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Structural and sedimentary origin of the Gargano - Pelagosa gateway and impact on sedimentary evolution during the Messinian Salinity Crisis

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Abstract :

Circulation of water masses, sediment, and biotope between the sub-basins of the Mediterranean Sea strongly depends on morphological oceanic gateways. These geological features react to geodynamic reorganisation through volcanism, vertical movements, and/or the segmentation of sedimentary basins. Despite the palaeogeographic relevance of straits and oceanic-gateways, their evolution and impact on sedimentary transports and deposition in the Mediterranean remain in general poorly constrained. The Gargano-Pelagosa gateway is here first recognized as an influential element of the palaeogeographic/environmental evolution of the central-southern Apenninic foredeep and wedge-top domains during the Messinian, as shown by the integration of (i) seismic lines, (ii) well information from the Adriatic Sea, and (iii) a review of both onshore and offshore structural data and Messinian depositional environments. A palinspastic evolution is proposed for the Apennine and south Adriatic foredeeps during the Messinian Salinity Crisis (MSC: 5.97–5.33 Ma). We highlight the implication of the pre-MSC structural legacy and the development of the Apennine and Dinarid-Albanian chains in 1) the isolation of the Apennine foredeep from the deep central Mediterranean domains at the peak of the MSC; 2) the vertical movements at the Gargano-Pelagosa structure and the Apulian Platform and 3) their implication in the deposition of a chaotic sedimentary body.

Keywords : Mediterranean Sea, Segmented basin, Marine pathways, Messinian Salinity Crisis, Palaeogeographic and Palinspastic, reconstruction

Introduction

The paleocurrents, and therefore the evolution of the paleoclimate but also of the dispersal of sediments and their deposition, is strongly linked to the presence and evolution of straits which can act as open passages (oceanic gateways) or barriers (Straume *et al.*, 2020). In the Mediterranean Sea, the present-day physiographic map shows a strong segmentation with several major oceanic gateways (i.e. the Gibraltar, Sicilian, Aegean straits) and secondary oceanic gateways (Figure 1). As circulation of water masses, sediment, and biotope between the sub-basins of the Mediterranean Sea strongly depends on these morphological oceanic-gateways, their evolution is of primary importance to understand the morphological and sedimentary evolution of the different basins (e.g. Leever *et al.*, 2010; Flecker *et al.*, 2015; Palcu *et al.*, 2017; Suc *et al.*, 2015; Balázs *et al.*, 2017, Pellen et a., 2017; Amadori *et al.*, 2018; Camerlenghi *et al.*, 2020). This is particulary critical in the case of large relative sea-level variations, such as during the MSC (5.97–5.33Ma) (Manzi *et al.*, 2013) when huge amount of gypsum was only deposited along the Apennine Foreland (Manzi *et al.*, 2020), and a understanding approach of the Mediterranean Sea needs very detailled local studies, such as for the Betic, Rifain, Balkan or Iron Gate gateways (Figure 1; Betzler *et al.*, 2006; Krijgsman *et al.*, 2006; Suc *et al.*, 2011, 2015; Do Couto *et al.*, 2016).

The Gargano-Pelagosa gateway, located on the Adria plate and separating the central and the south Adriatic basins, perfectly displays the relationship between the inherited sedimentary structure (e.g. Argnani, 2013), vertical tectonic motion and sea-level variation, and their impacts on water mass exchange during the Neogene. To understand the relationship between each process, we focus on the connection between the Adriatic foredeep, the South Adriatic Basin (SAB) and the deep Ionian Sea (through the former Lagonegro Basin) during the Messinian Salinity Crisis (MSC: 5.97-5.33 Ma) taking account of the pre-MSC inherited sedimentary and/or tectonic features.

In this study, we describe the segmentation and tectonic history of each domain surrounding the Gargano-Pelagosa gateway by compiling the onshore and offshore structural and sedimentary features. These observations are completed by the compilation of borehole data and seismic profiles between the Central Adriatic Basin (CAB) and the South Adriatic Basin (SAB).

This set of data allowed us to re-evaluate the relationships of MSC environment history with the structural heritage and to present palinspastic and environmental reconstructions for the Messinian period.

Regional setting

1. Early history of the Adria plate

The present-day structure of the central Mediterranean area and the Adria plate results from the interaction between the African, European, Iberic and Adria plates since the breakup of the mega-continent Pangea (for a review, see Cavazza *et al.*, 2004).

Mesozoic palaeogeographic reconstructions suggest two main sub-orthogonal extensional directions associated with the development of Neotethysian oceanic domains: NW-SE and NE-SW (Ciarapica and Passeri, 2002; in Vezzani et al, 2010; Stampfli and Hochard, 2009). Associated to these orientations several present-day NW-SE oriented carbonate platform and basin systems have been identified (Figure 2; Zappaterra, 1994; Wrigley *et al.*, 2015; Vezzani *et al.*, 2010). The present-day situation and stratigraphic evolution of each platform and basin-slope/deep-basin systems developed during Mesozoic and Cenozoic time is presented in figures 2 and 3. Even if the nature, age and orientation of the Ionian Sea remain a subject of debate (see Dercourt, 1972; Channell *et al.*, 1980; Mele, 2001; Panza *et al.*, 2003; Vezzani *et al.*, 2010; Roure *et al.*, 2012; Carminati *et al.*, 2012; Dellong *et al.*, 2018; van Hinsbergen *et al.*, 2020), northward extension have been associated to this domain such as the south Adriatic Sea or the deformed Mesozoic Sannio-Molise and Lagonegro basins.

2. A multi-segmented peri-Adriatic domain

The eastern border of the Adria plate is associated to the Dinarid and Albanid-Hellenid fold-and-thrust belts (Figure 2). The Scutari-Pec lineament separates the two fold-and-thrust belts and is interpreted as a major dextral polyphasic transform fault system (Figure 2; Chorowicz *et al.*, 1981; Grubic and Marovic, 1991) developed during Cretaceous and Cenozoic time. The Dinarid chains was mainly formed during Eocene – Oligocene time and incorporates large parts of the Adriatic-Dinaric platform systems (e.g. Schmid *et al.*, 2008; Stampfli and Hochard, 2009; Korbar, 2009; Handy *et al.*, 2010; van Hinsbergen *et al.*, 2020). The Albanid-Hellenid chain underwent two supplementary tectonic and exhumation stages - from the Middle-Late Miocene until the present-day (Kilias *et al.*, 2001; Frasheri *et al.*, 2009; Pashko and Aliaj, 2020). During the Neogene, two subsidence phases are recorded leading to the formation of the South Adriatic foredeep domain, the first in the Middle Miocene-Tortonian (Pannonian-Tortonian stage), and the second in the Late Miocene-Pliocene (Pontian s.l.). The two phases are separated by a short compressive phase at the Late Miocene (Pashko and Aliaj, 2020). At the scale of the Albanid-Hellenide chain, the system would be affected by several phases of counterclockwise rotations, and estimated at 40°ccw between 15-13 and 8 Ma and 10°ccw in the Late Miocene-Pliocene (van Hinsbergen *et al.*, 2005; Frasheri *et al.*, 2009).

On the western border the Apennine system is part of a wide peri-Mediterranean orogenic system developed from late Oligocene to present, associated with the counter-clockwise rotation of the Corsica-Sardinia blocks during the Early Miocene, and Tyrrhenian Basin opening since Middle-Late Miocene (e.g. Ricci Lucchi, 1986; Boccaletti *et al.*, 1990). Figure 3 summarize the deformation stage associated to each Mesozoic palaeogeographic domain now involved in the Central and South Apennine Chain, Several tectonic phases are reported, each one implying the folding and imbrication of the cover succession detached toward the foreland, and the progressive involvement of younger and easternmost fore-deep basins (Casero, 2004; Ghielmi *et al.*, 2010; Vezzani *et al.*, 2010; Artoni, 2013) (Figures 2 and 3).

The Central Apennines are delimited to the south by the Anzio-Ancona (A.A.) and Maiella-Roccamonfina (M.R.) lineaments (Figure 2). The Central Apennine chain accreted the Mesozoic Tuscany and Umbria-Marche pelagic domains (Figures 2 and 3 - Vezzani *et al.*, 2010; Fantoni and Franciosi, 2010). Several Neogene tectonic phases are recorded along the Apennine and are associated to the development of several foreland basins (see Figure 3 and Ghielmi *et al.*, 2010; Vezzani *et al.*, 2010 for further information), which were gradually cannibalized by the Apennine chain.

The Southern Apennine Chain is delimited by the Anzio-Ancona lineament (A.A.) to the north and the Calabria block to the south (Figures 2). The Neogene stratigraphy has been widely studied (see Vezzani *et al.*, 2010; Ascione *et al.*, 2012; Vitale and Ciarcia, 2013 for further detail) and related palaeoenvironmental domains have been associated with the inherited Mesozoic domains (Vezzani *et al.*, 2010; Figure 3). The first signs of Neogene deformation along the Apennine platforms are dated to post-Burdigalian-Langhian (Figure 3). From late Tortonian-early Messinian, the whole tectonic wedge, including the Apennine Platform, overthrust the Sannio-Molise and Lagonegro basins (Cippitelli, 2007; Vitale and Ciarcia, 2013). This new tectonic phase implies the development of fore-deep successions along the Lagonegro basin, until the late Messinian (Figure 3).

Since late Messinian several thrust fronts are activated along the south and central Apennine fold-and-thrust belt led to the progressive incorporation of the Messinian foredeep (including the Messinian Laga Basin) into the belt and marked the initiation of a late Messinian-early Pliocene foredeeps (Figure 3; Milli *et al.*, 2007; Vezzani *et al.*, 2010; Artoni, 2013).

3. Structural features affecting the Gargano-Pelagosa gateway

Several structural features affect the Gargano Peninsula and Palagruža Island (Figure 2), which mark the boundary between the south (SAB) and central (CAB) Adriatic basins. The Gargano Peninsula is part of the Apulian foreland, the most uplifted portion of a wide NW-SE trending flexural antiform influenced by both the SW-verging Dinaric-Hellenic and NE-verging Southern Apennine orogens (Moretti and Royden, 1987; Argnani *et al.*, 1993; Hairabian *et al.*, 2015). Around the Gargano Peninsula at least three main structural features have been described, but their relationship remains debated:

- **The Mid Adriatic Ridge (MAR),** developed along a general NW-SE axis, at the interface of the Apennine and Dinarid deformation fronts (Figure 2) (Finetti, 1982; Argnani and Gamberi, 1995). It consists of an array of structural highs, 10-40 km wavelength anticlinal structures and Triassic salt diapirism structures (Casero and Bigi, 2012). Sub-basins comprised between salt structures observe Triassic to Miocene sedimentary layers and highlight the salt diapir growth phase through time (Festa *et al.*, 2013).
- The SW-NE oriented **Tremiti Ridge** located north of the Apulian Platform and is defined by Triassic salt diapirism (Figure 2). A Late Miocene deformation period have been identified along this structural feature (e.g. Festa *et al.*, 2013), but not excluding earlier phases during Cenozoic and Mesozoic. Sedimentary hiatus on top of the Tremiti ridge suggest repeated emersion during Paleocene, Oligocene, and Messinian times (Andriani *et al.*, 2005).
- **The Mattinata Fault System** (MFS) is observed both on land and at sea (e.g. Argnani *et al.*, 2009; Billi *et al.*, 2007; Figure 2). The offshore Mesozoic and Tertiary succession defines a series of E-W to NE-SW trending anticlines. Secondary anticlinal axes, oriented NW-SE, are located south of the Mattinata system and connect further north to the main system. The system extends onshore within the Gargano Peninsula promontory and delimits two former Mesozoic shallow and deep environment domains by a NW-SE axis faulted system: the western part is

associated to Mesozoic carbonate platform deposit of the Apulian Platform and the eastern part to slope-deep Mesozoic carbonate deposit. Several tectonic reactivations and strike-slip motions linked to regional and tectonic phases are documented (Morelli, 2002; Argnani *et al.*, 2009).

The relationship between the MAR, the Tremiti Ridge and the MFS remains uncertain, as well as the importance of these features in a wider geodynamic framework or the possible involvement of the Hercynian basement (Fantoni and Franciosi, 2008, 2010). These structures have been interpreted as a micro-plate boundary linked to reorganisation of forces at the limits of the Adria microplates (Scisciani and Calamita, 2009), or as an eastward verging fault system delimiting the external Apennine deformation front (Bally *et al.*, 1986; Ori *et al.*, 1991; De Alteriis, 1995; Scrocca, 2006; Casero and Bigi, 2012) and connected to the Apennine front through the Tremiti Ridge (Funiciello *et al.*, 1991; Festa *et al.*, 2013). Crustal thickness modeling's suggest a thinner continental crust (~30 km) at the CAB-SAB transition (Ritzwoller *et al.*, 2007), as well as a shallower Moho depth from the CAB to the SAB (Moho rise from 30 to 20 km; Riguzzi and Doglioni, 2020). No sharp discontinuities are highlighted by tomographic modelling, but this does not invalidate the possibility of deep crustal structures or geodynamic hinge line as observed by geophysical data in the Liguria-Provence or Valencia basins (e.g. Afilhado *et al.*, 2015; Moulin *et al.*, 2015; Leroux *et al.*, 2015a, b; Pellen *et al.*, 2016).

The extension of the MAR towards the SAB is also problematic due to its possible interaction with the Tremiti Ridge, and its proximity to the Gargano peninsula and the Mattinata Fault System. In any case, these structures influence the vertical evolution of the Gargano promontory and the marine corridor between CAB and SAB during tectonic reorganisation phases (Festa *et al.*, 2013). These movements have been suggested during the Cenozoic and Late Miocene (Scisciani and Calamita, 2009; Argnani *et al.*, 2009; Festa *et al.*, 2013), but have not been quantified. Argnani *et al.* (2009) suggested that the development of the MSC succession west of the Mattinata fault system and the MAR could be assigned to a change of motion along the MFS from sinistral to dextral strike-slip motion. While the orientation and character of the different Mesozoic platform-basin domains primarily control the CAB-SAB connections, the marine corridor is strongly influenced by these structures. However many questions remain as to the origin of each structural features and role in the isolation of the CAB.

Understanding the oceanic gateways evolution helps us to understand why different sedimentary environments are observed on either side of the Gargano promontory during the different stages of the Messinian crisis, such as the presence and absence of halite deposition in the Caltanissetta and Po Plain basins respectively, although both basins presented similar water depths (Amadori *et al.*, 2018; Camerlenghi *et al.*, 2020).

4. Present-day observation of the Messinian deposits across the Adria plate

1. MSC evolution along the Adria plate

A consensus has been reached in the scientific community in subdividing the MSC into three main stages at the Mediterranean scale (between 5.97 and 5.33 Ma), each of them well time-constrained and characterized by specific evaporite deposits and palaeo-hydrological conditions (Clauzon *et al.*, 1997; CIESM, 2008; Roveri *et al.*, 2014; Manzi *et al.*, 2013, 2020). Nevertheless, in detail, this consensus is not so large considering the various options discussed in CIESM (2008) but restricted to one option only in Roveri *et al.* (2014). This is also demonstrated by recent investigations on deep Messinian basins using industry drilling results and seismo-stratigraphy (e.g. CIESM, 2008; Gorini *et al.*, 2015; Roveri *et al.*, 2016; Madof *et al.*, 2019; Andreetto *et al.*, 2021a,b), these three stages may not be applicable everywhere in deep water basins (essentially the Eastern Mediterranean and Levant basins). Accordingly, we follow the Bache *et al.* (2015)'s chronology which takes into account all the recent robust data:

- Stage 1 (5.97-5.60 Ma) is associated with the development of shallow-water primary evaporites (present only in marginal basins) (Clauzon *et al.*, 1997; CIESM, 2008), while organic-rich shales sedimented in deeper water (Manzi *et al.*, 2007). Up to 16 shale-gypsum cycles were deposited in relation to strong astronomical control and restriction of marine water connection between the Atlantic and Mediterranean domain through the Rifian and Betic corridors (Krijgsman *et al.*, 1996; Hilgen *et al.*, 2007; Lugli *et al.*, 2010).
- Stage 2 (5.60-5.55 Ma) marks the MSC paroxysm defined by the drastic marine water exchange restriction between the Atlantic and Mediterranean seas leading to an important sea-level drop in a hypersaline deep-basin system, sedimentary transfer to the deeper marine areas, and uplift and deep fluvial erosion along the marginal domains (Clauzon *et al.*, 1997). Estimates of sea-level drop magnitude at the Mediterranean scale range from 100-200 m (Manzi *et al.*, 2018) to 650-900 m (Amadori *et al.*, 2018; Ben-Moshe *et al.*, 2020), 1000 m

(Pellen *et al.*, 2019) or 1500 m (Clauzon *et al.*, 1997; Bache *et al.*, 2009; Lofi *et al.*, 2011), according to basin physiography and/or scenario hypotheses. The exact timing of deposition between east and west Mediterranean sub-basins and the presence of shallow vs. deep environments are still a matter of debate (Roveri *et al.*, 2014; Bache *et al.*, 2015; Gorini *et al.*, 2015).

- Stage 3: the timing of the Mediterranean marine reflooding (comprised between 5.55 and 5.33 Ma) also remains intensely debated (Andreetto *et al.*, 2021a; Popescu *et al.*, 2021) with a first numerical model proposing an ultra-rapid rise in sea level at the end of the Messinian event (Garcia-Castellanos *et al.*, 2009, 2020) and models proposing a stepwise reflooding of the Mediterranean domains based on seismic reflection data (Bache *et al.*, 2012, 2015; Gorini *et al.*, 2015). In this hypothesis, a late lowstand period (5.55 – 5.46 Ma) is proposed to explain the rapid precipitation of halite in the deep settings (Bache *et al.*, 2015; Gorini *et al.*, 2015). This phase is associated with a relatively slow sea level rise, which smoothed out the scarring of the MSC crisis producing a very flat marine ravinement surface. At 5.46 Ma, the rapid sea level rise helped to preserve the scars of the MSC crisis on the margin, later followed by a moderate sea-level rise at 5.33 Ma (Bache *et al.*, 2012; Popescu *et al.*, 2021). However, Bache *et al.* (2012) and Pellen *et al.* (2017) showed that the Mediterranean marine waters re-entered later the Apennine foredeep, at 5.36 Ma.

Figure 4 presents the present-day distribution of MSC-related deposits along the Adria plate compiled from the literature. The identification and description of Messinian formations have led to the subdivision of the Adria domain into three main subdomains: (1) the Central Adriatic Basin (CAB) fringed by the north and central Apennine chains, limited to the south by the Gargano Peninsula and Palagruža Island, (2) the south Apennine Chain bounded to the east by the Apulian Platform, and (3) the South Adriatic Basin (SAB) bounded to the south by the Otranto Strait and to the east by the outer Albanid front.

ii. The central Apennine foredeep and the Central Adriatic Basin

The Messinian stratigraphy of the CAB has been extensively studied with onshore and offshore sedimentary observations (Selli, 1960; Roveri *et al.*, 1998, 2001, 2004, 2008a,b; Milli *et al.*, 2006, 2007; Popescu *et al.*, 2007, 2008; Lugli *et al.*, 2010), geophysical observations (Ghielmi *et al.*, 2010, 2013; Rossi *et al.*, 2015), and land-sea correlations (e.g. Ori *et al.*, 1991; Artoni and Casero, 1997; Roveri and Manzi, 2006; Roveri *et al.*, 2005, 2008; Artoni, 2013; Pellen *et al.*, 2017; Manzi *et al.*, 2020). Significant effort has been made to simplify the Messinian lithostratigraphy at a regional scale (Roveri *et al.*, 2008, 2014) and to correlate onshore with offshore deposits. Table 1 summarizes the different studies and correlations of Messinian formations across the Central Apennine belt (Figure 4; Table 1). To simplify the description of the Messinian lithostratigraphy of each area across the Adria plate in this study, we adopted the nomenclature of Roveri *et al.* (2004, 2005).

The Messinian Apennine foredeep was formed by the migration of the Marnoso-arenacea foredeep during the Late Tortonian-Early Messinian tectonic phase, and includes three main depocenters along the CAB (Figure 4). Two megasequences (Table 1 ; T_2, MP, *sensu* Roveri *et al.*, 2005) have been associated with the Messinian Salinity Crisis and respectively dated between ca. 8Ma - 5.6 Ma, and 5.6 - 5.33 Ma.

The upper section of the T_2megasequence corresponds to the development in an active tectonic setting of 1) the primary evaporites (Primary Lower Gypsum – PLG) from 5.97 Ma to 5.6 Ma (stage 1) in marginal wedge-top basins and foreland domain (Vena del Gesso Fm., Roveri *et al.*, 2003, 2005, 2006; Rossi *et al.*, 2015; Manzi *et al.*, 2020 - Gessoso Solfifera Fm. (evaporate)) and 2) siliciclastic fan deltas which evolved laterally to anoxic clays and dolomicrites in the main depocenters (Milli *et al.*, 2006, 2007; Ghielmi *et al.*, 2010, 2013).

Associated with the MSC stage 2 and the reflooding step closing the crisis, the initiation of the MP megasequence (Table 1) corresponds to a wide stratigraphic unconformity dated at 5.60 Ma observed along the whole Apennine fold-and-thrust belt. This regional event is part of a major change of depocenters and is called "intra-Messinian phase" (Ciaranfi *et al.*, 1973; Elter *et al.*, 1975; Di Nocera *et al.*, 2006; Colalongo *et al.*, 1976; Roveri *et al.*, 2005; Milli *et al.*, 2007; Bigi *et al.*, 2009, 2011; Ghielmi *et al.*, 2010; Artoni, 2013). The eroded products of marginal domains were resedimented in deep basins (Resedimented Lower Gypsum – RLG, e.g. Roveri *et al.*, 2001; Artoni and Casero, 1997; Artoni, 2003, 2013; Roveri *et al.*, 2014; Milli *et al.*, 2007). These formations generate the general structure of $p-ev_1$ Fm (post-evaporate Fm.), which includes a regional scale rhyolitic cinerite dated at 5.532 +/-0.004Ma (Cosentino *et al.*, 2013). The $p-ev_1$ Fm. is devoid of fossils and mainly comprises thin-bedded siliciclastic turbidites considered to have been deposited in deep, freshwater conditions (Roveri *et al.*, 2001).

The base of the $p-ev_2$ Fm. is age debated (5.36 Ma in Popescu *et al.*, 2007; Bache *et al.*, 2012; Pellen *et al.*, 2017; 5.42 Ma *in* Roveri *et al.*, 2014; Manzi *et al.*, 2020) and could mark a change from a regressive to transgressive trend in the post-evaporitic succession (Manzi *et al.*, 2020). The $p-ev_2$ Fm. is considered to have mostly been deposited in hypohaline conditions (Popescu *et al.*, 2007; Pellen *et al.*, 2017) and known for its content in Paratethyan fossils (Lago Mare biofacies; Selli, 1973; Colalongo *et al.*, 1976; Corradini and Biffi, 1988). Based on the study of microfossils, at least four marine incursions are associated with $p-ev_2$ Fm. (Popescu *et al.*, 2007 ; Pellen *et al.*, 2017), which probably later invaded the Po Basin (Channell *et al.*, 1994 ; Sprovieri *et al.*, 2008 ; Violanti *et al.*, 2007, 2011) due to the compartmentalization of the Apennine foredeep (Amadori *et al.*, 2018).

3. The east Apulian Platform and the south Apennine fold-and-thrust belt

Contrary to the Central Apennine Messinian foredeep, the MSC deposits identified along the South Apennine chain are located in a wedge-top depositional zone (Amore *et al.*, 1988; Chiocchini *et al.*, 2003; Pescatore *et al.*, 2008; Matano *et al.*, 2005, 2014; Barone *et al.*, 2006, 2008; Vezzani *et al.*, 2010; Ascione *et al.*, 2012) or along the Apulian foreland system (Pellen, 2016; Petrullo *et al.*, 2017; Manzi *et al.*, 2020).

On the foreland domain close to the Apulian Platform, the pre-MSC late Miocene succession presents several stratigraphic gaps during Paleocene, Oligocene, upper Langhian and Tortonian times (Vezzani *et al.*, 2010; Petrullo *et al.*, 2017). On the Apulian Platform, a syn- or post-Messinian breccia deposit directly overlies the upper Cretaceous to Middle Miocene carbonate formation (Figure 3; Pellen, 2016; Manzi *et al.*, 2020). Towards the western side of the Apulian foreland and below the allochthonous nappes, pre-evaporitic Messinian marls, primary evaporites and post-evaporite successions are preserved (Petrullo *et al.*, 2017).

The allochtonous domain of the South Apennine Chain observe preserved pre-MSC and MSC formations on top of the former Sannio-Lagonegro Mesozoic basin (Matano *et al.*, 2007; Vezzani *et al.*, 2010). Development of the MSC successions seems to occur in a syn-tectonic setting (Matano *et al.*, 2007, 2014) with 1) organic-rich marls and diatomites and 2) PLG (stage 1 of the MSC), partially eroded and overlapped either by RLG or Pliocene conglomerate deposits depending on the tectono-stratigraphic context of the outcrop (Matano *et al.*, 2007). The absence of MSC formation belonging to a deep environment and/or foredeep system below the present-day south Apennine Chain (Matano *et al.*, 2005, 2014; Matano, 2007; Manzi *et al.*, 2020) may suggest: 1) a shallow depositional environment along the Apulian Platform system with a cannibalized deep Lagonegro domain or 2) in the case of the presence of such deposits below the south Apennine Chain, the possibility of a deeper Messinian depositional setting towards the south of the Apulian Platform edge and Lagonegro domain.

The SAB is the least studied of the three areas. The SAB Messinian deposits seem disconnected from those of the CAB and borehole information (Sparviero 001 borehole; Manzi *et al.*, 2020) shows the initiation of resedimented gypsum formation located along the SAB. The southward extension to the Ionian Sea through the Otronto Strait is still a matter of question (Figure 4). According to the nomenclature of Lofi *et al.* (2018), these deposits are interpreted as a detrital formation (Complex Unit - Manzi *et al.*, 2020; Upper Unit in Lofi *et al.*, 2011 of unknown origin. Their mapping and the tectonic/sedimentary processes associated with Messinian deposition in the SAB remain relatively unknown.

Data and methodology

To characterize the development of Cenozoic and MSC units along the Central Adriatic Basin (CAB) and South Adriatic Basin (SAB), we merged seismic reflection profiles studied during the academia-industry program GRI *Méditerranée* (Groupement Recherche-Industrie) and vintage industrial profiles obtained from the VIDEPI website (https://www.videpi.com/videpi/videpi.asp) and reprocessed. Figure 05 present the distribution of the seismic lines used in this study and highlight the line drawings presented figures 7 and 8 (Non-interpreted seismic lines are illustrated in supplementary material 1 and 2). B The regional distribution of these profiles allows us to re-evaluate the Neogene seismo-stratigraphy (Some of the main Neogene seismic horizons based on Videpi seismic lines are published in Pellen *et al.*, 2021) and compare the development of the different stratigraphic unit identified along the CAB and SAB. Information on available boreholes obtained from the VIDEPI website was also integrated in order to calibrate and correlate the identified megasequences between the SAB and CAB. This set of data led us to re-evaluate the relationships of MSC palaeo-environments history with the structural and sedimentary heritage and to present a set of palinspastic and palaeoenvironmental reconstruction maps for that period. These palinspastic maps were built using Placa (Matias *et al.*, 2005) and Placa4D (Pelleau *et al.*, 2015) free softwares (https://wwz.ifremer.fr/gm_eng/Products-and-services/Free-softwares).

Boreholes and seismic lines are illustrated in Figure 5, which combines the MSC sedimentary formations described earlier along the CAB and South Apennine Chain, and the new cartography of the MSC units detailed in this section. Table 2 presents the stratigraphic charts used in this study for (i) borehole correlation along the Adriatic Sea (Figures 2, 6a and 6b) and (ii) seismic stratigraphic interpretation across the CAB (Figure 7) and SAB (Figure 8). Beyond the age of the stratigraphic units, their delimitations are based on the recognition of angular unconformities and erosive discontinuities.

Results

1. Post-Mesozoic sedimentary evolution between the CAB and SAB from borehole observation

i. Observed structural features

The Gargano Peninsula and Palagruža Island (see location in Figure 2) mark the boundary between the south (SAB) and central (CAB) Adriatic basins. The depth of the top of the Mesozoic series reached in boreholes varies markedly between 2400-2900m in the SAB and 1700-2000m in the CAB (Figures 6a, and 6b). The transition between the two basins is influenced by several structural features of different wavelengths.

The Gargano Peninsula is the most elevated portion of the Apulian foreland and is influenced 1) by a north-westward bending within the entire CAB (Figure 7 – SONE03-06) under the influence of the NE-verging Apennine orogeny and 2) to a south-eastward bending within the SAB under the influence of the SW-verging Dinaric-Hellenic orogeny (Figure 8 – SONE 09) (Moretti and Royden, 1987; Argnani *et al.*, 1993; Hairabian *et al.*, 2015).

Offshore observations confirm an antiformal structural high delimited by the MFS and the MAR (Figure 7-SONE07; Figure 8 – SONE08-09) which mainly affected Mesozoic formations. Towards the southeast, at the termination of the MFS and MAR, this structural high disappears (Figure 8 – SONE09). Deformation decreases on either side of these structures with the general development of Miocene depocenter (Figure 5; Figure 8 – NOSE02-04, SONE09). Towards the north and respectively west and east the MFS and MAR features surround the Gargano Peninsula (Figures 2, 5). The transition between the CAB and SAB corresponds to a narrow Mesozoic slope-to-basin corridor –cropping out on the eastern part of the Gargano Peninsula– and strongly deformed by the MAR Mesozoic to present-day deformation that can be observed along several seismic lines (Figure7 - SONE03-07; Figure 8 – NOSE05) and could be associated with the structural basement/Mesozoic dome and Triassic salt diapirism.

A minimum of 2 s twt difference in depth is observed between the undeformed basin domain and the structural crest (Figure 8 – SONE08 (km120)), suggesting >3 km uplift since the Late Cretaceous and affecting the Gargano Peninsula. These deformation pulses may correlate with the development of several sedimentary hiatuses (see next section). Together with the development of the MAR, one of the main impacts could be the disconnection between the CAB and SAB through the Gargano-Pelagosa corridor including during the MSC.

2. Post-Mesozoic to Miocene megasequences

Seven megasequences were defined from borehole correlation and seismic interpretation (Figures 6a, 6b, 7, 8, 9). In this study we have focused our description on three megasequences: the Paleocene-Eocene and Oligocene, Miocene pre-MSC, and Messinian syn-MSC megasequences.

The **Paleogene-Eocene and Oligocene** megasequences mainly developed at the foot of the slopes of ancient Mesozoic carbonate platforms (i.e. Fantoni and Franciosi, 2010) or along the Dinarid fold-and-thrust belt in preserved foredeep depocenters (Figures 7, 8 – NOSE03, SONE03-04-08). On the Apulian Platform, a sedimentary hiatus is observed at the top (Figure 6b, boreholes Sonia 001, Rovesti 001) and is locally associated with breccia deposits (Figure 6b, borehole Edgar 002). Sediment are mainly composed limestone and argillaceous limestone along the CAB. Important Paleogene-to-Oligocene depositional and/or erosional hiatuses are locally observed on the Apulian Platform (Figure 6b – Sonia 001) or east of the Gargano Peninsula on the uplifted part of the Mesozoic Ionian domain (Figure 6a – Cigno Mare). Casero and Bigi (2012) also observed a Late Mesozoic-Burdigalian depositional hiatus north of the Gargano Peninsula. Other boreholes from this area show older hiatuses from the Coniacian to the Tortonian (Gargano Mare 001; Pellen, 2016). Within the SAB, a hiatus is observed at the Late Cretaceous–Eocene interval (Figures 6a, 6b - Sparviero bis), followed by an important deposition of carbonate and silt-marl during the Miocene.

The **Aquitanian to Messinian pre-MSC megasequence of the CAB and SAB** is mainly developed along the SAB along the former basinal Mesozoic domain. It is divided into two sub-sequences: Aquitanian-Langhian (Bisciaro formation) and Serravallian-Tortonian (Schlier formation). It is one of the series marking the greatest difference between the CAB and the SAB. The Miocene sequence in the CAB is marked by a condensed set of clay carbonates (average thickness of about 50 m) at the top of the carbonate platforms. Around the Gargano Peninsula, carbonate formations are either associated with Langhian-Tortonian formation (Figure 6a, Branzino borehole located on the Apulian Platform) or Aquitanian-Burdigalian formation (Figure 6a, Cigno Mare). The associated sedimentary hiatuses could either be the result of (i) uplift or subsidence linked to the development of new tectonic phases along the deformation fronts and/or (ii) emersion of the area related to tectonic and relative low sea level.. Conformable Aquitanian-Tortonian marls and carbonates with an average thickness of 150-200m exist at the foot of the slope of the Apulian Platform. Along the SAB, the Aquitanian-Tortonian megasequence fills the Mesozoic Ionian domain with a 900-m-thick depocenter (i.e. Sparviero bis, Figure 6a). In detail, the northern area of the MFS shows an Aquitanian-Burdigalian depocenter with carbonate to silt lateral transition (Figure 6a), whereas the southern area shows a Serravallian-Tortonian depocenter (Figure 6b). A Langhian to Piacenzian hiatus and an erosive unconformity mark the area east of the Gargano Peninsula (Figure 6a – Cigno Mare) and could indicate emersion during this time span.

3. Development of the Messinian syn-MSC megasequence

From the seismic and borehole observation, at least four seismic units were identified offshore across the CAB and SAB (Table 2)

4. The Central Adriatic Basin

The CAB domain in associated to two thin seismic unit named M1 and M2. The M1 Unit can be defined by its seismic facies and its lithological composition, whereas the M2 Unit unit was described from borehole sections only (Figure 6a).

The M1-M2 unit is defined coherently in the western side of the CAB by two continuous seismic reflection of high amplitude and low frequency. The thickness of the unit is homogeneous (0.1 s twt thick about 60 m thickness) and develops locally between the Triassic salt anticlines composing the MAR along the CAB (0.2 s twt thick; Figure 7 – SONE03). This facies was not observed on the eastern part of the CAB and east of the MAR, perhaps due to a different depositional environment and/or to post-Messinian polygenic erosive and wave-cut surfaces (Figure 7 – SONE03-04-06). From a lithological point of view (Figure 6a, 6b), M1 shows a basal clayey carbonate and marl formation (close to the Italian coastline) (Figure 6b –Silvana 001). This succession is conformably covered by gypsiferous beds alternating with either clay or carbonate levels and associated with the PLG (see Manzi *et al.*, 2020 for a review). In some boreholes, the PLG are conformably covered by a 10-m-thick section of clayey carbonate named in this study as the M2 Unit. Along the central part of the CAB, the Messinian units are cut by an erosive surface (Figures 6a, 6b, 7), locally marked by a strong V-shaped incisions (Figure 7 – NOSE03) suggesting a subaerial origin. At least three east-west oriented incised valley systems were observed (Figure 5), but their origins as well as their terminations could not be determined mainly due to the scarcity of seismic coverage in this study. According to our observations, the M1 and M2 units do not appear connected with the other MSC deposits identified along the SAB (Figure 5; Figure 7 – SONE07; Manzi *et al.*, 2020).

5. The South Adriatic Basin

The SAB domain is characterized by two main MSC units (Figure 5) named M3 and M4, and delimited by three erosional discontinuities S20, S22 and S30 (Table 2) which laterally evolve into conformable surfaces toward the eastern part of the SAB (Figure 8 – NOSE04-05). These units can be distinguished from the underlying formations by their seismic facies, their internal geometries and the boundary surfaces.

Lithological observations are available for the Sparviero-bis borehole (Figure 6a, 6b), which reaches the upper part of M3: In this area M3 lies on the Messinian Di Letto Fm. (~100m) composed of sandy clay. The upper part of M3 may be associated with the Gessoso-solfifera formation (about 70 m thick), here composed of alternating sandy-clay levels and reworked evaporites. Gamma Ray and Sonic logs (Sparviero bis; Rovesti 001) suggest a detrital origin for this formation instead of an in-situ evaporitic deposition as for the PLG (this study; Manzi *et al.*, 2020).

The base of M3 Unit is defined by an erosional surface of variable magnitude but traceable at the scale of the entire SAB. The development of the M3 Unit is delineated south of the MFS, on the northern edge of the Tremiti-MAR structure and is delimited south and north by the platform edge of the Apulian and Adriatic platforms (Figure 5). The Mattinata and MAR structures affect the morphology of the basal surface (Figure 8, SONE09: km 20-70), which form a high relief compared to the SAB basin. M3 shows a different seismic facies between the high MFS-MAR structure and the deeper domains, as well as lateral facies evolution towards the southern SAB domain (Figure 9).

Southwest of the Mattinata system, M3 is characterized by poor-continuity reflections of medium amplitude and medium frequency (Figure 8 – NOSE02: km 35-50; Supplementary material 2; Figure 9). A fan geometry can be seen in secondary fault systems. This seismic facies evolves laterally into a chaotic seismic facies with numerous diffraction hyperboles following a SW-NE axis, interpreted as a clastic mass transport deposit (MTD) (Figure 5; Figure 8; Figure 9). The detrital sediments, likely charged in gas, obscure the base of the unit and the underlying formations. The development of the MTD facies limits monitoring of the basal erosional unconformity, thus a maximum thickness of 0.6 s twt is proposed for M3 (Figure 8 – NOSE02). Its thickness is variable and estimated towards the north at 0.3 s twt, which suggests derivation from the Apulian Platform edge.

The unit shows gradual seismic facies change towards the SE with the development of more continuous and sub-parallel reflections (Figure 8 - NOSE02-SONE10; Figure 9). It is worth noting the presence of a pre-Messinian prograding facies developing at the same place as the pre-MSC progradations (Figure 8, NOSE02: km 30-60). In the deep domain of the SAB (Figure 7, SONE07: km 65-120), the edges are also associated with the development of forced regression prisms, with an average thickness of 0.2 s twt (Figure 8, SONE08: km 100-115; SONE09: km130-150).

Along the northern part of the SAB, the top of M3 (S22) is a discontinuity truncating the reflectors of M3, as well as the Aquitanian-Tortonian series where syn-MSC seismic units are absent. The surface becomes concordant towards the SE and underlines the roof of M3. Locally, V-shaped incised valley axes are observed (Figure 8, SONE08: km 123-135; Figure 8, NOSE06: km 95-108), probably related to a NW-SE valley axis developing along the Mesozoic carbonate platform. The origin of the incised valley observed along the CAB remains difficult to define (Figure 5).

M4 Unit is underlain by the S22 discontinuity and is characterized by continuous reflections towards the SE, of high amplitude and medium frequency. The unit also expands towards the SE of the SAB, with more than 0.2 s twt thickness, and fills the depressions at the top of the M3 detrital unit (Figure 8 - NOSE02: km60-168 - NOSE04: km 60-148). Note that prograding reflections develop along a NE-SW axis, within the old incised valley (Figure 8 - NOSE07: km 30-40; SONE09: km 105-120). Basinward, the seismic reflections of M4 become parallel to M3, but we could not estimate the evolution of its thickness towards the Albanid front and the Otranto Strait. Although, due to the lack of information from borehole data, we are unable to provide a direct age for its deposition, M4 corresponds to the development of a transgressive unit and could be correlated to the Upper Evaporites (DSDP 372: Hsü *et al.*, 1978; Lofi *et al.*, 2011; Roveri *et al.*, 2014) observed in the Western and Central Mediterranean basins.

Discussion

1. Evolution of marine corridors across the Adria plate during the Messinian (7.2 – 5.33 Ma)

The identification of the Gargano-Pelagosa strait and its impact on the distribution of MSC deposits makes it possible to draw detailed palaeotectonic-paleoenvironmental reconstructions of the study area of the Pelagosa Strait during Messinian times (Figures 10-15). For each stage, two maps show the palinspatic reconstruction and palaeoenvironmental information of the area. The kinematic motion of the Calabria block, the Adria plate, and the north Apulian block relative to the Corsica-Sardinia blocks (used as the fixed reference) were restored using Placa4D software (Matias *et al.*, 2005). Figures 10 to 15 illustrate the palinspastic evolution of the study area at 7.2, 5.9, 5.5, 5.36 and 5.3 Ma. Figure 10a (7.2 Ma) corresponds to the transition between rifting and drifting in the future central Tyrrhenian domain (Lymer *et al.*, 2018) which also marks a new compressive phase along the Apennine belt (Vezzani *et al.*, 2010; Ghielmi *et al.*, 2010, 2013).

Following Carminati *et al.* (2012) and Argnani *et al.* (2014), we rotated the Calabria-Peloritani block east of Sardinia and the north Gargano micro-block; however, these authors did not provide angles for the rotation. To be coherent with the geological and geophysical intraplate information, we applied an angle of -8.7° (Table 3) for the Calabria-Peloritain block for a total displacement of 450 km from 7.2 to 0Ma We also took into account a 10°ccw rotation of the Albanid-Hellenide chain with a rotation point located at the Scutari-Pec lineament (van Hinsbergen *et al.*, 2004).

A second constraint comes from the restoration of the limit of the Adria plate and the situation of the Mesozoic Adriatic, Apulia, and Apennine platforms. Palaeomagnetic data from the Apennine Platform show a ~60°ccw rotation (Gattacceca and Speranza, 2002) and constraints from thrust-top sedimentary basins overlying the Southern Apennine chain show ~40ccw rotation in the late Miocene (van Hinsbergen *et al.*, 2020). We elected a ~45 ccw rotation of the Apennine Platform with respect to the Apulian Platform (van Hinsbergen *et al.* (2020) (Figure 10). As suggested by Vezzani *et al.* (2010) and Vitale and Ciarcia (2013), the Apennine and Apulian platforms are connected by a slope domain (Figure 10). This restoration implies a

~200 km wide Sannio-Molise-Lagonegro Mesozoic basin system at the junction with the Ionian Sea. Argnani *et al.* (2009) also suggested that along the MFS compressional deformation dominated since the late Miocene, contributing to create the topographic elevation of the Gargano promontory. According to Tondi *et al.* (2005), dextral component of motion is compatible with the present-day stress field that could be active since the last 200 kyr at rates of 0.8+/- 0.1 mm/yr (0.8+/-0.1 km/Myr). According to these results and assuming constant motion during the Pliocene, total displacement of the deep Mesozoic domain north and south of the Mattinata fault system would not exceed 10 km from the late Messinian to Present.

The palaeoenvironmental maps are based on these palinspastic constraints and the information on the Messinian sedimentary deposits described in the previous sections. Bathymetry ranges are proposed according to the sedimentary domain, (shelves: 0-200 m; slopes: 200-2,000 m; basins and deep domain: 2,000-4,000 m). These values represent average estimates, as does the exact position of the coastline within areas of low constraint due to poor preservation of sedimentary deposits, such as the southern part of the future South Apennine Chain or along the Otranto corridor.

1. **Prior to the onset of the MSC (from 7.2 Ma to 5.9 Ma) (Figure 10-11)**

During late Tortonian-early Messinian (Figure 10a) the whole Apennine platform and the Molise-Lagonegro Basin were embodied in the Apennine deformation belt (Vezzani *et al.*, 2010; Vitale and Ciarcia, 2013) (. Flysch deposition is recorded on the Apennine Platform (Anversa flysch; Figure 3) and along its eastern border on the Sannio-Molise Basin (Agnone flysch) (Figure 3; Vezzani *et al.*, 2010). Calcarenite deposition along the western border of the Apulian Platform (Figure 3) marks the initiation of its deformation (Vezzani *et al.*, 2010). During this period the Laga Basin developed northeast of the deformed Apennine Platform (Milli *et al.*, 2006, 2007) (Figure 10a) which is part of the Marnoso-arenacea-Bolognano flexural basin (e.g. Roveri *et al.*, 2003; Milli *et al.*, 2006, 2007; Artoni, 2013). This end-Tortonian deformation phase subdivides the Apennine foredeep into more confined basins with the Po, Romagna, and Laga basins, and records the turbiditic sandstone and mudstone formation of Bagnolo Fm. and Laga Fm. (Table 01; Artoni, 2003; Ghielmi *et al.*, 2010) on top of the Serravallian-Tortonian foreland ramp. Associated with this tectonic phase, the inner part of the outer Marnoso-arenacea foredeep is involved in the fold-and-thrust belt (Ricci Lucchi, 1986).

This deformation phase also impacted the SE border of the Adria plate during the Messinian to present-day (Figures 10a-15a; Frasheri *et al.*, 2009; van Hinsbergen *et al.*, 2020), with the reactivation and uplift of the Albanid fold-and-thrust belt (Frasheri *et al.*, 1996, 2009), south of the Scutari-Pec lineament. Accordingly, this deformation involved the SE terminal part of the Apulian Platform, thus implying bending towards the south of the eastern part of the Apulian Platform. According to Argnani *et al.* (2009), these late Miocene tectonic phases are associated with a change in tectonic style along the Mattinata fault system, from normal and left-lateral strike-slip motion to compressive dextral strike-slip motion (Figures 10a, 11a).

Therefore, prior to the initiation of the MSC (Figure 10b), the Apulian Platform was an island respectively bordered east and west by the Gargano-Pelagosa, Lagonegro and Otranto straits. Both marine corridors delimitate the Messinian Apennine foredeep system from the deeper environmental domains (Figure 10b; Pellen *et al.*, 2017; Manzi *et al.*, 2020). At that time, the Gargano-Pelagosa Strait developed wackestone and argillaceous deposits (Schlier Fm.; Famoso001 borehole) suggesting a shallow to medium water depth (Figure 10b). Several sedimentary hiatuses and traces of erosion are associated with this corridor, suggesting that the Gargano Strait was shallow throughout the Cenozoic era (Patacca *et al.*, 2008) with periods of emersions. This palaeogeographic configuration could be linked to 1) the uplift of the Apulian Platform during Mesozoic and Cenozoic times associated with the Mattinata, Tremiti, and MAR systems, and 3) the uplift of the western part of the Adriatic Platform domain with the influence of the Dinarid-Albanid chains.

During late Tortonian-early Messinian time, the western border of the Molise-Lagonegro Basin was progressively affected by the eastward propagation of the Apennine fold-and-thrust belt and foredeep development (Agnone Fm.). According to the tectono-stratigraphic compilation of Ciarcia and Vitale (2013), from 7.2 Ma to 5.9 Ma, the Lagonegro-Molise domain was largely incorporated in the allochthonous tectonic wedge (Figures 10b-11b). The Lagonegro-Molise Strait is therefore interpreted as a shallow marine corridor during the MSC where the depocenters are occurring in a wedge-top or foreland setting.

Lastly, the Otranto Strait width remains hypothetic and dependent on the Albanid thrust-front propagation. For our reconstruction, we chose the Mesozoic palaeogeogeographic domain observed along the Albanid fold-and-thrust belt (the Sazani Platform domain (location Figure 3) associated with the Apulian Platform and the Ionian domain associated with the SAB). In this reconstruction (Figure 10b), the Otranto Strait brings the SAB and the Ionian Sea into contact. It is locked to the west by the Apulian Platform and to the east by the Albanid-Hellenide fold-and-thrust belt. The Messinian to Pliocene tectonic phases affecting this chain may have progressively limited the sedimentary transfer from the SAB toward the Ionian Sea.

2. First stage of the MSC (from 5.97 Ma to 5.6 Ma) (Figures 11-12)

The onset of the Messinian Salinity Crisis with a drastic reduction in the marine connection between the Mediterranean Sea and the Atlantic Ocean at 5.97 Ma (Manzi *et al.*, 2013). At this time, the Apenninic foreland was a shallow evaporitic marine domain (PLG Fm.; Lugli *et al.*, 2010; Manzi *et al.*, 2020) with an average palaeo-water depth not exceeding 200 m (Figure 11b). It then evolves towards the deeper part into organic-rich barren shale (Manzi *et al.*, 2007). The Laga and Romagna basins formed the main foredeep depocenter with at least 2.5-km-thick turbiditic deposition between 7.2 and 5.6 Ma (Milli *et al.*, 2007), associated with sediment sources related to the Apennine Chain and the Alps following a N-S palaeocurrent and NW-SE paleocurrent direction (Milli *et al.*, 2007). This depocenter was limited to the south by 1) the uplift of the former Apennine domain, now embedded in the allochthonous tectonic wedge, 2) the uplift of the Gargano-Pelagosa Strait, and 3) possible tectonic inversion along the MAR and MFS (Figure 11a). This substantial uplift of the area could be related to the opposing compressive reactivation of the Albanid and Apennine Chains (Fantoni and Franciosi, 2010) and/or the inversion of the MFS (Argnani *et al.*, 2009). This motion may have led to a restriction of the Gargano-Pelagosa Strait during stage 1 (Figures 11b, 12b), and/or even to outright marine closure between 5.97 and 5.6 Ma, as no PLG Fm. has been observed along the strait.

Narrow marine corridors could have existed along the former Molise-Lagonegro Strait during stage 1, bordered to the west and east by the Apennine front propagation and the Apulian Platform. The presence of decameter-sized PLG blocks on present-day wedge-top basin outcrops along the south Apennine Chain (Figure 16; Matano, 2007; Matano *et al.*, 2014; Manzi *et al.*, 2020) confirms the deposition of shallow evaporitic formations along the deformation front and/or on the Apulian foreland area. Along the Apennine foredeep, evaporitic deposits of this period are interbedded with marine clays, indicating marine incursions into the shallow basins and reconnection of the Mediterranean, as mainly evidenced by fish remains (Sturani, 1973; Fontes *et al.*, 1987; Carnevale *et al.*, 2008) and dinoflagellate cysts (Bertini, 2006).

3. Second MSC stage (from 5.6 Ma to 5.55 Ma) (Figures 12-13)

The major Mediterranean Sea level drawdown that characterized the paroxysmal step of the MSC occurred at 5.6 Ma (Clauzon *et al.*, 1996, 1997; Bache *et al.*, 2012, 2015; Gorini *et al.*, 2015). This period also corresponds to a new deformation phase recorded throughout the central Mediterranean area and particularly along the Apennine fold-and-thrust belt (Figure 3; Vezzani *et al.*, 2010; Milli *et al.*, 2007; Roveri *et al.*, 2008). The activation of several thrust fronts along the Apennine fold-and-thrust belt as well as on the southern border of the Laga Basin led to incorporate the Messinian foredeep in the belt and initiated a late Messinian-early Pliocene foredeep (Figure 3; Figures 12a-13a; Milli *et al.*, 2007; Vezzani *et al.*, 2010; Artoni, 2012).

Several observations attest to a total disconnection of the Apennine foredeep with respect to the SAB or the Ionian Sea. The marginal domains and thrust-top basins are affected by a subaerial erosional surface; the deeper domains and foredeeps are associated with the development of gypsum-rich turbidites resulting from the erosion of the PLG. The occurrence of an incised-valley system on the foreland part (Figure 13b) confirms a relative sea-level fall comprised between 200 and 800 m, following the flexural back-stripping results modelled by Amadori *et al.* (2018). This relative sea-level fall estimate differs depending of the studied area (marginal basin connected or disconnected to the deeper basins; the hydrogeological and climatic system), where higher estimates of relative sea-level fall have been inferred for the western and eastern Mediterranean (~1000-1500 m) through stratigraphic observation and backstripping modelling (Leroux *et al.*, 2017; Ben-Moshe *et al.*, 2020; Pellen *et al.*, 2019). Freshwater, probably supplied in abundance by the surrounding uplands (Alps: Fauquette *et al.*, 2015a; Apennines: Fauquette *et al.*, 2015b), filled the Apennine foredeep and Po Basin where relatively high water levels persisted during the lowered Mediterranean Sea level in subaqueous brackish environments (Lago Mare biofacies; Gillet, 1968; Colalongo *et al.*, 1976; Bellagamba, 1978; Corselli and Grecchi, 1984; Esu and Taviani, 1989; Faranda *et al.*, 2007; Gliozzi *et al.*, 2007; Popescu *et al.*, 2007; Esu, 2007; Bache *et al.*, 2012; Pellen *et al.*, 2017) (Figure 13b).

At 5.6 Ma, the western side of the Apulian Platform edge was overthrust by the tectonic prism of the southern Apennine Chain (Figures 12a, 13a; Barone *et al.*, 2006; Matano, 2007; Vezzani *et al.*, 2010; Matano *et al.*, 2014). The southern Apennines experienced a strong tectonic phase as attested by syn-tectonic thrusting during the deposition of RLG and after the erosion of PLG (Figure 16; Matano, 2007). This mass transport complex includes pluri-decameter PLG blocks which suggest a close source of erosion and resettlement in the nearby narrow and shallow environment. Important wedge uplifts were recorded by apatite fission-track data (cooling ages clustering around 5.5 Ma; Corrado *et al.*, 2005; Mazzoli *et al.*, 2008; Ascione *et al.*, 2012), which suggest important horizontal and vertical motions from late Messinian to the present. Along the Apulian foreland, the RLG deposits are also specific to the footwall of normal faults associated with the Mesozoic extensional phase along the Apulian Platform (Manzi *et al.*, 2020). Along the western side of the Apulian foreland, breccia, erosive surface or conglomerate deposits are observed in boreholes, overlain by early Pliocene marls (Figure 5; Pellen, 2016; Manzi *et al.*, 2020). These different observations suggest a relative sea level drop either linked to a sea level fall and/or a tectonic uplift. A different sedimentary history is preserved along the present-day south Apennine chain compared to the CAB and central Apennine chain. These different observations suggest a complete disconnection between the Messinian Apenninic foredeep and the deep Ionian Sea during the MSC paroxysm across the Molise-Lagonegro Strait or the Gargano-Pelagosa Strait.

Along the SAB, the MSC paroxysm is associated with the development of a mass transport deposit, embedded in the M3 seismic unit. The latter includes resedimented clastic gypsum (Figure 6b – Sparviero bis borehole), which indicates the erosion and re-sedimentation of primary evaporites. A possible origin of this MTD could be associated with the eastern Apulian Platform edge and is synchronous with the development of M3 detrital unit during the MSC paroxysm. As there is no major MSC fluvial system located west of the Apulian platform, a possible origin for the MTD could be linked to slope destabilization and submarine landslide. Third MSC stage (from 5.55 Ma to 5.33 Ma) (Figures 13-15).

An age of 5.46 Ma has been proposed for the marine reflooding of the Mediterranean (Bache *et al.*, 2012, 2015; Gorini *et al.*, 2015; Popescu *et al.*, 2021). However, marine waters did not immediately enter the Apennine foredeeps because the marine ingression in such domain, corresponding to the boundary between the p-ev1 and p-ev2 formations (see Table 1; Popescu *et al.*, 2007), has been precisely dated at 5.36 Ma (Bache *et al.*, 2012). From 5.36 Ma (Figure 14b), marine waters overflowed the paleobarrier made by the Gargano-Pelagosa gateway and penetrated the Apennine foredeep composed of brakish water from Paratethyan origin (the third Lago Mare biofacies in Popescu *et al.*, 2015). At least four overflows of marinewaters have been suggested (Pellen *et al.*, 2017), which possibly later flooded the Po Basin (Channell *et al.*, 1994; Sprovieri *et al.*, 2008; Violanti *et al.*, 2011). From a brakish environment, this process was probably forced, first by the isostatic response of the palaeo-barrier linked to the Apennine deformation phase and/or to the reflooding of the Mediterranean Basin, and then by the continuous global sea-level rise after 5.33 Ma (Figure 15b; Gorini *et al.*, 2015).

Three Lago Mare events have been distinguished and documented in the Mediterranean Basin by Do Couto *et al.* (2014) and Popescu *et al.* (2015) but Roveri *et al.* (2014) considered only one Lago Mare event on the basis of the Apennine foredeep data where only the third Lago Mare event occurred (Pellen *et al.*, 2017). In a recent synthesis on this biofacies, Andreetto *et al.* (2021a) surprisingly followed the model of one Lago Mare event for the whole Mediterranean Basin although they confirmed the marine context of Lago Mare 1 and 3 (Andreetto *et al.*, 2021b) consistently with Do Couto *et al.* (2014), Clauzon *et al.* (2015), and Popescu *et al.* (2015).

After 5.3 Ma and the marine reflooding of the Bradanic and Apennine foredeeps, two more tectonic phases were recorded along the Apennine fold-and-thrust belt (Figure 3): Early-Middle Pliocene and Late Pliocene-Early Pleistocene (Vezzani *et al.*, 2010; Artoni, 2013; Ascione *et al.*, 2012; Vitale and Ciarcia, 2013). These tectonic phases led to the inclusion of the Laga Basin and other Messinian foredeep systems in the fold-and-thrust belt. The total estimated shortening along the central Apennine Chain is estimated between 13 km (L.S to A.A. lineaments) and 32 km (A.A. to M.R. lineaments) (Artoni, 2013; see Figure 2 for the location of lineaments), depending on the segment affected by the deformation. Along the Southern Apennine, the Apennine allochthonous wedge continued to be thrusted over the Apulian Platform (Mazzoli *et al.*, 2008). Active thrusting migrated to the underlying platform during the Pliocene, and was accompanied by a switch from thin-skinned thrusting to thick-skinned inversion-dominated shortening (Mazzoli *et al.*, 2000; Butler and Mazzoli, 2006; Shiner *et al.*, 2004; Ascione *et al.*, 2012). From 5.3 Ma to the present, the migration of the allochthonous tectonic wedge has been estimated between 50 and 60 km (Ascione *et al.*, 2012).

2. Intra-Messinian isostatic rebound and platform destabilization

Neogene horizontal and vertical motion changes should have affected the morphology of the Gargano-Pelagosa gateway as well as the SAB: the MAR and MFS seem to delimitate the SAB into two sub-basins following a NW-SE axis (Figure 8). The eastern part of the basin has thicker Paleogene-Miocene, Messinian, and Pliocene-Quaternary sedimentary successions compared to the western sub-basin.

The distribution of the different MSC-related formations around the Gargano-Pelagosa strait provides cogent constraints on the palaeoenvironmental and tectonic evolution along the Adria plate (Figures 5, 11-15). Moreover, the development of the MTD (M3 seismic unit) – originated from the Apulian platform edge – could be associated to several tectonic and/or eustatic processes affecting the area.

Similar MSC deposits have been recognized along the Mediterranean: the Valencia-Menorca basins (Maillard *et al.*, 2006; Cameselle and Urgeles, 2016; Pellen *et al.*, 2019), the Alboran Sea (del Olmo and Comas, 2008; del Olmo, 2011), the Malta Escarpment (Micallef *et al.*, 2018; Garcia-Castellanos *et al.*, 2020). MTDs have been associated with various processes (Canals *et al.*, 2004; Moscardelli and Wood, 2007) in the case of the Messinian event. Their origin is associated with seismotectonic activity and/or strong sea-level fluctuation and marine gas-hydrates release, isostatic rebound, and adaptation of river equilibrium profiles. In view of their stratigraphic position in the Alboran and Valencia basins, the emplacement of the MTDs was dated at around 5.60 Ma as a consequence of the sea-level fall and ensuing isostatic rebound of the continental shelves (del Olmo and Comas, 2008; Pellen *et al.*, 2019). The development of MTDs along the Maltese Escarpment was associated with the rapid sea-level rise at the end of the MSC (Garcia-Castellanos, 2009; Micallef *et al.*, 2018), but a tectonic origin linked to the destabilisation of the platform cannot be ruled out. Modelling of isostatic rebound only linked to the withdrawal of water masses around the Gargano-Pelagosa Strait suggests isostatic uplift values between 200 and 1000 m (DeCelles and Cavazza, 1995; Cavazza and DeCelles, 1998; Gargani et al, 2010; Amadori *et al.*, 2018). This wide range is dependent on the palaeogeography and the nature of the associated basins and landforms (Govers *et al.*, 2009) as well as the tectonic setting, and reflects the important vertical movements affecting the Mediterranean marginal domains. More than 1.3 km were measured on the Gulf of Lion margin for the MSC period and associated with water withdrawal and large sediment transfers (Rabineau *et al.*, 2014).

Major tectonic re-organization are documented along the Adria plate during the MSC: (1) the intra-Messinian tectonic phase impact the whole Apennine chain (see Discussion 1.3) and Albanid chain (e.g. Pashko and Aliaj, 2020); (2) change from sinistral to dextral strike-slip motion and folding along the MFS have been documented for the late Miocene (Argnani *et al.*, 2009). Together with the abrupt changes in sea level, these tectonic processes are perfect candidates to explain the establishment of the MTD (M3 unit) in the SAB.

At a regional scale other major tectonic change (Giaconia *et al.*, 2018) and major magmatic pulse (Sternai *et al.*, 2017) are observed. These Mediterranean tectonic/magmatic pulses have been also linked to a more global plate kinematic reorganization affecting the earth during Messinian time (Leroux *et al.*, 2018). These changes in horizontal motion also affect the sub-marine morphology and kilometer scale uplift have been documented world-wide (Rabineau *et al.*, 2014; Masters *et al.*, 2020). As highlighted by Booth-Rea *et al.* (2018) or Masters *et al.* (2020), these uplift affecting the gateways favoured the faunal and floral migration between continents. The episodic emergence of the Gargano-Pelagosa gateway during the MSC, and more generally during the Mesozoic and Cenozoic, could also explain the faunal migration between the different Mesozoic platforms of the former Greater Adria plate (Zarcone *et al.*, 2010; van Hinsbergen *et al.*, 2020).

Conclusions

The Gargano-Pelagosa gateway is here first recognized as an influential element of the palaeogeographic/environmental evolution of the central-southern Apenninic foredeep and wedge-top domains during the Messinian, as shown by the integration of (i) seismic lines, (ii) well information from the Adriatic Sea, and (iii) a review of both onshore and offshore structural data and Messinian depositional environments. Several processes concur to explain the isolation of the Apennine foredeep during the MSC. Primarily, NW-SE oriented Mesozoic platforms and basins systems controlled the Neogene sedimentary environments around the Gargano-Pelagosa Strait. Messinian tectonic rejuvenation along the Apenninic and Albanid fold-and-thrust belts, the Mid-Adriatic Ridge and Mattinata Fault System, led to the isolation of the Apennine foredeep during the MSC paroxysm. We propose a coherent tectonic and environmental evolution along the Adria plate during the MSC:

1. During MSC stage 1, the CAB evolved into a large evaporitic basin (Manzi *et al.*, 2020) only connected to the deep Mediterranean basins east and west of the Apulian Platform through the Gargano-Pelagosa and Lagonegro straits, respectively.
2. During the initiation of the stage 2, the combined effects of the MSC sea-level fall and the ensuing intra-Messinian tectonic rejuvenation along the Apennine Chain led to the closure of the Lagonegro Strait. We suggest that the widespread deposition of mass transport deposits across the SAB is related to the isostatic rebound along the Apulian Platform. Tectonic inversion of the Mattinata Fault System could also be associated with

intra-Messinian tectonics. These multiple tectonic processes led to the closure of the Gargano-Pelagosa Strait and isolation of the Apennine foredeep, as suggested by Pellen *et al.* (2017) and Manzi *et al.* (2020).

In the same way, the Otranto Strait could have been also influenced during the MSC by the isostatic rebound related to sea-level fall and sedimentary transfer, and by tectonic deformation along the Albanid-Peloponnese fold-and-thrust belt. Further seismic and borehole investigation could highlight the sedimentary relationship between the SAB and the Ionian Sea.

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Conflict of interest

We confirm that we have no conflicts of interest related to this research, this work is original to its form and has not been published elsewhere, nor is under consideration for publication elsewhere.

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Figure

Figure 1: Physiographic map of the Mediterranean highlighting the main oceanic gateways (in light red) during the Last Glacial Maximum and during the Neogene. The color scale is adapted to the LGM sea level and highlight the main present-day gateways. These gateways control the water, sediment, and biotope exchange between sub-basins and oceans.

Figure 2: Illustration of the general palaeoenvironmental and structural framework compiled from Vezzani *et al.*, (2010); Bigi *et al.*, (1990); van Hinsbergen *et al.*, (2020). The structural zones are associated with the deformation fronts of the Apennines, Dinarids and Albano-Hellenid (synthetized from Zappaterra, 1994; Vezzani *et al.*, 2010; van Hinsbergen *et al.*, 2020; this study). Sestri-Voltaggio lineament (S.V.); the Anzio-Ancona lineament (A.A.); Maiella-Roccamonfina lineament (M.R.); M.A.R. – Mid-Adriatic Ridge; T.R. – Tremiti Ridge; M.F.S. –Mattinata Fault System; CAB – Central Adriatic Basin; SAB – South Adriatic Basin.

Figure 3: Synthesis of the evolution of the Cenozoic deposit environments specific to each palaeogeographic domain developed during the Mesozoic (synthesized from Vezzani *et al.*, 2010). The involvement of palaeogeographic domain inside the fold-and-thrust belt and the associated wedge-top formation are represented in orange. Major tectonic phase reported by Vezzani *et al.* (2010) are highlighted in light red and numbered from 1 to 6.

Figure 4:
Previously published MSC formations along the Central Mediterranean area.
Liguri-Provence Basin (Sage *et al.*, 2005; Lofi *et al.*, 2011; Bache *et al.*, 2015). Tyrrhenian Sea (Lymer *et al.*, 2018). **Sicily and Calabria** (Butler *et al.*, 1995, 2019 ; Pedley *et al.*, 2007; El Euch-El Kundi *et al.*, 2009; Roveri *et al.*, 2008a; Henriquet *et al.*, 2020 ; Cavazza and DeCelles, 1998). **Northern and Central Apennine Chain** (Roveri *et al.*, 2005, 2008b; Ghielmi *et al.*, 2013; Rossi *et al.*, 2015; Pellen *et al.*, 2017; Manzi *et al.*, 2013, 2020; Iaccarino *et al.*, 2008; Milli *et al.*, 2006, 2007; Artoni, 2003; Bigi *et al.*, 2009). **South Apennine Chain** (Vezzani *et al.*, 2010; Manzi *et al.*, 2020). **South Adriatic Basin** (Frasheri *et al.*, 2009; Silo *et al.*, 2013; Argnani *et al.*, 2009). **Ionian Basin** (Micallef *et al.*, 2018 ; Garcia-Castellanos *et al.*, 2020 ; Gutcher *et al.*, 2017).

Table 01: Correlation table of the different deposit units identified along the Apennine foredeep by [Milli *et al.*, 2007] compared to the nomenclature of Roveri *et al.* [2004, 2005].
Legend: pre-ev: pre-evaporitic unit; post-ev: post-evaporitic unit. U1, U2, U3 and I1, I2, I3 are non-conforming surfaces. The dashed line indicates the position of the cinerite level.

Figure 5: Map showing our new interpretation of the sedimentary facies and stratigraphic units observed along the Adriatic Sea and associated with the Messinian event. The mapping of geological formations on land refers to that used in the figure 4. The Messinian-Pliocene basal (yellow to bluish) and Tortonian (pinkish) deposits are highlighted.

Table 02: Stratigraphic chart correlation

Figure 6a: Stratigraphic correlation between 6 boreholes selected on both sides of the promontory of Gargano. This synthesis highlights a different sedimentary filling dynamics in the Tertiary between the CAB (Central Adriatic Basin) and SAB (South Adriatic Basin).

Figure 6b: Illustration of three stratigraphic sections based on industrial boreholes along the CAB and SAB. Significant Oligocene-Tortonian depocenter is observed within the SAB, while strong depocenter is observed during the Pliocene-Quaternary within the CAB.

Figure 7: SW-NE oriented line-drawings along the CAB.

Figure 8: SW-NE oriented line-drawings along the SAB.

Figure 9: Detailed seismic sections (location Figure 8) highlighting the initiation (left) and lateral evolution (right) of the Mass Transport Deposit which mainly compose the M3 seismic unit. The lateral transition from chaotic to continuous seismic reflections allowed to identify the western limit of the MTD observed on Figure 5.

Table 3: Retro-translation and back-rotation values of Adria, Africa, and Calabria-Peloritain blocks with respect to stable Europe (and Corsica-Sardinia blocks). Sources: Sioni (1996); Fidalgo-Gonzàlez (2001), this study.

Figure 10:
A (Top): Palinspastic reconstruction of the Central Mediterranean area at 7.2 Ma.
B (Bottom): Palaeoenvironmental reconstruction of the Central Mediterranean area at 7.2 Ma.

Figure 11:
A (Top): Palinspastic reconstruction of the Central Mediterranean area at 5.9 Ma.
B (Bottom): Palaeoenvironmental reconstruction of the Central Mediterranean area at 5.9 Ma.

Figure 12:
A (Top): Palinspastic reconstruction of the Central Mediterranean area at 5.6 Ma.
B (Bottom): Palaeoenvironmental reconstruction of the Central Mediterranean area at 5.6 Ma.

Figure 13:
A (Top): Palinspastic reconstruction of the Central Mediterranean area at 5.5 Ma.
B (Bottom): Palaeoenvironmental reconstruction of the Central Mediterranean area at 5.5 Ma.

Figure 14:
A (Top): Palinspastic reconstruction of the Central Mediterranean area at 5.36 Ma.
B (Bottom): Palaeoenvironmental reconstruction of the Central Mediterranean area at 5.36 Ma.

Figure 15:
A (Top): Palinspastic reconstruction of the Central Mediterranean area at 5.3 Ma.
B (Bottom): Palaeoenvironmental reconstruction of the Central Mediterranean area at 5.3 Ma.

Figure 16:
Monte Ferrara section belonging to the evaporitic Formation of the Castello Mounts, located SE of the Gargano Peninsula (Geographic location Figure 5). The base of the MSC Monte Ferrara succession lies conformably on the Serravallian-Tortonian Serra Palazzo Fm., where primary gypsum facies (massive, banded and branching selenite) are defined.

A major unconformity erodes the Primary Lower Gypsum, then overlapped by pluri-decametric PLG blocks and rich gypso-aneritic beds composing the Resedimented Lower Gypsum. Desiccation cracks and brecciated deposits at the level of the angular unconformity suggest a possible subaerial exposure of the whole Castello Evaporitic Fm. along the south Apennine Chain.

Supplementary material 1: Non-interpreted SW-NE oriented seismic profiles along the CAB. Confidential agreement with Spectrum did not allow us to publish the seismic profiles of the CRO132D campaign.

Supplementary material 2: Non-interpreted SW-NE oriented seismic profiles along the SAB. Confidential agreement with Spectrum did not allow us to publish the seismic profiles of the CRO132D campaign.

Figure 01

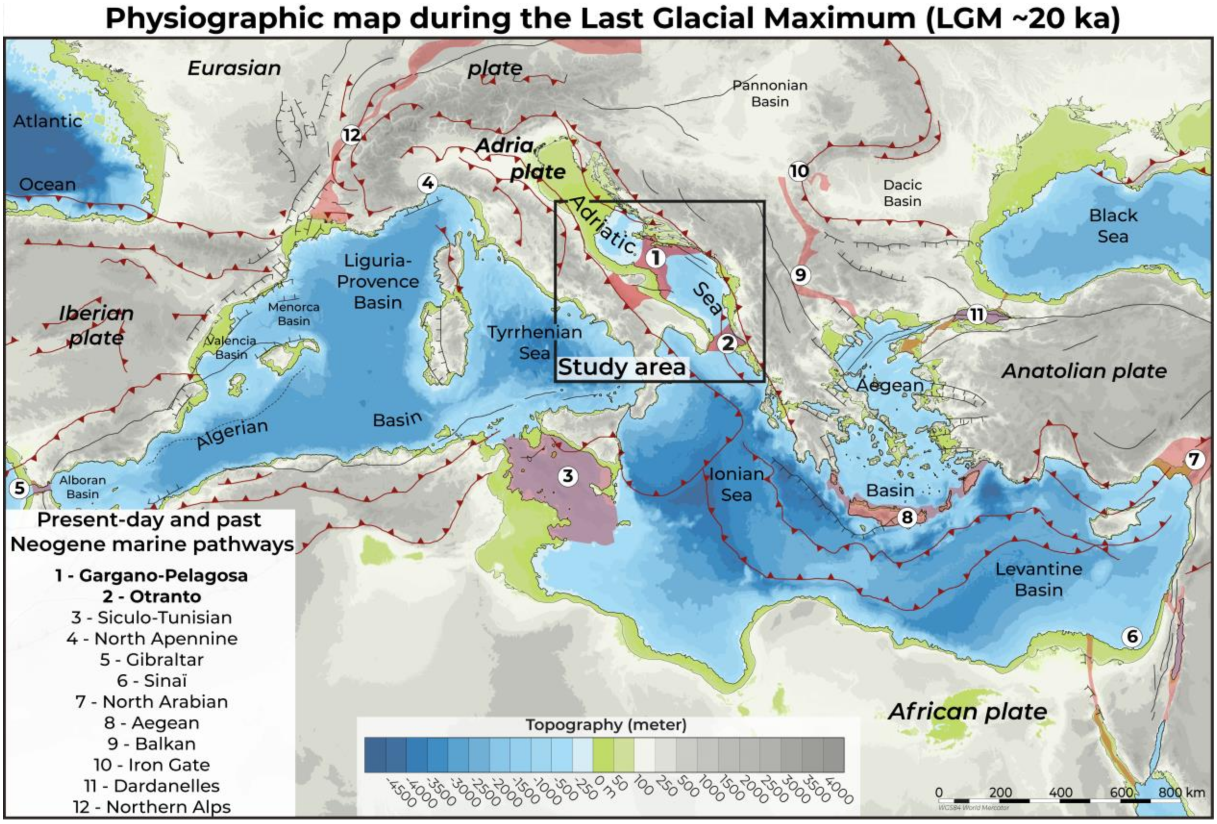
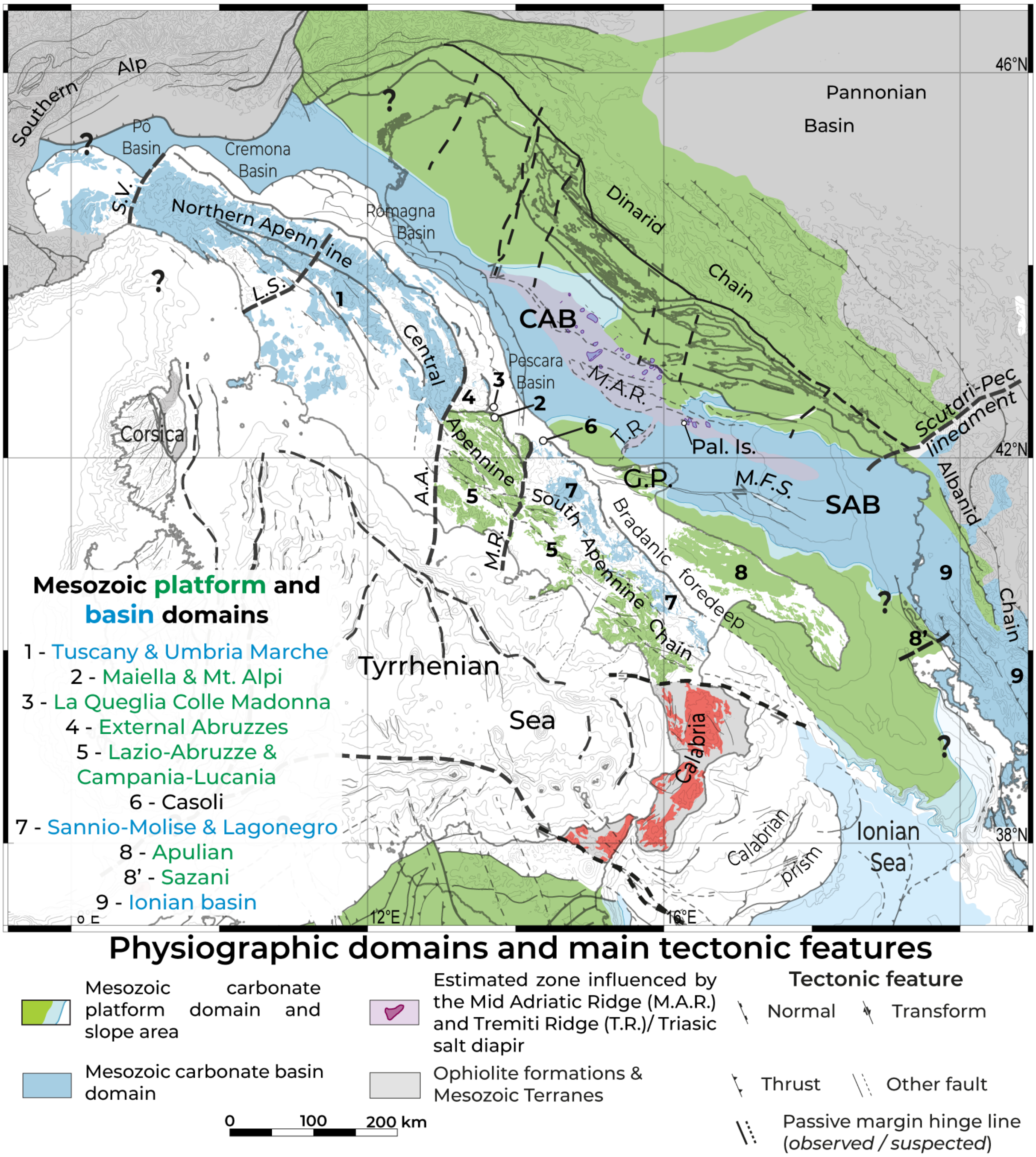

Physiographic map during the Last Glacial Maximum (LGM ~20 ka)
Eurasian
plate
Pannonian Basin
Atlantic
Ocean
Adria plate
Dacic Basin
Black Sea
Adriatic Sea
Liguria-Provence Basin
Iberian plate
Menorca Basin
Valencia Basin
Tyrrhenian Sea
Study area
Aegean
Anatolian plate
Algerian
Basin
Alboran Basin
Ionian Sea
Basin
Levantine Basin
African plate
Present-day and past Neogene marine pathways
1 - Gargano-Pelagosa
2 - Otranto
3 - Siculo-Tunisian
4 - North Apennine
5 - Gibraltar
6 - Sinaï
7 - North Arabian
8 - Aegean
9 - Balkan
10 - Iron Gate
11 - Dardanelles
12 - Northern Alps
Topography (meter)
-4500 -4000 -3500 -3000 -2500 -2000 -1500 -1000 -500 -250 0 m 50 100 250 500 1000 1500 2000 2500 3000 3500 4000
0 200 400 600 800 km

Figure 02



1383

Figure 03

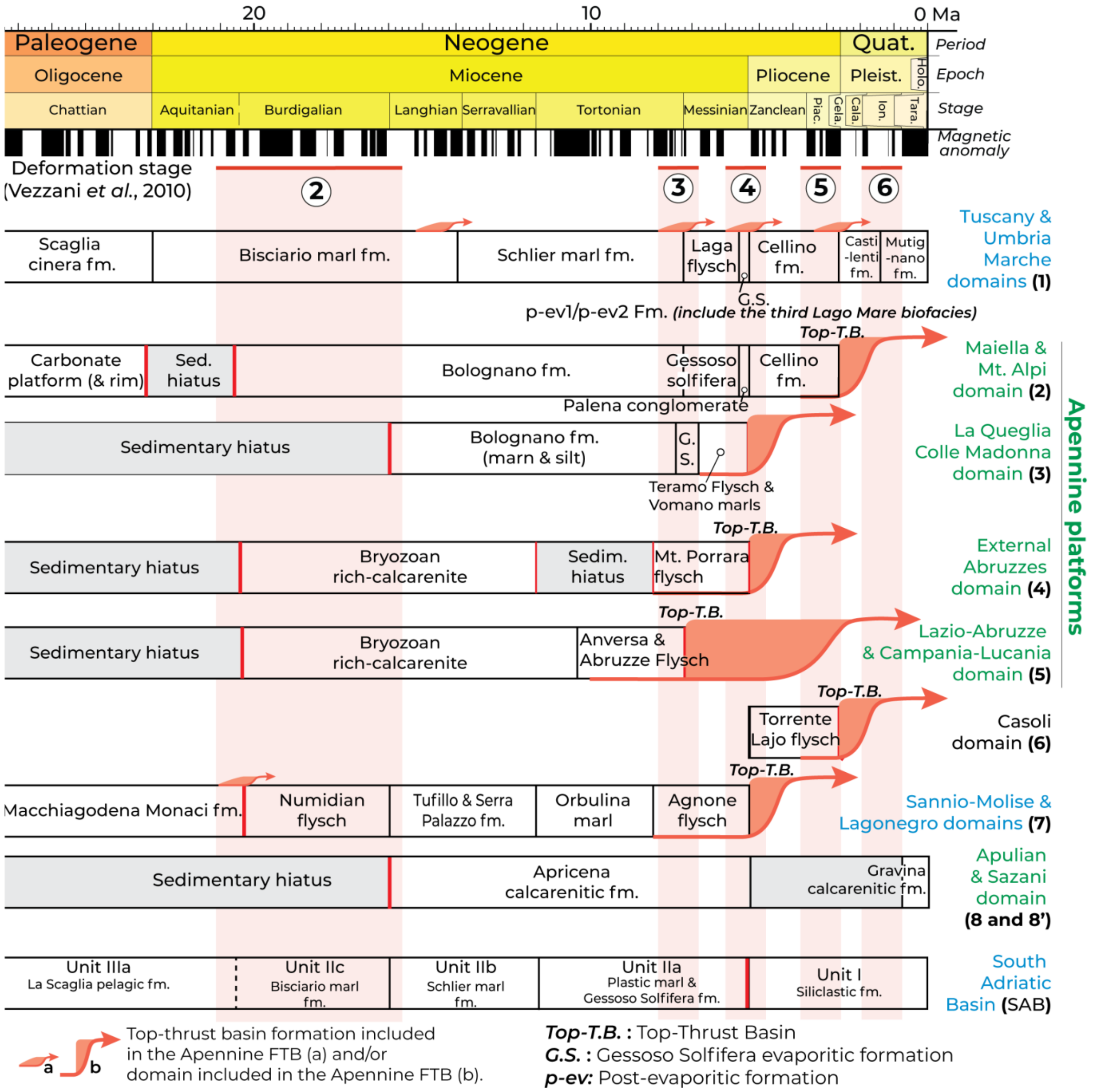

20
10
0 Ma
Paleogene
Neogene
Quat.
Period
Oligocene
Miocene
Pliocene
Pleist.
Holo.
Epoch
Chattian
Aquitanian
Burdigalian
Langhian
Serravallian
Tortonian
Messinian
Zanclean
Piac.
Gela.
Cala.
Ion.
Tara.
Stage
Magnetic anomaly
Deformation stage (Vezzani et al., 2010)
2
3
4
5
6
Scaglia cinera fm.
Bisciario marl fm.
Schlier marl fm.
Laga flysch
Cellino fm.
Castilenti fm.
Mutignano fm.
Tuscany & Umbria Marche domains (1)
G.S.
p-ev1/p-ev2 Fm. (include the third Lago Mare biofacies)
Top-T.B.
Carbonate platform (& rim)
Sed. hiatus
Bolognano fm.
Gessoso solfifera
Cellino fm.
Maiella & Mt. Alpi domain (2)
Palena conglomerate
Sedimentary hiatus
Bolognano fm. (marn & silt)
G. S.
Teramo Flysch & Vomano marls
La Queglia Colle Madonna domain (3)
Top-T.B.
Sedimentary hiatus
Bryozoan rich-calcarenite
Sedim. hiatus
Mt. Porrara flysch
External Abruzzes domain (4)
Top-T.B.
Sedimentary hiatus
Bryozoan rich-calcarenite
Anversa & Abruzze Flysch
Lazio-Abruzze & Campania-Lucania domain (5)
Apennine platforms
Top-T.B.
Torrente Lajo flysch
Casoli domain (6)
Top-T.B.
Macchiagodena Monaci fm.
Numidian flysch
Tufillo & Serra Palazzo fm.
Orbulina marl
Agnone flysch
Sannio-Molise & Lagonegro domains (7)
Sedimentary hiatus
Apricena calcarenitic fm.
Gravina calcarenitic fm.
Apulian & Sazani domain (8 and 8')
Unit IIIa La Scaglia pelagic fm.
Unit IIc Bisciario marl fm.
Unit IIb Schlier marl fm.
Unit IIa Plastic marl & Gessoso Solfifera fm.
Unit I Siliclastic fm.
South Adriatic Basin (SAB)
a
b
Top-thrust basin formation included in the Apennine FTB (a) and/or domain included in the Apennine FTB (b).
Top-T.B. : Top-Thrust Basin
G.S. : Gessoso Solfifera evaporitic formation
p-ev: Post-evaporitic formation

Figure 04

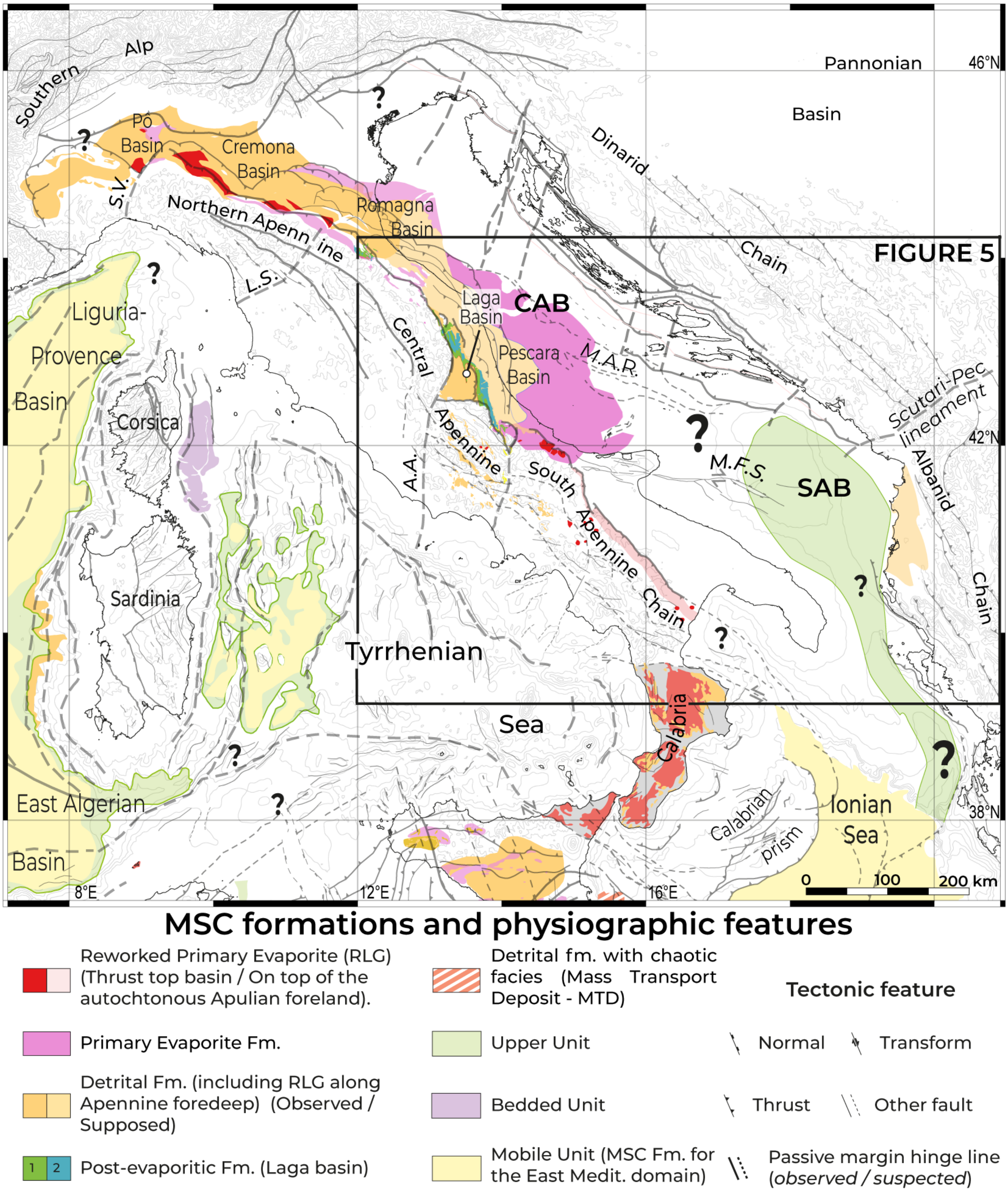
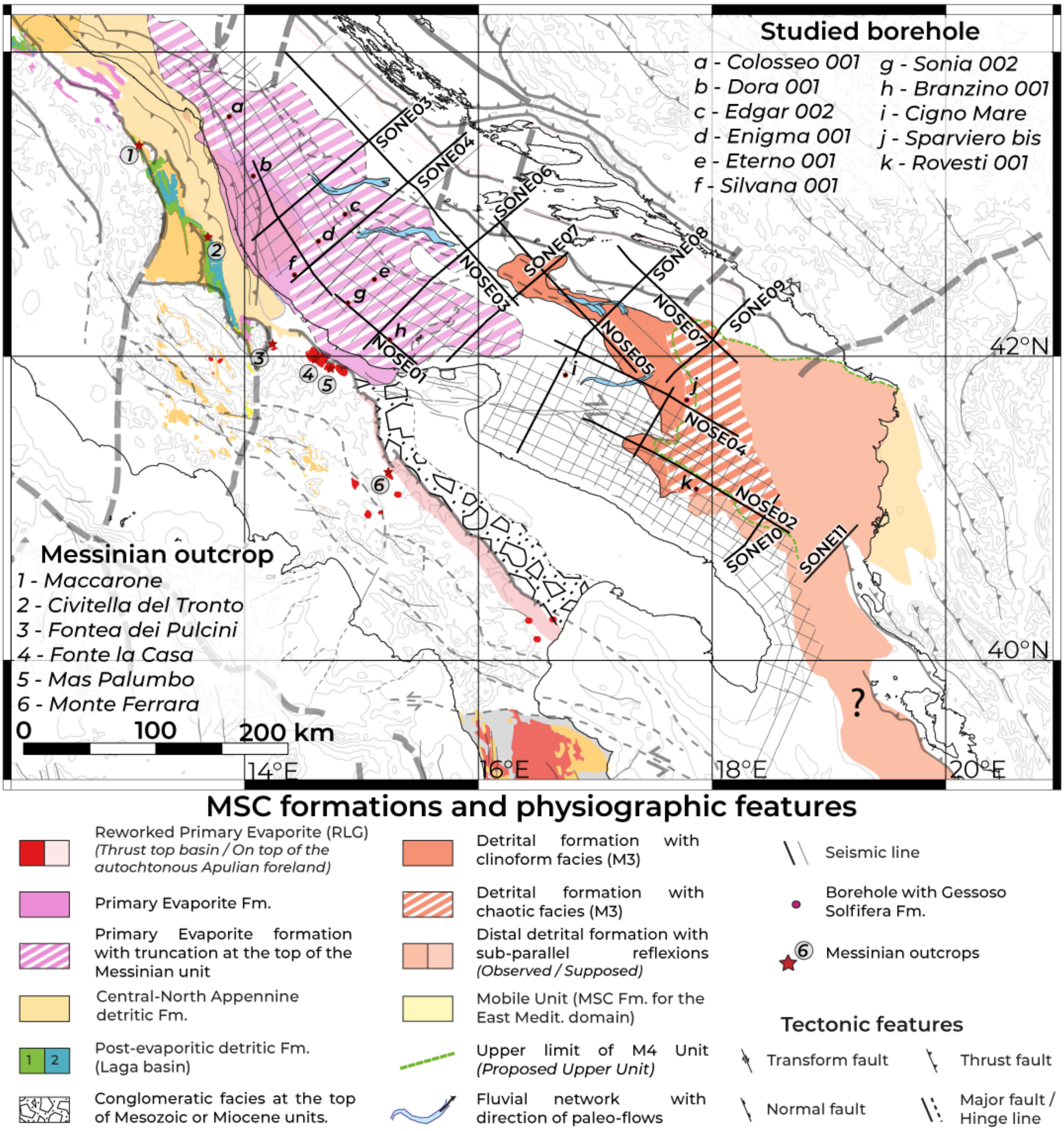

Southern Alp
Po Basin
Cremona Basin
S.V.
Northern Apenn ine
Romagna Basin
Dinarid
Chain
Pannonian
Basin
46°N
FIGURE 5
L.S.
Liguria-
Provence
Basin
Corsica
Central
Laga Basin
CAB
Pescara Basin
M.A.R.
Scutari-Pec lineament
42°N
Albanid
M.F.S.
SAB
Apennine
South
A.A.
Apennine
Chain
Sardinia
Tyrrhenian
Sea
Calabria
Calabrian prism
Ionian
Sea
Chain
East Algerian
Basin
8°E
12°E
16°E
38°N
0
100
200 km
MSC formations and physiographic features
Reworked Primary Evaporite (RLG) (Thrust top basin / On top of the autochtonous Apulian foreland).
Primary Evaporite Fm.
Detrital Fm. (including RLG along Apennine foredeep) (Observed / Supposed)
Post-evaporitic Fm. (Laga basin)
1
2
Detrital fm. with chaotic facies (Mass Transport Deposit - MTD)
Upper Unit
Bedded Unit
Mobile Unit (MSC Fm. for the East Medit. domain)
Tectonic feature
Normal
Transform
Thrust
Other fault
Passive margin hinge line (observed / suspected)

Figure 05



Studied borehole
a - Colosseo 001
b - Dora 001
c - Edgar 002
d - Enigma 001
e - Eterno 001
f - Silvana 001
g - Sonia 002
h - Branzino 001
i - Cigno Mare
j - Sparviero bis
k - Rovesti 001
SONE03
SONE04
SONE06
SONE07
SONE08
SONE09
SONE10
SONE11
NOSE01
NOSE02
NOSE03
NOSE04
NOSE05
NOSE07
42°N
40°N
14°E
16°E
18°E
20°E
?
Messinian outcrop
1 - Maccarone
2 - Civitella del Tronto
3 - Fontea dei Pulcini
4 - Fonte la Casa
5 - Mas Palumbo
6 - Monte Ferrara
0
100
200 km
MSC formations and physiographic features
Reworked Primary Evaporite (RLG)
(Thrust top basin / On top of the autochtonous Apulian foreland)
Primary Evaporite Fm.
Primary Evaporite formation with truncation at the top of the Messinian unit
Central-North Appennine detritic Fm.
Post-evaporitic detritic Fm. (Laga basin)
1
2
Conglomeratic facies at the top of Mesozoic or Miocene units.
Detrital formation with clinoform facies (M3)
Detrital formation with chaotic facies (M3)
Distal detrital formation with sub-parallel reflexions
(Observed / Supposed)
Mobile Unit (MSC Fm. for the East Medit. domain)
Upper limit of M4 Unit
(Proposed Upper Unit)
Fluvial network with direction of paleo-flows
Seismic line
Borehole with Gessoso Solfifera Fm.
Messinian outcrops
Tectonic features
Transform fault
Thrust fault
Normal fault
Major fault / Hinge line

Figure 06A

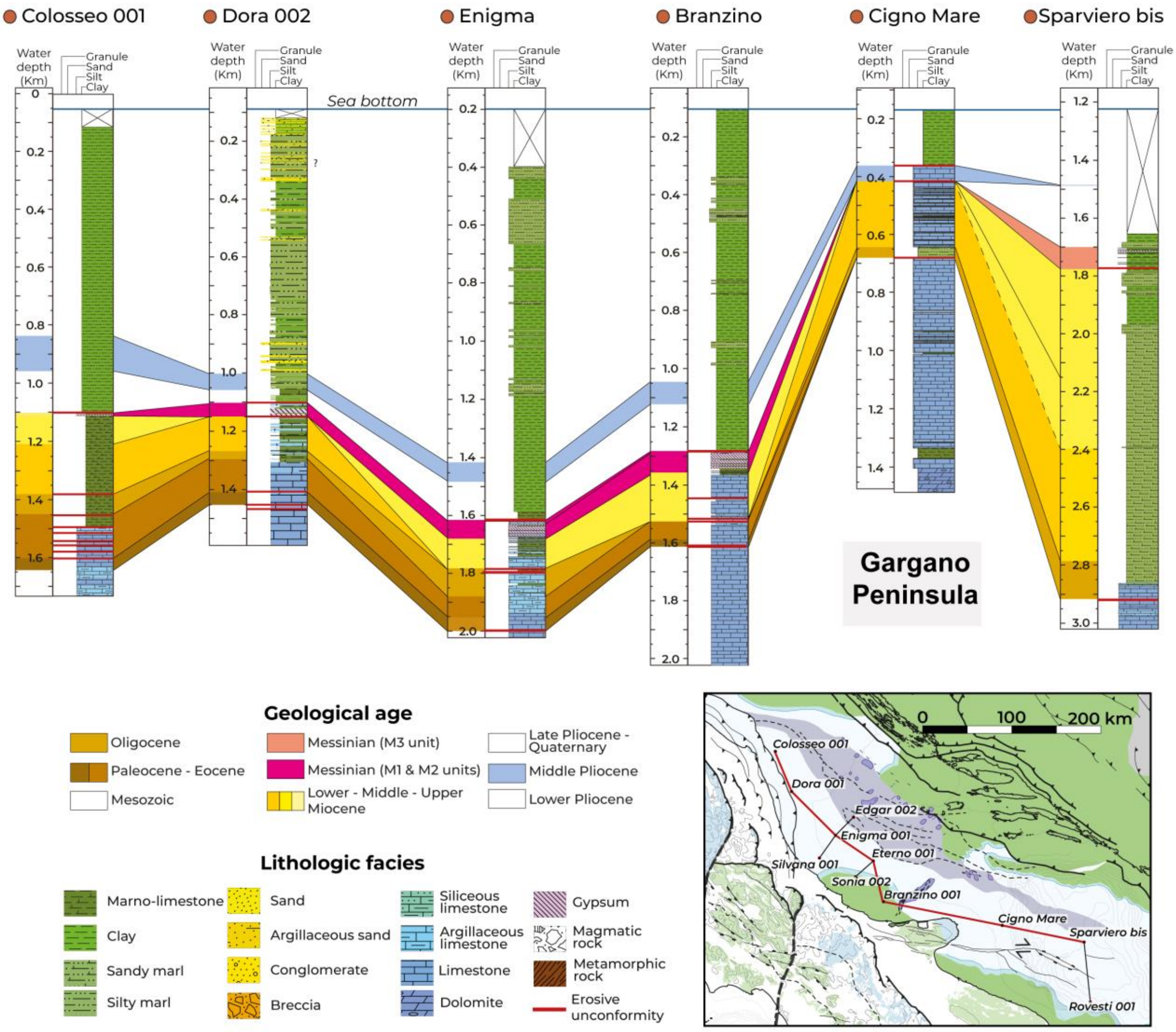

Colosseo 001
Dora 002
Enigma
Branzino
Cigno Mare
Sparviero bis
Water depth (Km)
Granule
Sand
Silt
Clay
Sea bottom
Gargano Peninsula
Geological age
Oligocene
Paleocene - Eocene
Mesozoic
Messinian (M3 unit)
Messinian (M1 & M2 units)
Lower - Middle - Upper Miocene
Late Pliocene - Quaternary
Middle Pliocene
Lower Pliocene
Lithologic facies
Marno-limestone
Clay
Sandy marl
Silty marl
Sand
Argillaceous sand
Conglomerate
Breccia
Siliceous limestone
Argillaceous limestone
Limestone
Dolomite
Gypsum
Magmatic rock
Metamorphic rock
Erosive unconformity
0
100
200 km
Colosseo 001
Dora 001
Edgar 002
Enigma 001
Eterno 001
Silvana 001
Sonia 002
Branzino 001
Cigno Mare
Sparviero bis
Rovesti 001

Figure 06B

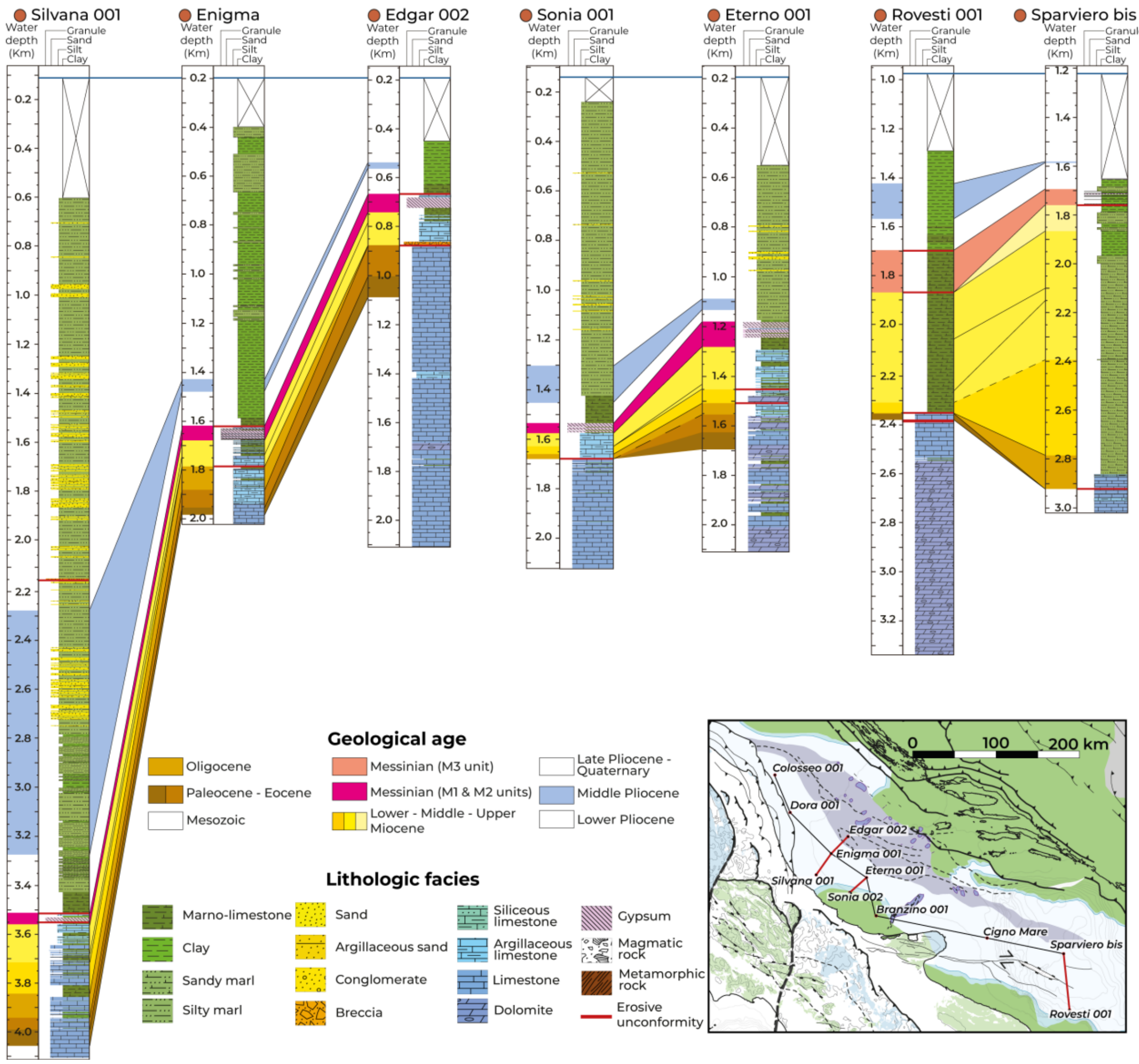
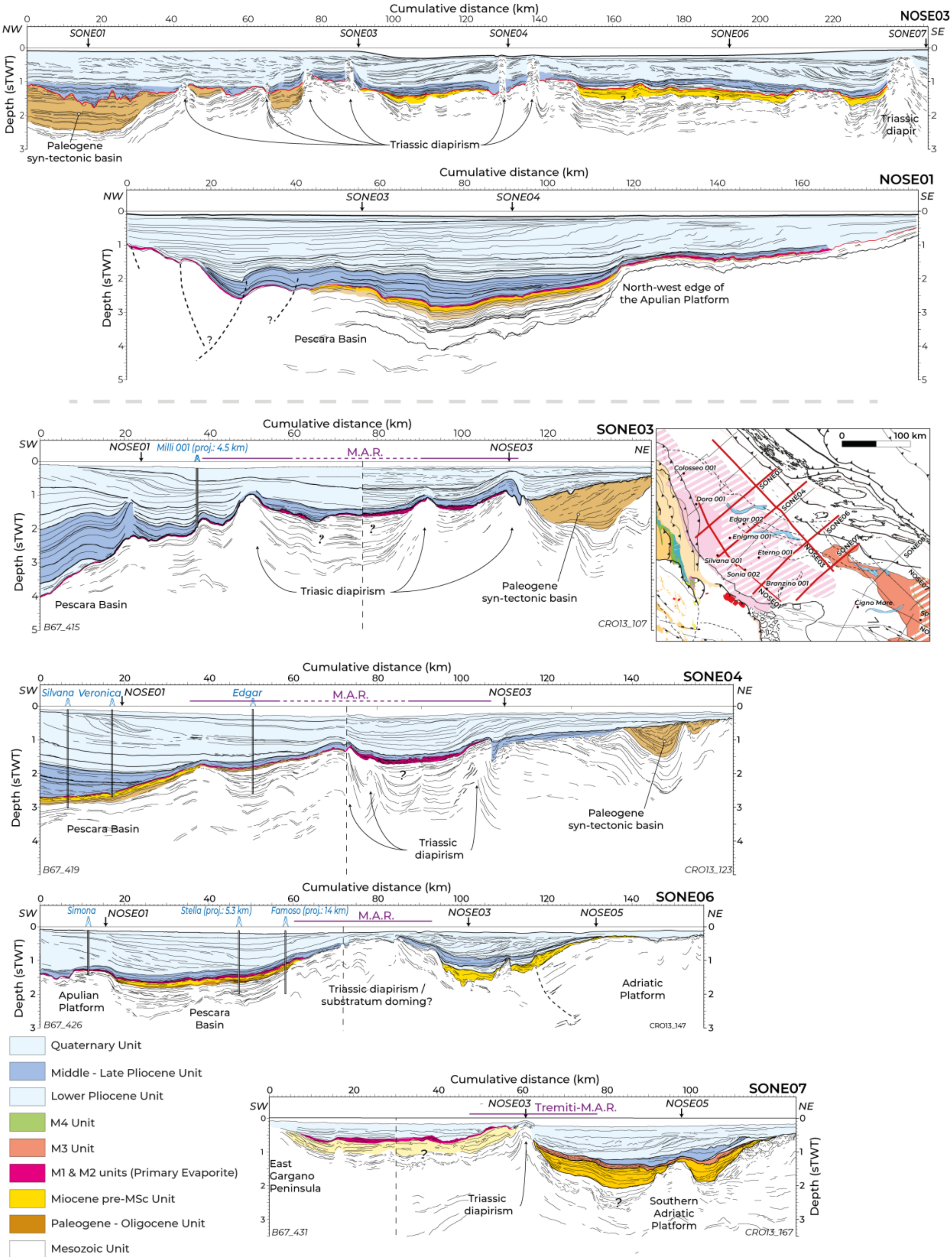
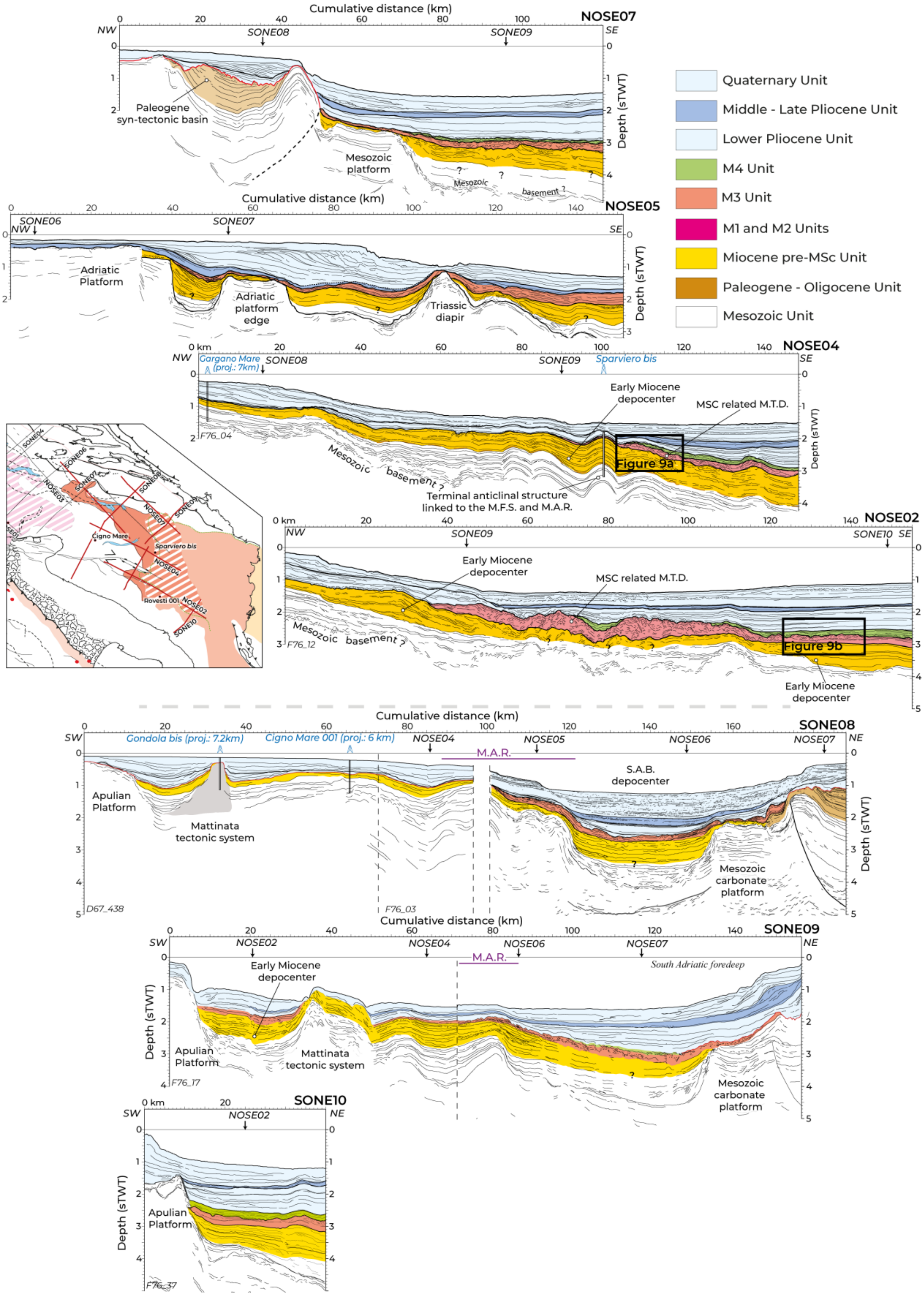

Silvana 001
Enigma
Edgar 002
Sonia 001
Eterno 001
Rovesti 001
Sparviero bis
Water depth (Km)
Granule
Sand
Silt
Clay
Geological age
Oligocene
Paleocene - Eocene
Mesozoic
Messinian (M3 unit)
Messinian (M1 & M2 units)
Lower - Middle - Upper Miocene
Late Pliocene - Quaternary
Middle Pliocene
Lower Pliocene
Lithologic facies
Marno-limestone
Clay
Sandy marl
Silty marl
Sand
Argillaceous sand
Conglomerate
Breccia
Siliceous limestone
Argillaceous limestone
Limestone
Dolomite
Gypsum
Magmatic rock
Metamorphic rock
Erosive unconformity
0
100
200 km
Colosseo 001
Dora 001
Edgar 002
Enigma 001
Eterno 001
Silvana 001
Sonia 002
Branzino 001
Cigno Mare
Sparviero bis
Rovesti 001

Figure 07



NOSE03
Cumulative distance (km)
NW
SE
SONE01
SONE03
SONE04
SONE06
SONE07
Depth (sTWT)
Paleogene syn-tectonic basin
Triassic diapirism
Triassic diapir
NOSE01
Pescara Basin
North-west edge of the Apulian Platform
SONE03
SW
NE
NOSE01
Milli 001 (proj.: 4.5 km)
M.A.R.
NOSE03
Triasic diapirism
Paleogene syn-tectonic basin
B67_415
CRO13_107
0
100 km
Colosseo 001
Dora 001
Edgar 002
Enigma 001
Eterno 001
Silvana 001
Sonia 002
Branzino 001
Cigno Mare
SONE04
Silvana
Veronica
Edgar
Triassic diapirism
B67_419
CRO13_123
SONE06
Simona
Stella (proj.: 5.3 km)
Famoso (proj.: 14 km)
NOSE05
Apulian Platform
Pescara Basin
Triassic diapirism / substratum doming?
Adriatic Platform
B67_426
CRO13_147
Quaternary Unit
Middle - Late Pliocene Unit
Lower Pliocene Unit
M4 Unit
M3 Unit
M1 & M2 units (Primary Evaporite)
Miocene pre-MSc Unit
Paleogene - Oligocene Unit
Mesozoic Unit
SONE07
Tremiti-M.A.R.
East Gargano Peninsula
Southern Adriatic Platform
B67_431
CRO13_167

Figure 08



Cumulative distance (km)
NOSE07
NW
SE
SONE08
SONE09
Paleogene
syn-tectonic basin
Mesozoic
platform
Mesozoic
basement ?
Depth (sTWT)
Quaternary Unit
Middle - Late Pliocene Unit
Lower Pliocene Unit
M4 Unit
M3 Unit
M1 and M2 Units
Miocene pre-MSc Unit
Paleogene - Oligocene Unit
Mesozoic Unit
NOSE05
SONE06
SONE07
Adriatic
Platform
Adriatic
platform
edge
Triassic
diapir
NOSE04
Gargano Mare
(proj.: 7km)
Sparviero bis
Early Miocene
depocenter
MSC related M.T.D.
Figure 9a
F76_04
Mesozoic basement ?
Terminal anticlinal structure
linked to the M.F.S. and M.A.R.
Cigno Mare
Sparviero bis
Rovesti 001
NOSE02
SONE10
Figure 9b
F76_12
Early Miocene
depocenter
SONE08
SW
NE
Gondola bis (proj.: 7.2km)
Cigno Mare 001 (proj.: 6 km)
NOSE04
NOSE05
NOSE06
NOSE07
M.A.R.
S.A.B.
depocenter
Apulian
Platform
Mattinata
tectonic system
Mesozoic
carbonate
platform
D67_438
F76_03
SONE09
NOSE02
South Adriatic foredeep
F76_17
SONE10
F76_37

Figure 09

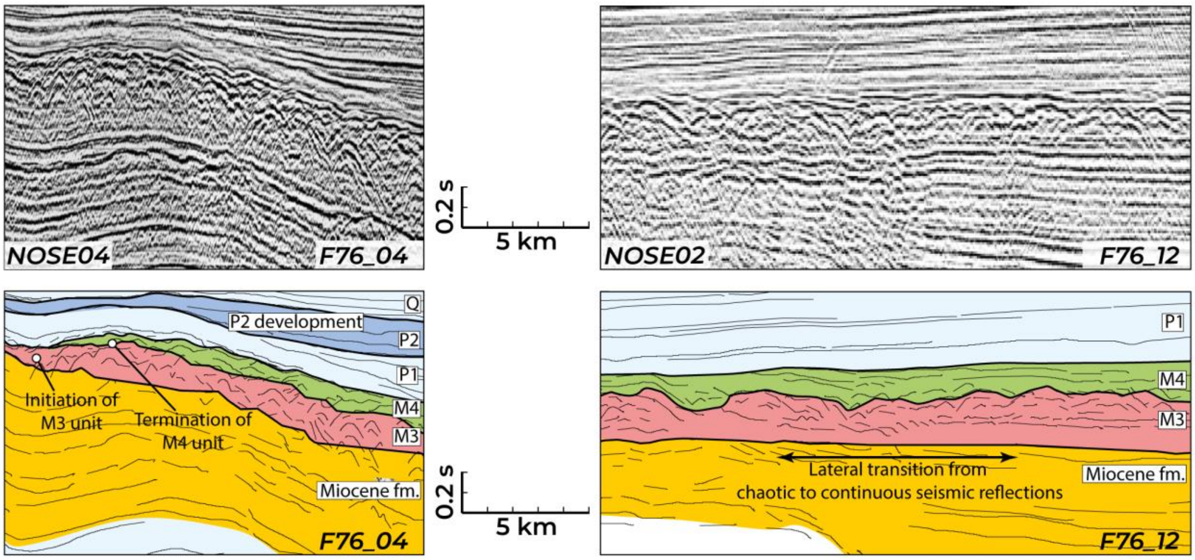

NOSE04
F76_04
0.2 s
5 km
NOSE02
F76_12
Q
P2 development
P2
P1
M4
M3
Initiation of M3 unit
Termination of M4 unit
Miocene fm.
F76_04
0.2 s
5 km
P1
M4
M3
Lateral transition from chaotic to continuous seismic reflections
Miocene fm.
F76_12

Figure 10

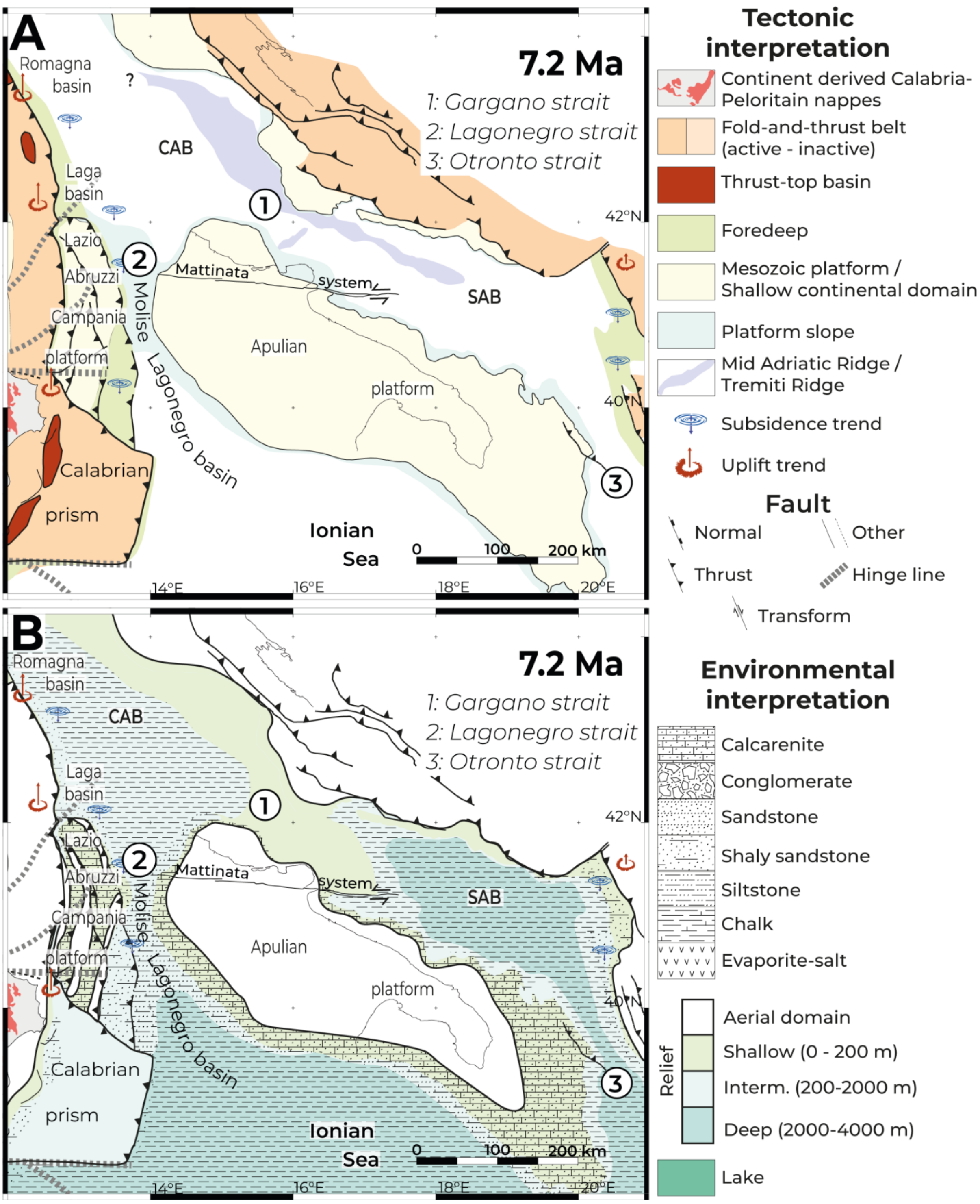

A
7.2 Ma
1: Gargano strait
2: Lagonegro strait
3: Otronto strait
Romagna basin
CAB
Laga basin
Lazio
Abruzzi
Campania
platform
Molise
Lagonegro basin
Mattinata
system
SAB
Apulian
platform
Calabrian
prism
Ionian
Sea
42°N
40°N
14°E
16°E
18°E
20°E
0
100
200 km
B
7.2 Ma
1: Gargano strait
2: Lagonegro strait
3: Otronto strait
Tectonic interpretation
Continent derived Calabria-Peloritain nappes
Fold-and-thrust belt (active - inactive)
Thrust-top basin
Foredeep
Mesozoic platform / Shallow continental domain
Platform slope
Mid Adriatic Ridge / Tremiti Ridge
Subsidence trend
Uplift trend
Fault
Normal
Other
Thrust
Hinge line
Transform
Environmental interpretation
Calcarenite
Conglomerate
Sandstone
Shaly sandstone
Siltstone
Chalk
Evaporite-salt
Relief
Aerial domain
Shallow (0 - 200 m)
Interm. (200-2000 m)
Deep (2000-4000 m)
Lake

Figure 11

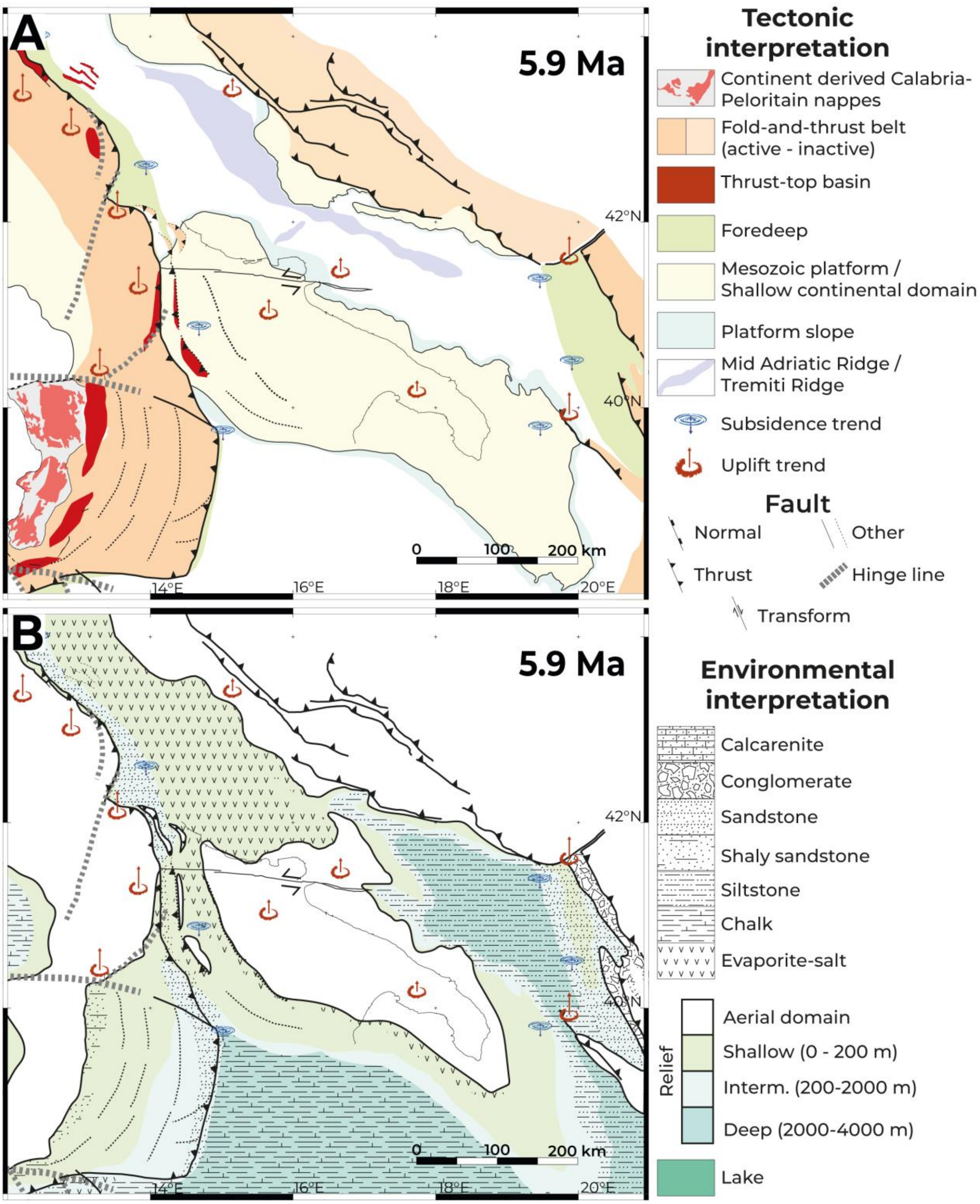

A
5.9 Ma
B
5.9 Ma
42°N
40°N
14°E
16°E
18°E
20°E
0
100
200 km
Tectonic interpretation
Continent derived Calabria-Peloritain nappes
Fold-and-thrust belt (active - inactive)
Thrust-top basin
Foredeep
Mesozoic platform / Shallow continental domain
Platform slope
Mid Adriatic Ridge / Tremiti Ridge
Subsidence trend
Uplift trend
Fault
Normal
Other
Thrust
Hinge line
Transform
Environmental interpretation
Calcarenite
Conglomerate
Sandstone
Shaly sandstone
Siltstone
Chalk
Evaporite-salt
Relief
Aerial domain
Shallow (0 - 200 m)
Interm. (200-2000 m)
Deep (2000-4000 m)
Lake

Figure 12

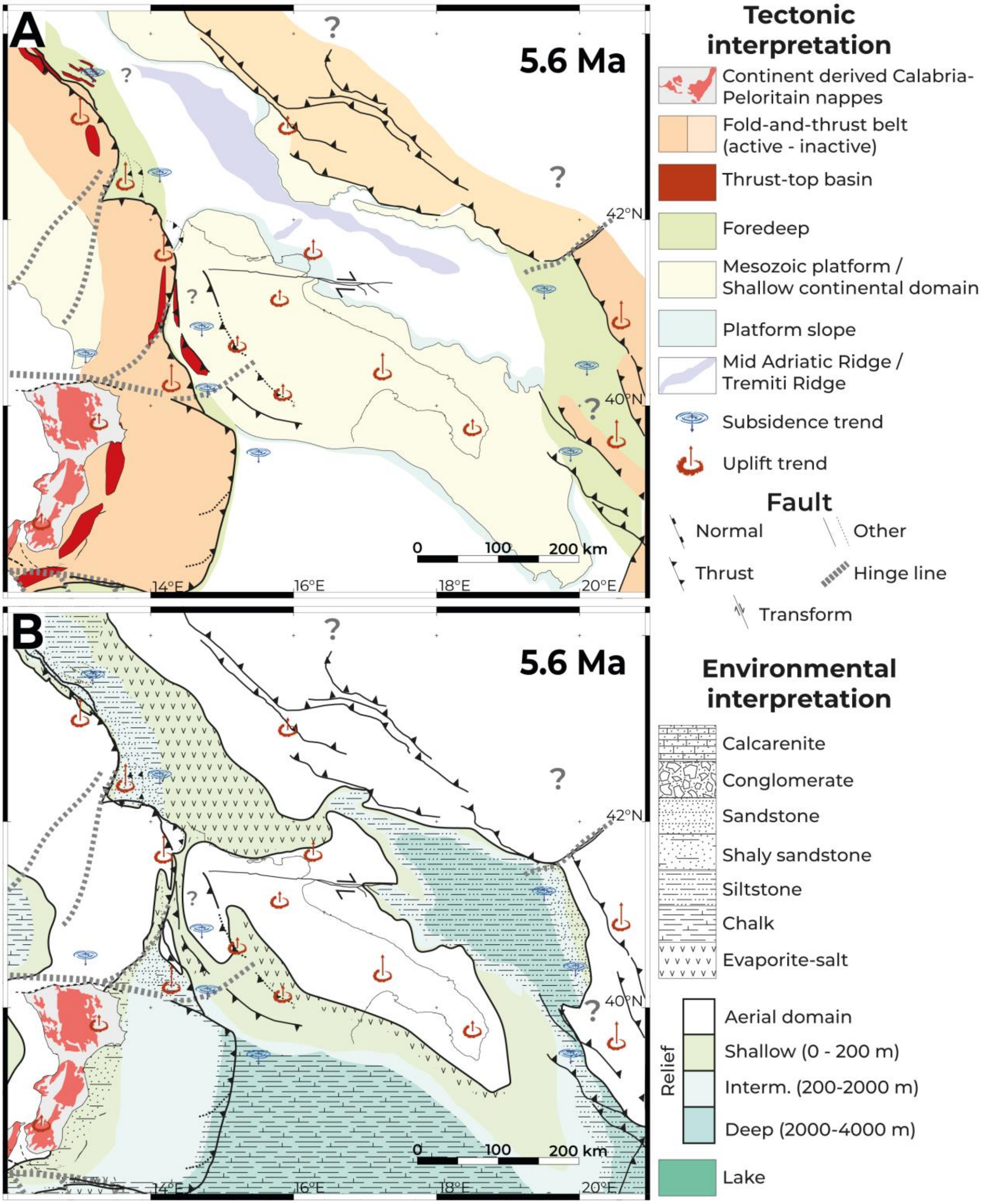

A
5.6 Ma
B
5.6 Ma
14°E
16°E
18°E
20°E
42°N
40°N
0
100
200 km
Tectonic interpretation
Continent derived Calabria-Peloritain nappes
Fold-and-thrust belt (active - inactive)
Thrust-top basin
Foredeep
Mesozoic platform / Shallow continental domain
Platform slope
Mid Adriatic Ridge / Tremiti Ridge
Subsidence trend
Uplift trend
Fault
Normal
Other
Thrust
Hinge line
Transform
Environmental interpretation
Calcarenite
Conglomerate
Sandstone
Shaly sandstone
Siltstone
Chalk
Evaporite-salt
Relief
Aerial domain
Shallow (0 - 200 m)
Interm. (200-2000 m)
Deep (2000-4000 m)
Lake

Figure 13

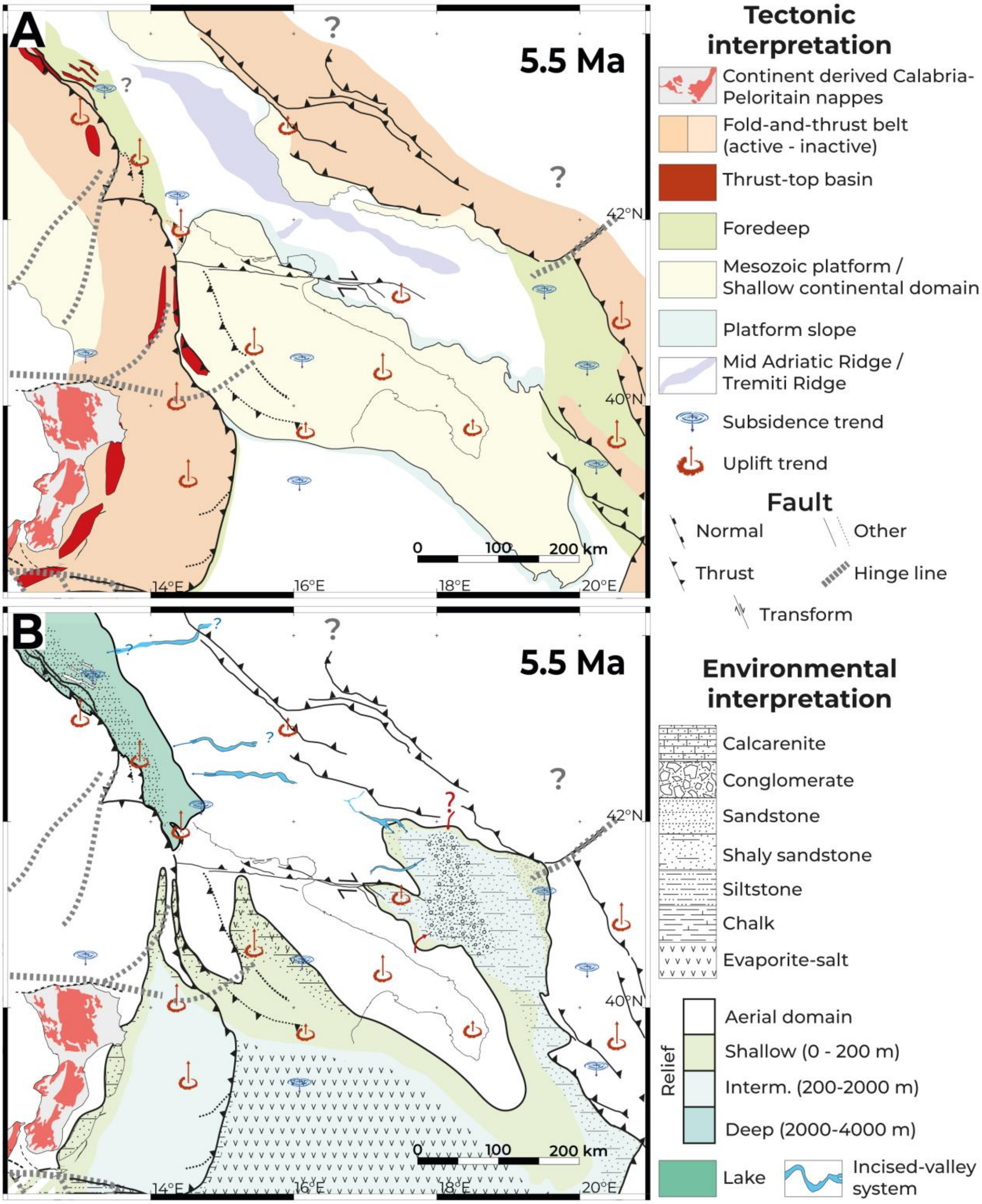
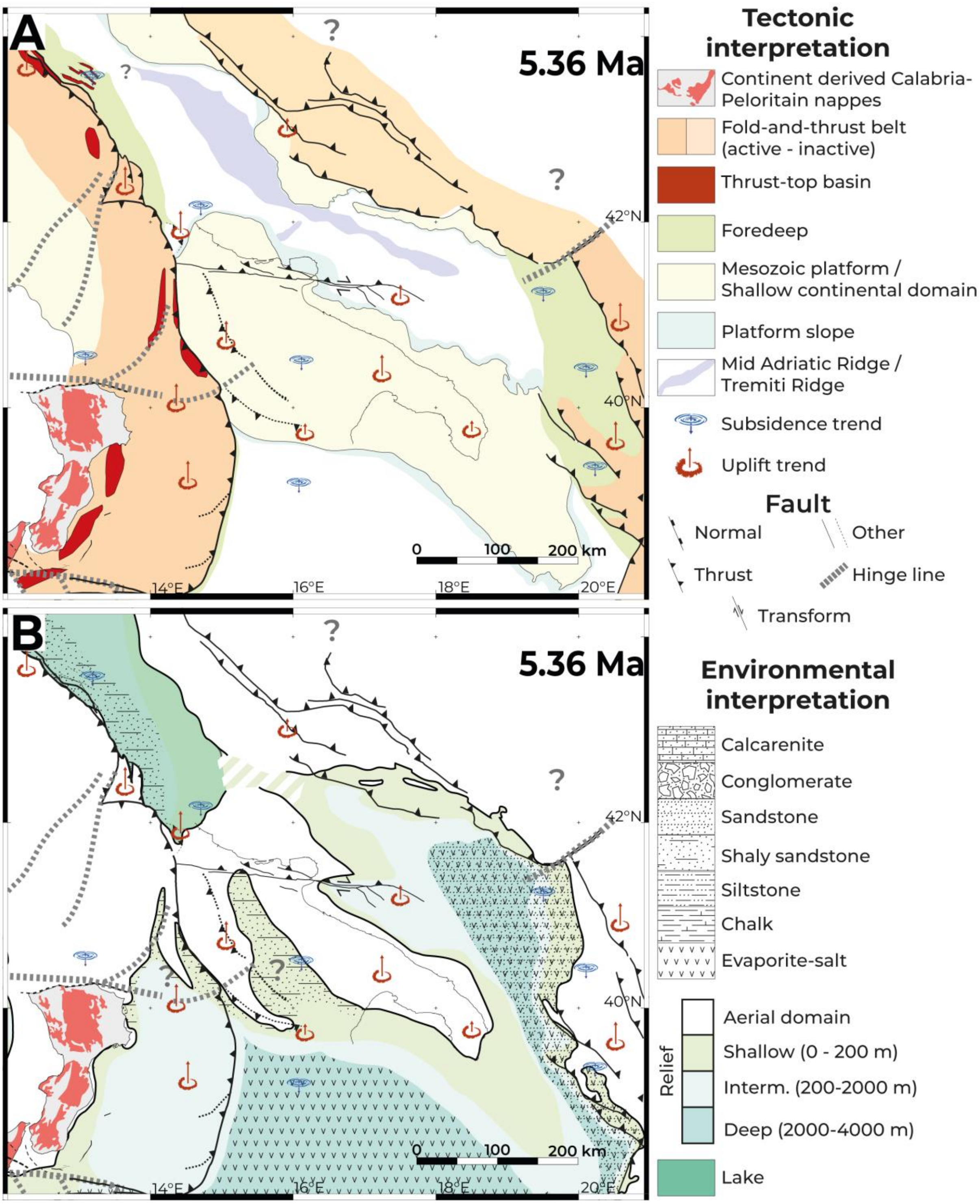

A
5.5 Ma
B
5.5 Ma
42°N
40°N
14°E
16°E
18°E
20°E
0
100
200 km
Tectonic interpretation
Continent derived Calabria-Peloritain nappes
Fold-and-thrust belt (active - inactive)
Thrust-top basin
Foredeep
Mesozoic platform / Shallow continental domain
Platform slope
Mid Adriatic Ridge / Tremiti Ridge
Subsidence trend
Uplift trend
Fault
Normal
Other
Thrust
Hinge line
Transform
Environmental interpretation
Calcarenite
Conglomerate
Sandstone
Shaly sandstone
Siltstone
Chalk
Evaporite-salt
Relief
Aerial domain
Shallow (0 - 200 m)
Interm. (200-2000 m)
Deep (2000-4000 m)
Lake
Incised-valley system

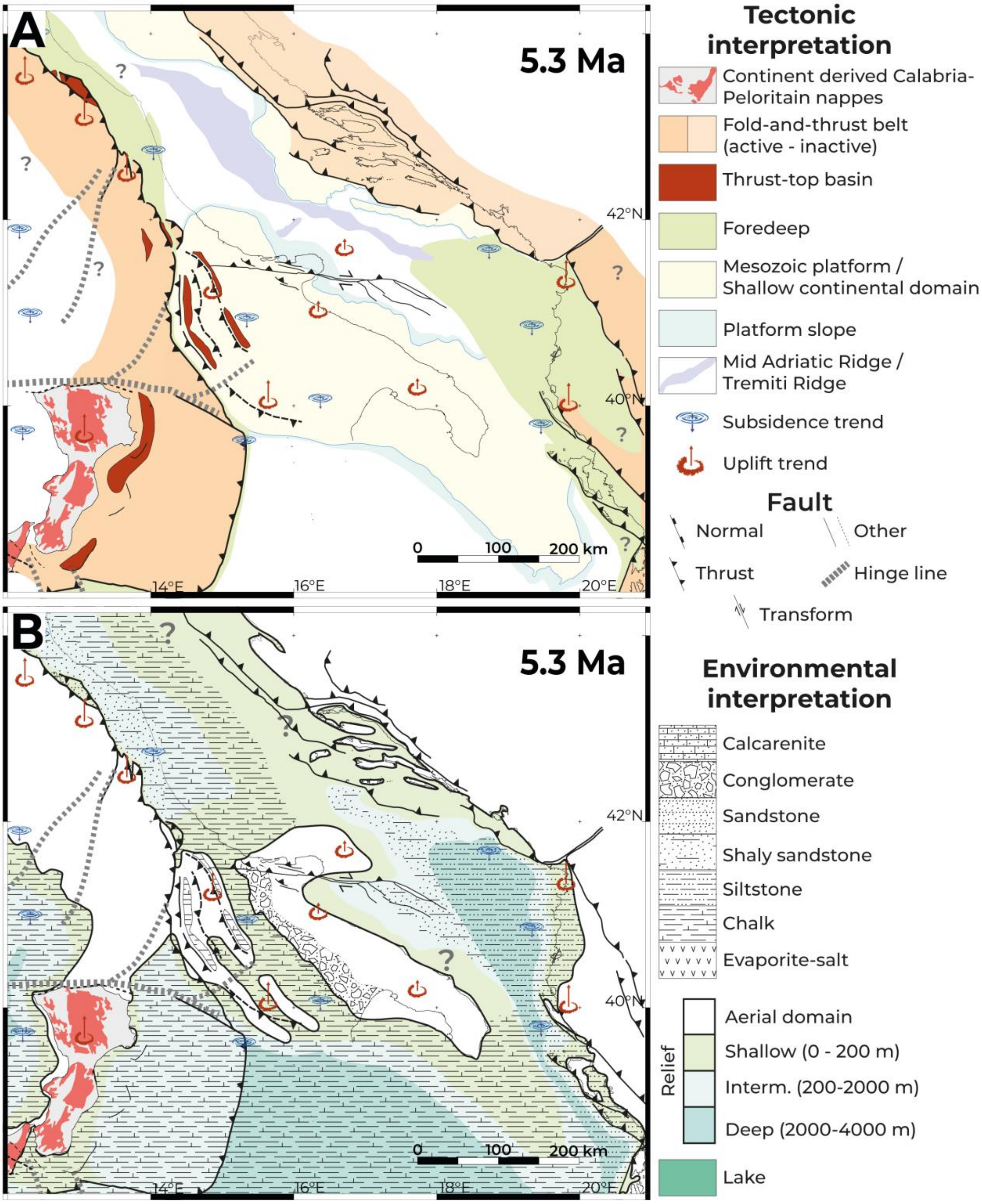
Figure 14



A
5.36 Ma
B
5.36 Ma
?
42°N
40°N
14°E
16°E
18°E
20°E
0
100
200 km
Tectonic interpretation
Continent derived Calabria-Peloritain nappes
Fold-and-thrust belt (active - inactive)
Thrust-top basin
Foredeep
Mesozoic platform / Shallow continental domain
Platform slope
Mid Adriatic Ridge / Tremiti Ridge
Subsidence trend
Uplift trend
Fault
Normal
Other
Thrust
Hinge line
Transform
Environmental interpretation
Calcarenite
Conglomerate
Sandstone
Shaly sandstone
Siltstone
Chalk
Evaporite-salt
Relief
Aerial domain
Shallow (0 - 200 m)
Interm. (200-2000 m)
Deep (2000-4000 m)
Lake

1410

Figure 15



1411

Figure 16

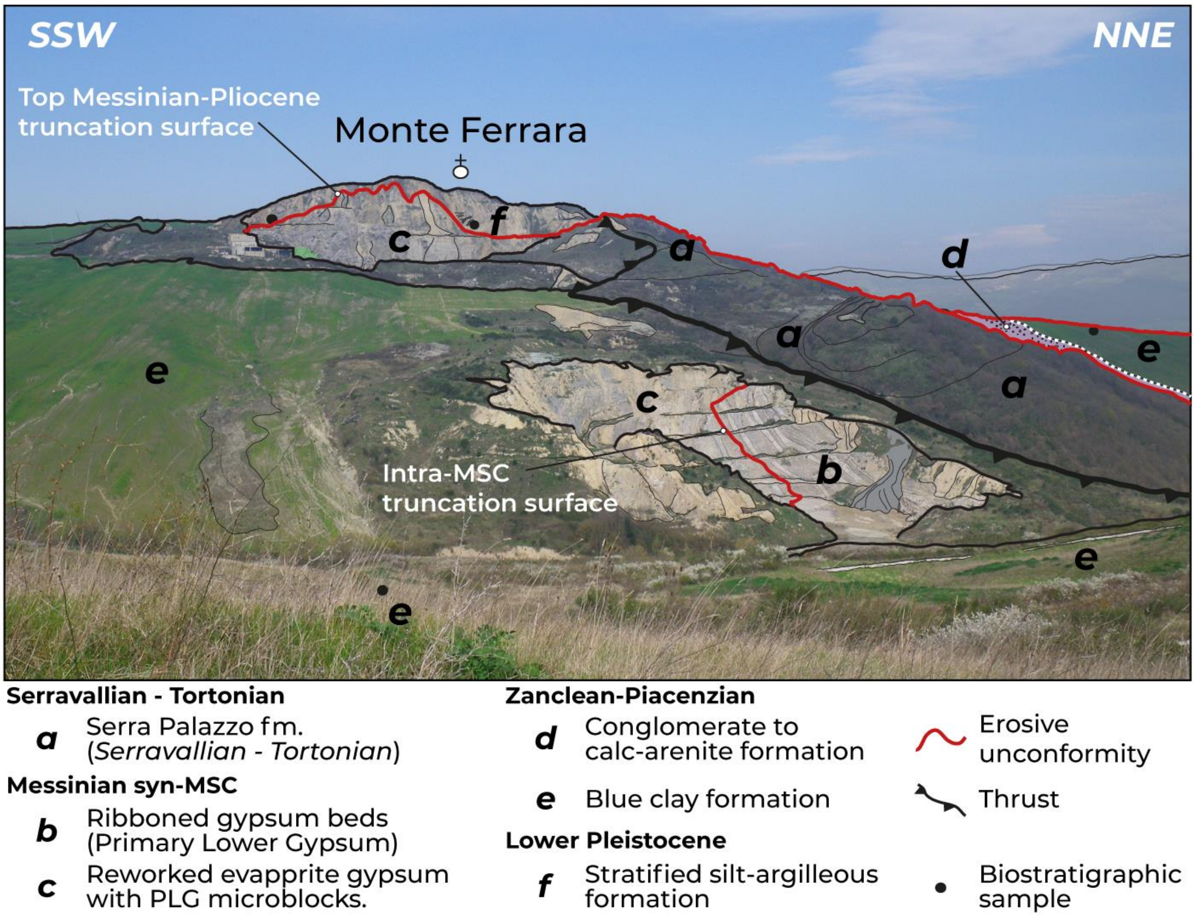

SSW
NNE
Top Messinian-Pliocene truncation surface
Monte Ferrara
c
f
a
d
a
e
a
e
c
Intra-MSC truncation surface
b
e
e
Serravallian - Tortonian
a Serra Palazzo fm. (Serravallian - Tortonian)
Messinian syn-MSC
b Ribboned gypsum beds (Primary Lower Gypsum)
c Reworked evapprite gypsum with PLG microblocks.
Zanclean-Piacenzian
d Conglomerate to calc-arenite formation
e Blue clay formation
Lower Pleistocene
f Stratified silt-argilleous formation
Erosive unconformity
Thrust
Biostratigraphic sample

Table 01

Central Apennine stratigraphy

Pô plain: Ghielmi *et al.*, 2010		Romagna Basin: Roveri et al., 2004, 2005 – Marginal basins	Romagna Basin: Deep basins	Romagna Basin: Sequence		Age	Laga Basin: Artoni, 1993 – allounits	Laga Basin: Artoni, 2003 – allounits	Laga Basin: Milli et al., 2007 – allounits	Milli et al., 2007 – sequence	Centamore and Nisio, 2003 – sequence		Centamore and Nisio, 2003 – Lithostratigraphic units
PL_1		Argile Azurre	Argile Azurre	U.B.S.U.			Unit 0	Pliocene	Laga 3	Cellino depositional sequence	Pla	P1	
M_4	LM	Colombacci fm.	Colombacci fm.	p-ev2	MP	5.33 Ma	Colombacci unit	p-ev2			M3b	M3	Post-evaporitic member
M_3		hiatus; intra-messinian unconformity	S. Donato fm.; *ash layer*; Sapigno fm.; Resedimented evaporite	p-ev1		5.42 Ma	post-ev pelitic unit; post-ev arenaceous fm.	U4; p-ev1; post-ev arenaceous fm.			M3a; M2b		
M_2		Vena del Gesso fm. (ex. Gessoso Solfifera fm. shallow water member) Autochtonous evaporite	*'euxinix shales'*		T_2	5.6 Ma	Evaporitic member	U3; ev	I3; Laga 2	Laga depositional sequence	M2a	M2	Evaporitic member
M_1	T_2					5.97 Ma	Pre-evaporitic member	U2; pre-ev	I2; Laga 1		M1	M1	Pre-evaporitic member
		Marnoso-arenacea fm. *'euxinic shales'*				7.25 Ma	Cerrogna marls	U1; Cerrogna marls	I1; Cerrogna marls	Marnoso depo. seq.			Cerrogna marls and Pteropoda

Table 02

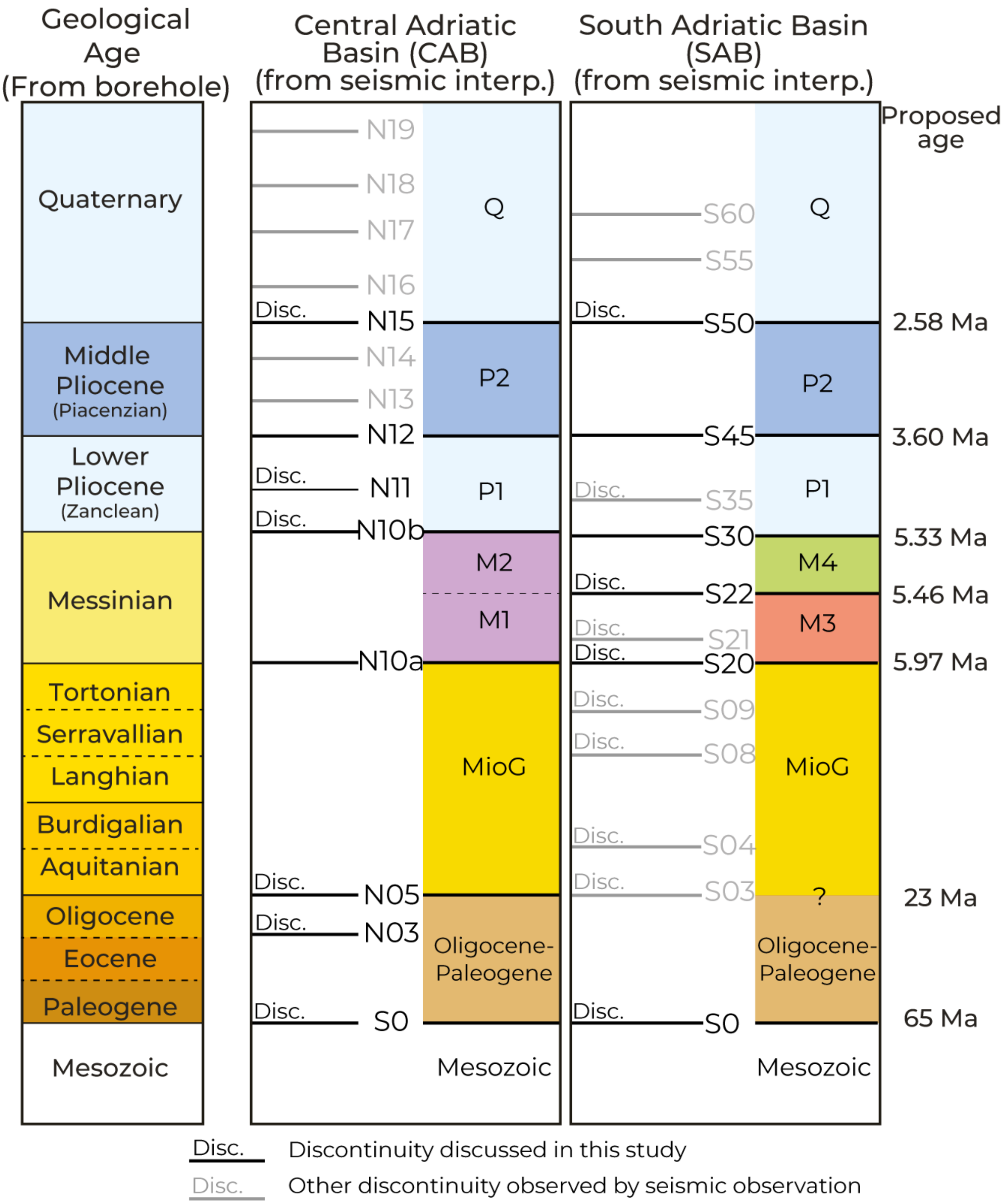

Geological Age (From borehole)
Central Adriatic Basin (CAB) (from seismic interp.)
South Adriatic Basin (SAB) (from seismic interp.)
Proposed age
Quaternary
Middle Pliocene (Piacenzian)
Lower Pliocene (Zanclean)
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Oligocene
Eocene
Paleogene
Mesozoic
N19
N18
N17
N16
Disc.
N15
N14
N13
N12
N11
N10b
N10a
N05
N03
S0
Q
P2
P1
M2
M1
MioG
Oligocene-Paleogene
S60
S55
S50
S45
S35
S30
S22
S21
S20
S09
S08
S04
S03
M4
M3
?
2.58 Ma
3.60 Ma
5.33 Ma
5.46 Ma
5.97 Ma
23 Ma
65 Ma
Disc. Discontinuity discussed in this study
Disc. Other discontinuity observed by seismic observation

Table 03

Magnetic anomaly / Aged step	Geological age (Ma)	Rotation parameters		
		Latitude	Longitude	Angle
Motion of Adria vs Eurasian plate (Sioni, 1996)				
Ano0	0.0	0	0	0
Ano6	20.0	42.8	5.1	-5.7
Motion of Calabria vs Eurasian plate (this study)				
Ano0	0.0	0	0	0
Age2.5	2.5	-14.9	-168.9	-3.0
Age4	4.0	-14.3	-170.5	-4.8
Age7.2	7.2	-14.3	-170.5	-8.7
Ano6	20.0	47.0	12.9	-47.8
Motion of Africa-Sicily vs Eurasian plate (Fidalgo, 2001)				
Ano0	0.0	0	0	0
Ano5	8.92	15.2	-20.4	-0.9
Ano6	20.0	15.0	-18.6	-2.1