of any serpentinization (Allen, 2021; Padron et al., 2021). In the same way, the Lau back-arc basin (Pacific Ocean) shows a similar order of basaltic crust thickness, and is also featured by intrusive felsic gabbroic bodies and underplated mafic gabbroic bodies that support our observation in the LPB (Arai and Dunn, 2014). Thus, as exemplified in this study, the Vp/Vs ratio allows to better constrain the nature of the crust, including some specific petrological features in magmatic rocks and the morphology of sediment strata like the Messinian salt. This latter appears to have a typical diapiric shape, with a variable depth of the layer base, between 6.5 and 5 km, and a variable thickness about 0.5 and 2 km resulting from diapirism, as it has been observed in seismic reflection data by Contrucci et al. (2001) and Dannowski et al., 2020.

5. Conclusion

Geophysical data with Vp, Vs and Vp/Vs ratios allows an accurate imaging of the Ligurian-Provence back-arc basin, and a precise localisation of geological interfaces. Based on these data, an improved petrological model of the back-arc crust is proposed. Our model suggests a heterogeneous crust with thick sedimentary layers in which a diapiric salty interface can be observed very precisely at 5 km depth. Then, the oceanic crust is emphasized by relatively thick, 4.5–5 km, basaltic crust comprised of slightly altered lava flows. This crust is punctuated by rounded intrusive felsic gabbroic bodies rooting down into the Moho and some underplated more mafic cumulative gabbros below the Moho. These melts were formed by the fractional crystallization of hydrous magmas which originated from the subducting slab, resulting in the fractionation of magnetite and amphibole. The geophysical signature of the mantle is similar to that of anhydrous peridotites. This oceanic crust structure is thought to represent an immature oceanic ridge, interpreted as resulting from a fast opening of the Ligurian back-arc basin. For these reasons, the Ligurian-Provence basin is devoid of any serpentinized mantle, as it was never exhumed and exposed at sea floor level.

CRediT authorship contribution statement

L. Boschetti: Writing – original draft. **S. Schwartz:** Writing – review & editing, Validation, Supervision. **Y. Rolland:** Writing – review & editing, Validation, Supervision. **T. Dumont:** Visualization, Validation. **A. Nouibat:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Schwartz reports administrative support was provided by ISTerre.

Data availability

Data will be made available on request.

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