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The role of the Messinian evaporites in the identification of potential gas storage sites: A review of the Adriatic foreland basin system (Italy)

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Abstract

Focusing on the late Miocene succession stratigraphic successions including the evaporite deposits from the Messinian salinity crisis (MSC) of the Adriatic foreland basin, a revision of available boreholes and seismic data allowed us to recognize the presence of reservoirs and seals systems that can be considered of potential interest for the storage of natural and synthetic gas. Potentially good reservoir sites can be found where porous rocks referable to siliciclastic turbiditites (Marnoso-arenacea and Laga Fms) or shallow-water carbonates (Bolognano Fm) preferentially involved in anticlinal structures and covered by thick MSC evaporites, which may represent effective reservoir seals. The integrated reconstruction of porous rocks distribution and facies, thickness, and lateral continuity of the overlying evaporites, allows the identification and zonation of geological settings in the Adriatic foredeep, backbulge and foreland with peculiar stratigraphy and deformations, only partially considered before, that may deserve consideration in the research of potential gas storage sites.

KEYWORDS

Adriatic foreland basin system, carbon capture and storage, evaporites, gas storage, Messinian

1 | INTRODUCTION

What will be the increase in Earth's average temperature in the next decades due to global warming is a strongly debated argument. A larger agreement in the scientific community regards the elevated, and never achieved in the recent past, values of carbon dioxide concentration in the atmosphere and its important role as a greenhouse gas in global warming (IPCC, 2018).

Among the different strategies to reduce the atmospheric concentration of carbon dioxide, the process of carbon capture usage and storage aims at capturing carbon dioxide from industrial waste, reusing and storing it into exhausted hydrocarbon reservoirs (Bashir et al., 2024; Boot-Handford et al., 2014; Bradshaw et al., 2007; Bui et al., 2018; Civile et al., 2013; Proietti et al., 2023; Volpi et al., 2015). Depleted and no longer exploitable reservoirs are of great interest also for the creation of stocks of natural gas, like methane or hydrogen, in the subsoil. In shorter terms, this storage policy is aimed at protecting the European and national economies from sudden increases in hydrocarbon prices caused by production and transportation issues, also in relationships with both armed and commercial world conflicts. At longer terms, the possibility of storing large amounts of gas, as in the case of hydrogen, is pivotal for the independence from hydrocarbons and the green transition journey (Bashir et al., 2024; Duffy et al., 2022).

Whatever the gas type and the purposes for its storage, the availability of effective reservoirs is among the priorities of European countries, especially those, like Italy, with reduced availability of hydrocarbon resources. From the geological point of view, the definition of a potential site of gas storage is based on (i) the existence of a significant volume of reservoir rocks and (ii) the presence of an effective top seal or structural trap able to avoid leaking of the stored gas (Bachu et al., 2007; Bashir et al., 2024; Volpi et al., 2015).

Preliminary investigations for potential storage of natural gas in the Italian territory were based on a large amount of borehole and reflection seismic data acquired during intensive campaigns for hydrocarbon explorations in the Apennines foreland basin system since the early 1970s (Casero & Bigi, 2013; Cremonini & Ricci Lucchi, 1982; Fantoni et al., 2003; Fantoni & Franciosi, 2010; Ghielmi et al., 2013; Manzi et al., 2020; Pellen et al., 2017, 2022; Rizzini, 2005; Rossi et al., 2015). The overall evolutionary scenario for this region includes the late Tortonian-early Messinian deposition of thick sandstone turbidites (mainly Marnoso-arenacea and Laga Fms; Milli et al., 2007; Mutti & Ricci, 1972; Ricci Lucchi, 1986) and shelfal carbonates (Bolognano Fm; Brandano et al., 2013, 2016, 2020), both providing potential good reservoir rocks, subsequently covered by thick Messinian evaporites, representing a potential effective seal. Preliminary statistical analyses for the recognition of suitable geological units as storage reservoirs in the Po Plain were recently performed (Benetatos, 2023; Buttinelli et al., 2011; Colucci et al., 2016; Donda et al., 2011; Livani et al., 2023). Moreover, late Miocene salt deposits were preliminary investigated for the recognition of potential hydrogen storage caverns (Benetatos et al., 2020).

Despite such recent works for potential reservoir identifications, we observe that: (i) the investigations addressed a small portion of the Italian territory; (ii) the research has been limited to Pliocene or Mesozoic porous rocks; (iii) the distribution of the different evaporitic facies has been largely overlooked; (iv) the seal properties of the evaporites have never been considered. To overcome such limitations, we have reviewed available borehole and seismic data, in order to: (i) recognize potential areas/sites useful for gas storage in the late Miocene succession of the Adriatic foreland basin system; (ii) differentiate and qualitatively evaluate the potential reservoirs on the basis of lithology, thickness, sedimentological properties and tectonic deformation; (iii) recognize the presence of a potential evaporite seal; and (iv) qualitatively evaluate the seal properties (facies, thickness, lateral continuity) of the evaporitic unit.

Highlights

- Messinian sulfates are potential seals for natural gas storage.
- A thick and continuous evaporite unit if found in the Adriatic foredeep.
- Late Miocene porous units are preserved below the evaporites.
- New potential sites for natural gas storage can be recognized.

2 | GEOLOGICAL SETTING

The study area is located in the foredeep and foreland systems (De Celles & Giles, 1996) of the Northern and Central Apennines, which is bounded by the exhumed Apennine chain to the southwest. The Apennine thrust-and-fold belt is undergoing northeastward accretion against the Adriatic microplate, which is indenting into the European plate (Figure 1a).

During the late Miocene, the Apennines orogenic system underwent an overall structural re-organization, including one of the most important outward migration steps of the deformation front, which caused partial segmentation of the outer foredeep and its incorporation into the inner foredeep as wedge-top basins at the thrust wedge toe (Ricci Lucchi, 1986). The foredeep was filled by the Marnoso-arenacea and Laga Fms siliciclastic turbidites, mainly fed by the Alps extending all along the Northern and Central Apennines. During the subsequent Messinian salinity crisis (MSC), km-thick evaporitic units accumulated in the deep Mediterranean settings. In the Adriatic foredeep, during the first stage of the crisis (5.97–5.60 Ma), up to 250 m-thick primary evaporites (Primary Lower Gypsum, PLG; Lugli et al., 2007, 2010) were deposited in the wedge-top basins, to the west, and in the back-bulge basin, to the east. The latter area hosted the largest evaporitic marginal basin of the entire Mediterranean basin (Manzi et al., 2020). The PLG unit is characterized by an impressive lateral continuity allowing stratigraphic correlations at the scale of the whole Mediterranean basin (Lugli et al., 2010). The Messinian erosional surface (MES; Roveri, Flecker, et al., 2014), of both subaerial and

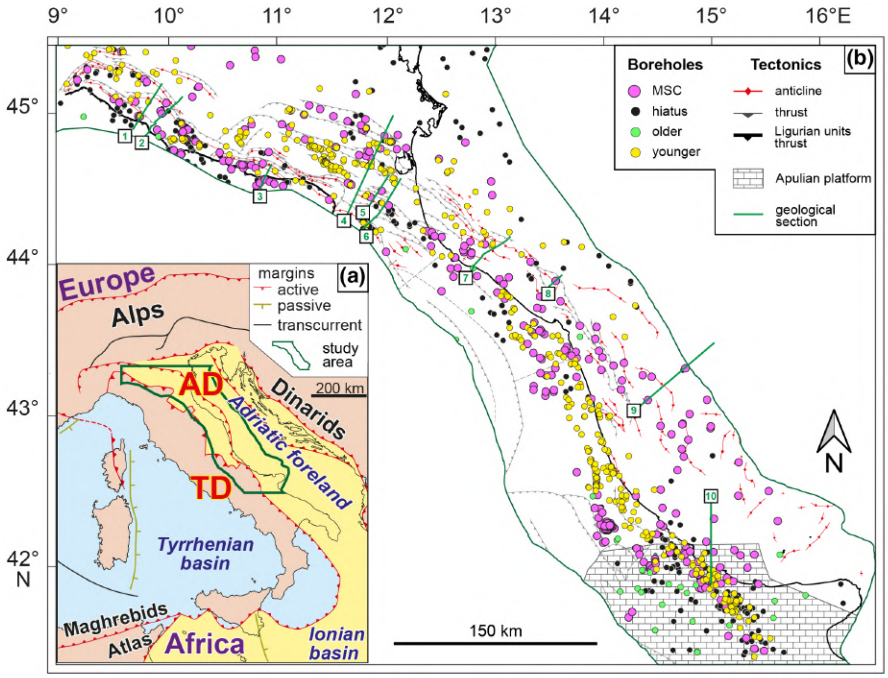

FIGURE 1 (a) Geological-structural map of Italy illustrating the main tectonic structures; AD Adriatic domain; TD Tyrrhenian domain. (b) Location of boreholes and seismic profiles used in this work. The main tectonic structures and the traces of the cross sections presented in this work are also indicated.

subaqueous origin, irregularly cuts the top of the PLG unit. The generation of this erosional surface during the second stage of the crisis (5.60–5.55 Ma) is associated, with the dismantlement of the PLG unit and its resedimentation in the morphological lows as a large variety of gravity-driven clastic deposits including gypsum-bearing mass-wastes and turbidites (Manzi et al., 2005; Parea & Ricci Lucchi, 1972; Ricci Lucchi, 1973). Differently from what occurred in other parts of the Mediterranean, no halite deposits accumulated in the Adriatic foredeep basin system. The third and final stage of the salinity crisis was characterized by the reprise of the siliciclastic sedimentation following the enhancement of the meteoric precipitations and ended with the return of fully marine conditions at the beginning of the Pliocene (5.33 Ma; Roveri, Flecker, et al., 2014; Roveri, Lugli, et al., 2014; Van Couvering et al., 2000 and reference therein).

After the Messinian, the Apennine orogen tectonic evolution included: (i) overthrusting of the Umbro-Marche-Romagna succession by the allochthonous Ligurian units during the Pliocene; (ii) foreland tilting of thrusts wedge tip region induced by out-of-sequence thrusting in the basement (Roveri et al., 2003) and (iii) strong subsidence of thousands of meters of the foredeep, as witnessed by the present-day burial depth of shallow water Tortonian and Messinian (PLG) deposits (Manzi et al., 2020).

3 | METHODS

Our work is based on the ViDEPI database (Visibilità dei Dati afferenti all'attività di Esplorazione Petrolifera in Italia; Visibility of petroleum exploration data in Italy), which contains released data related to the Italian hydrocarbon exploration (including expired mining permits and concessions) filed since 1957 by the National Mining Office for hydrocarbon and geothermal energy (UNIMIG) of the Ministry for Economic Development. The ViDEPI data, which can be freely (http://www.videpi.com/videpi/videpi.asp), include:

- Up to 2305 boreholes were drilled in Italy from 1895 to 2016; with a detailed final well log (scale 1:1000), commonly including a lithologic log and some geophysical logs (mainly Gamma Ray, Resistivity and Sonic).
- More than 3000 seismic lines from reconnaissance campaigns of the offshore marine areas and for characterizing areas potentially suitable for hydrocarbon extraction.

In this work, the main stratigraphic data have been obtained from the boreholes, whereas seismic profiles have been used only to verify the units' lateral continuity and to highlight the presence of tectonic structures.

3.1 | Well logs

We focused on the boreholes crossing the late Tortonian-early Pliocene stratigraphic interval defined on the basis of the biostratigraphic information as a very helpful support for stratigraphic correlations. Up to 1306 boreholes from the ViDEPI database are located in the Northern and Central Apennines and in the Adriatic offshore

(ViDEPI zones A and B; Figure 1b; SI-BOREHOLES.xlsx). Among these, 950 were not considered because drilled in younger (574) or in older (30) deposits, or because the MSC interval is not preserved due to erosion (325). Other boreholes (21) with unreadable logs were discarded. Consequently, we analyzed the remaining 356 boreholes crossing the MSC units. They have been grouped according to the types of both evaporitic and pre-evaporitic deposits. The evaporitic deposits of the large part of these boreholes have been described by Manzi et al. (2020). In this work, we have refined and implemented the study of the dataset in order to reconstruct:

1. The distribution of the Late Tortonian pre-evaporitic deposits, providing potential reservoir rocks paying attention to separate individual sandstone, marl and shale, and carbonate deposits.
2. The thickness of potential reservoir rocks (in particular of the Bolognano Fm).
3. The distribution of Messinian evaporites as potential reservoir seals; the evaporites have been differentiated according to the criteria of Manzi et al. (2020) into PLG and Resedimented Lower Gypsum (RLG) mainly on the basis of the bed thickness (20–30 m versus1–5 m, respectively), geophysical logs pattern (blocky vs. spiky), and resistivity (200–600 vs. 400–1000 Ohm•m).
4. The thickness of the evaporite seal, differentiating PLG from RLG, when possible.
5. The presence of anhydrite versus gypsum (commonly indicated in the original description as whitish gypsum or crystalline gypsum, respectively).
6. The presence of an erosional surface, recognizable as the MES above the PLG unit or below the RLG unit.
7. The presence of terrigenous upper Messinian (Lagomare) or Pliocene deposits above the evaporites.

3.2 | Seismic reflection profiles

Due to the poor quality and low resolution, the industrial seismic reflection profiles available on ViDEPI cannot provide reliable stratigraphic details of the late Tortonian-early Pliocene succession; thus, these data were only qualitatively analyzed to verify the correlatability of the lithostratigraphic units and recognize the presence of tectonic structures (Manzi et al., 2020). Moreover, in this work, we have added details regarding the thickness and typology of the evaporitic deposits and standardized the use of the stratigraphic units of some published line drawings of seismic reflection profiles (Manzi et al., 2020; Proietti et al., 2023; Rizzini, 2005) that in our opinion are very useful to describe the main tectonic structures potentially hosting reservoirs.

3.3 | Isopach and structural maps

We obtained the thickness of the evaporites and of the Bolognano Fm directly from borehole data; The Marnoso-arenacea Fm and the Schlier Fm, commonly exceeding hundreds of meters in thickness, were not measured. Only in those areas with high lateral continuity and sub-horizontal bed dips (confirmed by seismic profiles and dipmeter data) we have considered the thickness obtained from boreholes as the real thickness; consequently, we have reconstructed the isopach maps using a manual interpolation based on three near points with no reduction factor. Adopting the same procedure, interpolating the data from boreholes, we have reconstructed the contour lines of the depth of the top of the evaporitic seal (both PLG and RLG), the thickness of the post-evaporitic successions and the isopach maps of the evaporites.

4 | RESERVOIR AND SEALS STRATIGRAPHIC FRAMEWORK

4.1 | Potential reservoirs

By definition, a good reservoir rock is characterized by a high and interconnected porosity that can have a primary (textural) or a secondary (tectonic) origin, or both; among the sedimentary rocks, the highest porosities are commonly observed in sandstone and shallow water carbonate rocks (Warren, 2006). Reservoir quality is controlled by the degree of homogeneity and by the volumetric distribution of the petrophysical properties. Among the potential reservoirs existing in the Adriatic foredeep, we have focused on the late Miocene deposits below the Messinian evaporites, which are commonly overlooked in previous studies typically focusing on the Mesozoic carbonate plays developed in the Calcare Massiccio and Scaglia Fms or in the Pliocene siliciclastic turbiditic systems of the Porto Corsini and Porto Garibaldi Fms (Civile et al., 2013; Donda et al., 2011; Livani et al., 2023; Proietti et al., 2022, 2023; Volpi et al., 2015). Thus, we focused on pre-MSC deposits capped by evaporites. Among them, according to the original reconstruction of the main migration steps of the foreland basin system in the Northern Apennines (Ricci Lucchi, 1986) from the Oligocene to Recent, we identified three main types of sedimentary units (Figure 2): *clastic fills* (representing the coarse-grained turbiditic deposits accumulated in the more subsiding portion of

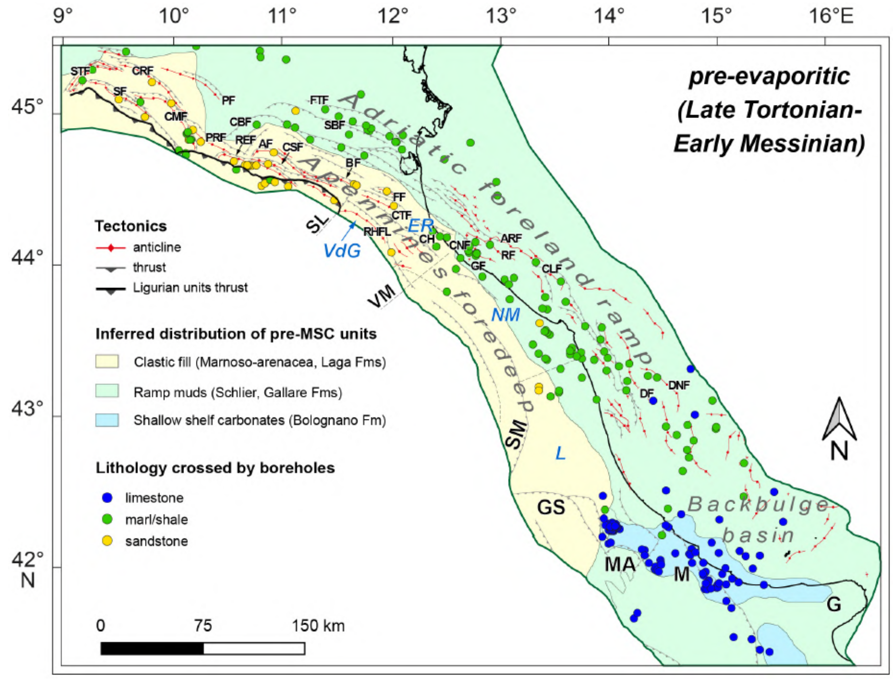

FIGURE 2 Map of the late Miocene pre-evaporitic units in the Adriatic foredeep providing potential sites for carbon capture and storage. A lithological distinction of the different pre-evaporitic deposits is reported for each available borehole. Main thrust Fronts: AF, Albareto; ARF, Arabella; BF, Budrio; CBF, Cavone-Bova; CLF, Cornelia; CMF, Cortemaggiore; CNF, Canopo; CRF, Cremona; CSF, Crespellano-Spilamberto; CTF, Cotignola; DF, Dante; DNF, Daniel; FF, Fusignano; FTF, Ficarolo-Tresigallo; GF, Gabicce; GS, Gran Sasso; MA, Maiella; PF, Piadena; PRF, Parma; REF, Reggio Emilia; RF, Riccione; SBF, Sabbioncello; SF, Salsomaggiore; SM, Sibillini Mountains; STF, Stradella. Other tectonic structures: CH, Cesena High; G, Gargano high; M, Murge high; RHFL, Riolo high – Forlì line; SL, Sillaro Line; VM, Val Marecchia Line. Main Basins: VdG, Vena del Gesso; ER, Eastern Romagna; NM, Northern Marche; L, Laga.

the foredeep), *ramp muds* (the time-equivalent finer-grained turbiditic and hemipelagic facies deposited in the more external and more elevated portions of the foredeep) and *shallow shelf carbonates* (mostly carbonate deposits found in the shallow water environments located far from the terrigenous inputs).

4.1.1 | Clastic fills (Marnoso-arenacea and Laga Formations)

The Marnoso-arenacea Fm represents the siliciclastic fill of the Miocene foredeep of the Apennine orogen (Mutti & Ricci, 1972; Muzzi Magalhaes & Tinterri, 2010; Ricci Lucchi, 1981, 1986; Roveri et al., 2002). It consists of a sedimentary wedge extending from the Northern Apennine (north-western Emilia Romagna region), where it is buried below the Po Plain and is partially over-thrusted by the allochthonous Ligurian sheet, to the south in the Central Apennines (Umbria-Marche region). In relation with the migration of the foreland basin system, two main depocenters can be recognized (Mutti et al., 2002; Ricci Lucchi, 1986): the inner one, mainly developed during the (late Burdigalian)-Langhian-Serravallian interval, and the outer one, mainly active in the Tortonian-early Messinian. In both stages, the turbiditic flows, with major entry points located in the southern Alps, run along the Apennine foredeep for hundreds of kilometers; accordingly, an overall southeastward reduction of the grain-size of the turbiditic deposits can be recognized toward the SE (Ricci Lucchi, 1986; Roveri et al., 2002). An overall coarsening-upward trend can be defined moving from the older deposits of the inner area to the younger ones of the outer area (Ricci Lucchi, 1975); the coarser-grained deposits and the residual facies, namely dune-shaped bedform units produced by bypassing flows during sediment transfer (Mutti, 1992), are presumed to be buried in the northwestern sector of the Apennines and below the Po Plain (Roveri et al., 2002). In outcrop (Figure 3), these deposits are commonly referred to as the Fontanelice Mb (Member 4 sensu Mutti & Ricci, 1972), which includes turbiditic lobe facies deposited from unconfined flows in the distal area (surroundings of Mercato Saraceno, Savio valley; Figure 3d) or from confined flows filling erosional features (Fontanelice, Santerno Valley; Ranchio, Borello Valley; Capozzi et al., 1991; Mutti & Ricci, 1972; Ricci Lucchi, 1986; Roveri et al., 2002; Figure 3a). The latter consist of tens of m-thick lenticular bodies with an overall fining-upward trend; their basal portion locally includes coarse sandstones and conglomerates and is followed by

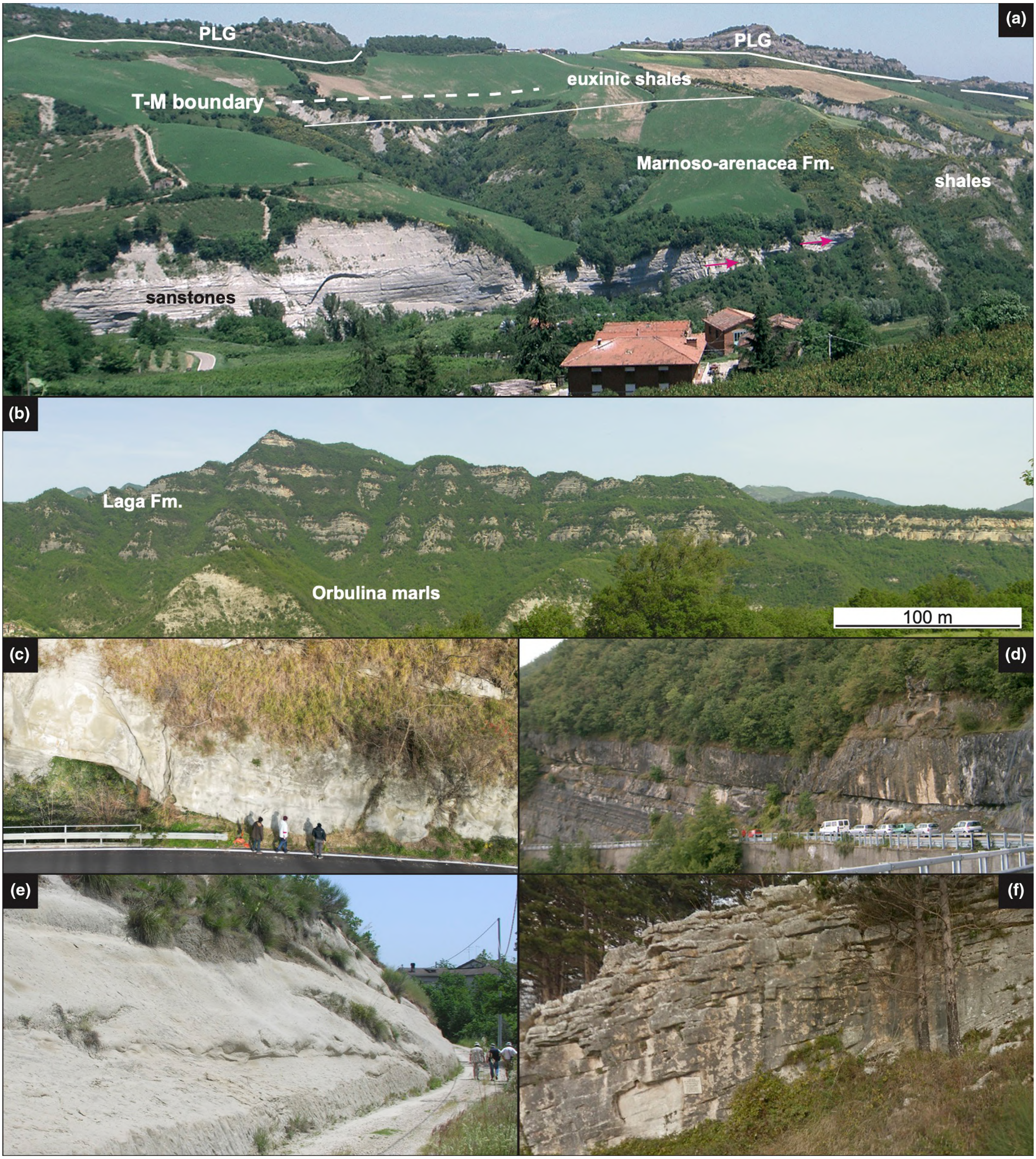

FIGURE 3 Late Miocene pre-evaporitic porous rocks as they appear in the Apennine outcrops. (a) Erosional channel filled by turbiditic lobes of the Marnoso-arenacea Fm., encased in a shale unit and capped by the PLG deposits (Lugli et al., 2010) in the Vena del Gesso basin, close to Fontanelice (see also Mutti & Ricci, 1972; Roveri et al., 2003). (b) Panoramic view of the pre-MSC turbiditic lobes of the Laga formation; they progressively onlap against the Orbulina marls eastward due to the uplift of the Montagnone anticline (see also Bigi et al., 2009; Milli et al., 2013). Close views of turbiditic lobe megabeds deposited in the distal portion of the Marnoso-arenacea (c; Mercato Saraceno; Cesena) and Laga (d; Agnova, Teramo); Coarse hybrid gypsum-bearing siliciclastic bed (e, Paranesi; Teramo) basins. Close view of the carbonatic deposits with medium-scale cross stratification of the lower Bolognano Fm (km 11, SP65; from Street view; the outcrop is ca. 4 m high; trees for scale).

massive to crudely even-laminated sandstones showing low shale content and scarce cementation suggesting good reservoir properties. These coarse sediments were deposited in the internal portion of the foredeep, which was later incorporated within the wedge-top basins. Other coarse-grained sandstone deposits are also recognized south of the Marecchia Valley Ligurian sheet (Urbania sandstones; Ardanese et al., 1987; Chiocchini & Cipriani, 1992; De Feyter, 1991).

The analysis of the ViDEPI dataset allowed the recognition of a sandstone unit referable to the Marnoso-arenacea Fm, forming a continuous layer buried in the south-eastern portion of the Po Plain (Figure 2). These buried deposits are poorly known. In general, the described coarse-grained facies are expected to be present in smaller volumes, but locally the presence of growing tectonic structures, segmenting the main foredeep, could have interfered with the turbiditic flows, forcing the deposition of coarser sediments and promoting the by-pass of the finer ones. In more recent times (Plio-Pleistocene), such tectonic structures may have been responsible for the formation of fracture-related porosity changes.

The Laga Fm (Milli et al., 2007; Mutti & Ricci, 1972, 2023) is a thick sedimentary wedge formed by sandstone turbidites deposited from the Tortonian throughout the MSC. In the deeper portion of the Adriatic foredeep, as in the Laga basin, this event is recorded by the deposition of clastic evaporites and no significant stratigraphic hiatuses or evidence of desiccation have been found (Parea & Ricci Lucchi, 1972; Manzi et al., 2005). The Laga Fm has been historically separated into lithostratigraphic units in relationships with the Messinian evaporites, namely pre- syn- and post-evaporitic members (Bigi et al., 1999; Centamore & Nisio, 2003). However, different subdivisions based on the recognition of allostratigraphic units bounded by regional-scale unconformities have been proposed (Artoni, 2003; Marini et al., 2015; Milli et al., 2007, 2013). Channel, channel-lobe transition, and lobe are the prevalent facies of the pre-evaporitic interval (Figure 3b,d), typically found in up to 10 m-thick mega-beds characterized by amalgamation surfaces, very good lateral continuity (several kilometers), and reduced amount of shale (see detailed description in Bigi et al., 2009; Marini et al., 2015; Milli et al., 2007, 2013). The stage 1 of the MSC in deep-intermediate settings is represented by an organic-rich shale interval recording a relatively short starvation stage (Manzi et al., 2005, 2007). The reprise of the clastic input is marked by the so-called “evaporitic interval”, an up to 30 m-thick interval consisting of m-thick graded beds of coarse hybrid gypsum-bearing siliciclastic sandstones (Figure 3e) laterally transitional with thinner gypsarenite beds and with thin organic-rich dolomitic shales that mostly accumulate out of the main depocentral areas (Manzi et al., 2005; Parea & Ricci Lucchi, 1972; Ricci Lucchi, 1973; see their gypsum clastic facies R4–R5). The Sr isotopic signature (Muller & Mueller, 1991; Roveri, Flecker, et al., 2014; Roveri, Lugli, et al., 2014) and the paleocurrent indicators (Manzi et al., 2005) suggest that these deposits derived from the resedimentation of primary gypsum accumulated in shallow evaporitic settings located more to the south, like those of the Maiella sector (MA in Figure 2). The deposition of the Laga Fm was conditioned by the tectonic evolution of this area, as witnessed by the spectacular eastward onlap against the Montagna dei Fiori—Montagnone Anticline (Bigi et al., 2009, 2011; Milli et al., 2013; Figure 2) of the turbiditic beds over the deformed foreland ramp characterized by the deposition of hemipelagic sediments (Cerrogna and Orbulina marls units; Artoni, 2003; Centamore et al., 1991). Due to the post-Messinian activation of deep thrusts involving the Mesozoic succession (Sibilini and Gran Sasso thrust fronts; MS and GS in Figure 2), the Laga Fm is in large part outcropping and mainly limited to the east by the Montagna dei Fiori and Montagnone thrust fronts (Artoni, 2003; Bigi et al., 2009, 2011, 2013; Marini et al., 2011, 2015; Milli et al., 2013).

4.1.2 | Ramp muds (Schlier Fm and Gallare Fm) and older units

The typical succession that is found below the Messinian evaporites in the foreland ramp (sensu Ricci Lucchi, 1986), in relationship to the terrigenous input, consists of marls (Schlier Fm) in the central Adriatic sector and shales (Gallare Fm; Rossi et al., 2015) in the northern Po Plain (Figure 2). These units are expected to be characterized by low porosity of both primary and secondary origin but, locally, rocks with better petrophysical properties could be found. Moreover, some carbonate rocks characterized by intense tectonic deformations may be found at moderate depth below the evaporites, due to the presence of tectonic structures related to deep thrusts involving the Triassic evaporites (Manzi et al., 2020; Wrigley et al., 2015).

4.1.3 | Shallow shelf carbonates (Bolognano Fm)

The Bolognano Fm is a Oligocene-late Miocene complex sedimentary unit including thick carbonate bodies, separated by shale and marl horizons, that can be regarded as potential carbonate reservoir for the abundance of well-sorted skeletal grainstone facies, interpreted as shallow-water carbonate ramp deposits strongly reworked by submarine currents (Brandano et al., 2013, 2016, 2020;

Mutti et al., 1997, Figure 3f). The best outcrops described in the literature are located in the hanging-wall block of the Maiella thrust (Figure 2). Petrophysical analyses have been recently carried out in the Lepidocyclina calcarenite 2 unit cropping out in the NW sector of the Maiella massif (Trippetta et al., 2020). Analysis of the ViDEPI dataset allowed us to recognize these deposits both in the onshore and offshore sectors of the Abruzzo and Molise regions (Manzi et al., 2020). Although a detailed description of these buried carbonate facies is not available, due to their position above the Apulian promontory, shallow facies similar to those described above are expected.

4.2 | Evaporites as top seals

The sealing capacity of a rock is related to the presence of extremely low permeabilities (Warren, 2006, 2010). The seal integrity has to be maintained for km- to tens of km-large areas, in relationship to the size of the reservoir; thus, implying the need of sufficient thick and laterally continuous deposits. Evaporite rocks are well-known in hydrocarbon exploration for their sealing properties; among them, halite is commonly considered the best one due to its ductile behavior and very low permeability (Warren, 2006). Also sulphate rocks show very good seal properties, especially anhydrite, which is characterized by slightly lower ductility and higher resistance to dissolution by fresh water compared to halite. Anhydrite mostly forms by burial-induced dehydration of gypsum rocks (Murray, 1964), at temperature generally higher than ca. 52°C (Hardie, 1967). This process may occur at variable depth depending on the local geothermal gradient and on the time of permanence at critical temperatures; in the Northern Apennines the gypsum-anhydrite transition for the Messinian gypsum generally occurs at ca. 1 km of depth (Rossi et al., 2021) and the minimum time necessary to start the de-hydration process is poorly known.

During the MSC, the Mediterranean Sea was characterized by the widespread accumulation of thick evaporite sediments consisting of halite and gypsum, interbedded with shale, that can be regarded as effective seal units. However, in the Adriatic foredeep the deposition of halite did not occur and large amount of gypsum accumulated (Roveri, Flecker, et al., 2014; Roveri, Lugli, et al., 2014; Manzi et al., 2020) both as primary (Figure 4) or clastic deposits (Figure 5); the distribution of the different

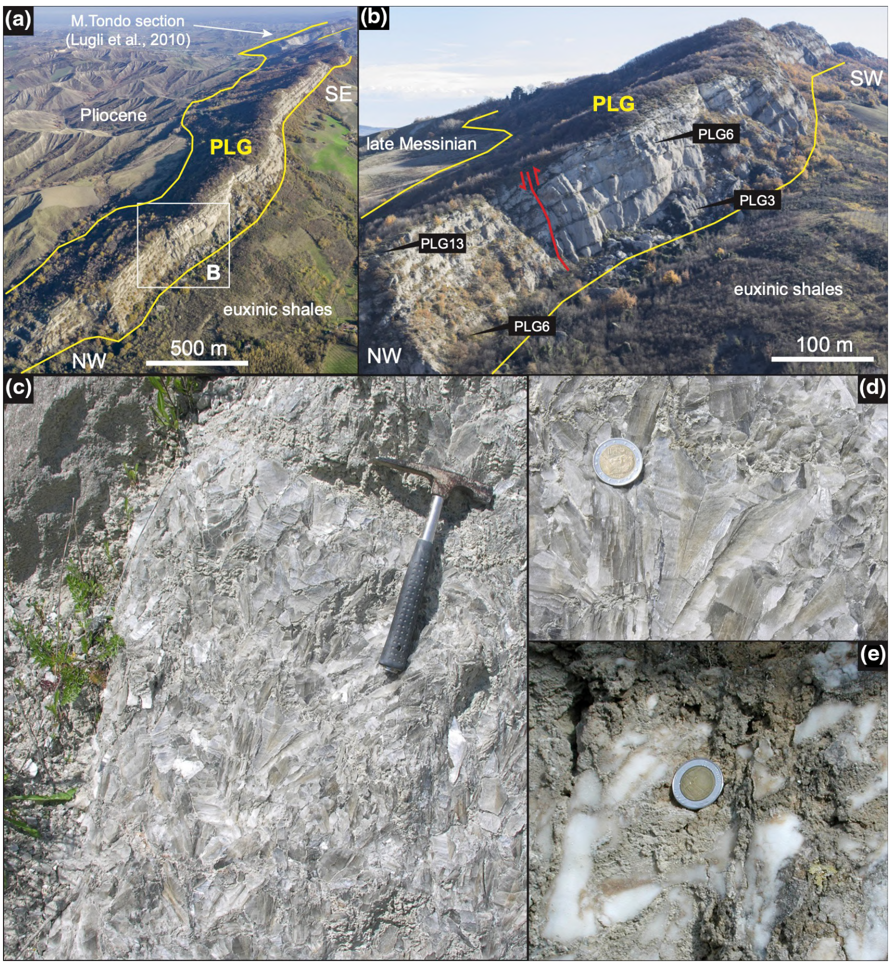

FIGURE 4 Messinian primary evaporite seal rocks (PLG, Primary Lower Gypsum unit); examples from the Romagna Apennines outcrops. (a) Aerial view (courtesy of P. Lucci) of the Vena del Gesso from Borgo Tossignano up to the Monte Tondo quarry hosting the complete PLG succession (Lugli et al., 2010). (b) Enlargement of inset in (a), the famous Riva San Biagio outcrop where a rotated direct fault allows the direct comparison of the lower (right) and upper (left) beds of the PLG unit. (c) Massive selenite, the more common facies of the PLG unit; closer view of the massive selenite to compare the primary (d) and the secondary (e; after anhydrite rehydration) gypsum facies.

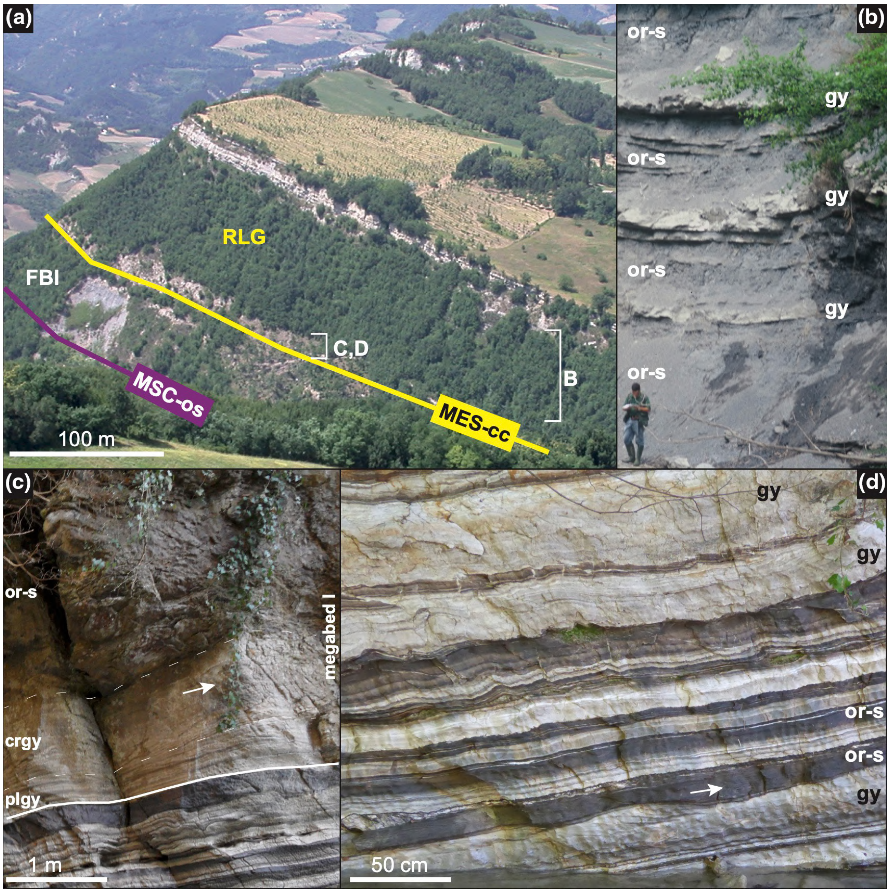

FIGURE 5 Messinian clastic evaporite seal rocks (RLG, Resedimented Lower Gypsum unit) as they appear in the Apennine outcrops. (a) The Fanantello section described in Manzi et al., 2005. Clastic evaporites of the Resedimented Lower Gypsum (RLG) conformably overlying the deep time-equivalent of the Primary Lower Gypsum (PLG) unit represented by the organic-rich shale foraminifer barren interval (FBI; Manzi et al., 2007, 2018). The intermediate portion of the RLG succession (b) is characterized by m-thick gypsum-bearing hybrid deposits (gy) alternated to dark euxinic shales (or-s). Conversely, the lower part is characterized by a clastic evaporites with higher gypsum content and by an alternation of different facies. (c) gypsum composite megabed showing from the base plane laminated (plgy) and climbing-ripples gypsarenites (crgy) capped by a dark organic-rich shale tale (or-s) lying above a thin-bedded gypsum turbidites interval which lower portion (not included in c) is shown in d). Notice the white gypsarenite beds (gy), showing plane (above) or ripple-cross stratification (below) alternated to the dark organic-rich shales (or-s).

evaporites in the Adriatic foredeep, as obtained from the analysis of the ViDEPI boreholes, is reported in Figure 6.

It is worth noting that in the Apennine foreland basin system gypsum deposits have been mostly dehydrated to form anhydrite (Figures 4e and 5c,d). In the inner portion of the foredeep, anhydrite has been more recently exhumated and rehydrated back to gypsum by ground and meteoric waters. Conversely, the gypsum deposited in the deeper portion of the foredeep and in the foreland backbulge underwent a strong post-depositional subsidence, that hindered exhumation and consequent re-hydration. The map of the top of the evaporites (Figure 6b), obtained from the interpolation of boreholes, highlights that a large part of the Messinian gypsum is now at depths exceeding the expected anhydrite transition. In the Adriatic offshore, evaporites reached impressive burial depths, commonly exceeding 2 km. Even more remarkable are those cases where the PLG deposits are found at depth exceeding 3 km below sea level, as in the Ancona (Varano_001, −3402 m; Alex_001, −3606; Afrodite_001, −3705 m) and Pescara (Elsa_001, −3055 m; Silvana_001, −3506 m; Fratello_001, −4309 m) offshore areas.

4.2.1 | Primary Lower Gypsum (PLG unit)

The PLG unit consists of bottom-grown massive gypsum crystals forming tens of m-thick gypsum beds separated by thin (dm- to m-thick) shale veneers (Figure 4a,b). The type-section of Monte Tondo, located in the Vena del Gesso basin (see precise location and additional information in Lugli et al., 2007, 2010), has an overall thickness of ca. 230 m; it contains up to 16 gypsum beds showing from the base (Figure 4b): (i) two lowermost

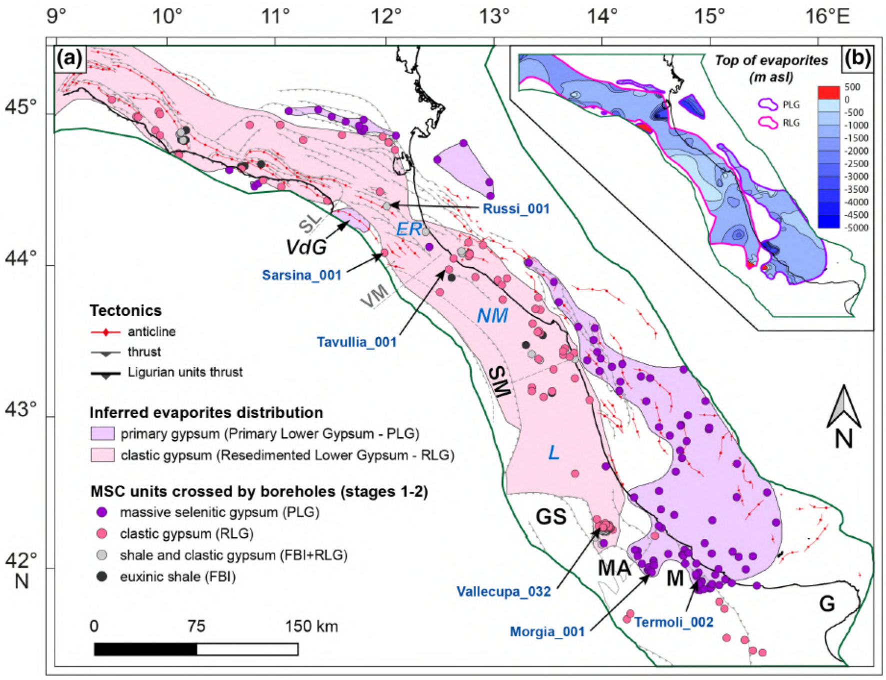

FIGURE 6 (a) Distribution of the evaporites in the Adriatic foredeep providing potential seal for reservoir; the lithology of the different sin-evaporitic deposits is reported for each available borehole. (b) structural map of the present-day depth of the top of the evaporites; contour lines of the depth of the top of the evaporites have been obtained after interpolation of boreholes data.

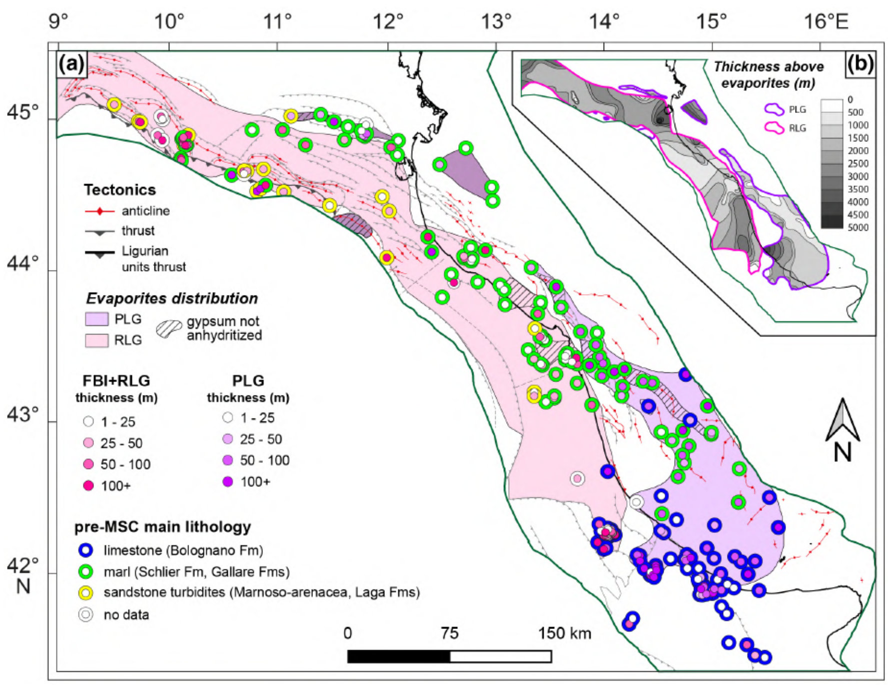

FIGURE 7 (a) Distribution and thickness of evaporites in the Adriatic foredeep providing potential seal for reservoir. For each available borehole the internal circles provide information of the thickness of the evaporite seal (distinguished between PLG, Primary Lower Gypsum, and RLG, Resedimented Lower Gypsum) and the outer donuts provide information about the pre-evaporitic lithologies. The sandstone turbidites are mostly found in the deeper portion of the foredeep (north-west), the carbonate units in the shallower one (south-east), the marl deposits in between. The areas where the gypsum has not been transformed into anhydrite are also reported. (b) Thickness of the post-evaporitic succession above the evaporites; contour lines of the thicknes of the post-evaporitic succession have been obtained after interpolation of boreholes data.

discontinuous beds (PLG1 and PLG2) laterally transitional to limestone beds, (ii) four thick (25–30 m) beds (cycles PLG3-PLG6); (iii) up to 10 thinner (10–15 m-thick) beds (PLG7-PLG16). This organization has been recognized widely along the Mediterranean (Lugli et al., 2010) and related to astronomically-controlled climate cyclicity (Manzi et al., 2013; Vai, 1997). The deposition of the PLG unit has been limited to shallow settings, while organic-rich shales were deposited in deeper settings (Manzi et al., 2007). The PLG unit is commonly cut on top by the MES.

The vertical organization with thick gypsum beds separated by very thin shale veneers is well imaged in geophysical logs by a typical blocky pattern (see Section 3.1). This allowed Manzi et al. (2020) to recognize a very large PLG occurrence in the Adriatic offshore (Figures 6 and 7), characterized by an overall moderate tectonic deformation; these conditions allowed the reconstruction of the thickness of the individual PLG cycles. Manzi et al. (2020) and also the very good lateral continuity of this unit and the thickness of the lower and thicker beds. In this work, we have coupled the PLG thickness data with the distribution of the pre-evaporitic deposits (Figure 7), showing in detail the distribution of the potential reservoirs and the thickness of the overlaying potential evaporitic seal. It is worth noting that the greater part of the gypsum unit has been transformed into anhydrite due to burial. In fact, in ca. 76% of the boreholes the top of the PLG unit is found at depths greater than 1000 m; i.e., below the transition depth defined for the Northern Apennines (Rossi et al., 2021).

4.2.2 | Resedimented Lower Gypsum (RLG unit)

This unit includes a large variety of gypsum-bearing deposits emplaced by mass-wastes and gravity flows and derived from the dismantlement of the PLG unit. The best outcrops are in the Eastern Romagna (Giaggiolo-Cella and Sapigno synclines; Figure 5) and Marche (Peglio-Pietrarubbia and Montecalvo in Foglia synclines; Manzi et al., 2005). The evaporite-bearing sediments range from pure gypsarenites (Fanantello section; Figure 5) to hybrid (i.e with mixed siliciclastic and gypsum-bearing composition) sandstones (Laga basin) according to the composition of the older deposits resedimented together with gypsum. The RLG unit is floored by the regional-scale unconformity surface (MES), which can be traced upslope on top of the PLG unit. In general, the clastic gypsum is organized in dm- to m-thick laminated and graded beds separated by dark euxinic (organic-rich) shales (Figure 5), to form tens of meters-thick horizons, with a good lateral continuity. In the deeper and more distal settings the base of the clastic gypsum is a correlative conformity surface (MES-cc; Roveri et al., 2008), laying at the top a shale unit representing the deep-water equivalent of the PLG, characterized by high content of organic matter and dolomite, and paucity of fossils, named Foraminifer Barren Unit (FBI; Manzi et al., 2007, 2018) overlying the MSC-os surface at the onset of the MSC (Figure 5a; Roveri et al., 2019). Deposited in the main bathymetric lows of the foredeep, these sediments were buried by a thick late Miocene and Plio-Quaternary thick succession and are commonly characterized by microcrystalline gypsum as the final result of the gypsum-anhydrite-gypsum transitions. In the Northern Apennines, mass-wasting deposits have also been recognized in the main evaporitic basins; being the large-scale slide blocks of the Vena del Gesso basin outstanding examples (Roveri et al., 2003). In the subsurface, the thickness of the clastic evaporites ranges from a few meters to few tens of meters; both stratified and chaotic deposits are present respectively in the footwall synclines of the main active thrusts limiting the main evaporitic basins that hosted the deposition of the PLG (Manzi et al., 2005; Rizzini, 2005).

4.3 | Potential sites for gas storage

Analysis of the Adriatic foreland basin system allows the definition of two main structural settings with different characteristics in terms of presence and typology of potential reservoirs and potential evaporitic seals: the Northern Apennines Foredeep (NAF) and the Foreland and Backbulge (FB).

4.3.1 | Northern Apennines Foredeep

In the Northern Apennines the potential reservoir is the late Miocene Marnoso-arenacea Fm, whereas the seal is provided by clastic evaporites (RLG) and/or by shale deposits (FBI). Three sectors can be described (Figure 8).

4.3.1.1 | *Western sector (NAF-W)*

This sector is characterized by the presence of turbidite sandstone deposits that can be referred to the more proximal portion of the Marnoso-arenacea Fm turbiditic system (Ricci Lucchi, 1986) buried below the Po plain (Cremonini & Ricci Lucchi, 1982; Dondi et al., 1982a, 1982b, 1982c; Fantoni et al., 2003; Fantoni & Franciosi, 2010; Rizzini, 2005; Rossi et al., 2015). The buried area comprised between the towns of Parma, Piacenza and Cremona is well-known for the presence of thrust-related folds deforming the late Miocene turbidites (Figure 9; Artoni et al., 2007; Rizzini, 2005; Rossi et al., 2002) and covered by a thick Plio-Quaternary succession including at its base thick gypsum-bearing olistostromes recognized from boreholes (i.e. Campore 001; Figure 9d) and followed in seismic profiles (Figure 9b,c) which can provide potential seals. A further seal is provided by the Pliocene Santerno Clays. The Cortemaggiore thrust front (CMF, Figure 9c,d; Artoni et al., 2007) has been recently considered for gas storage in the Emilia-Romagna region (ARPAE-ER

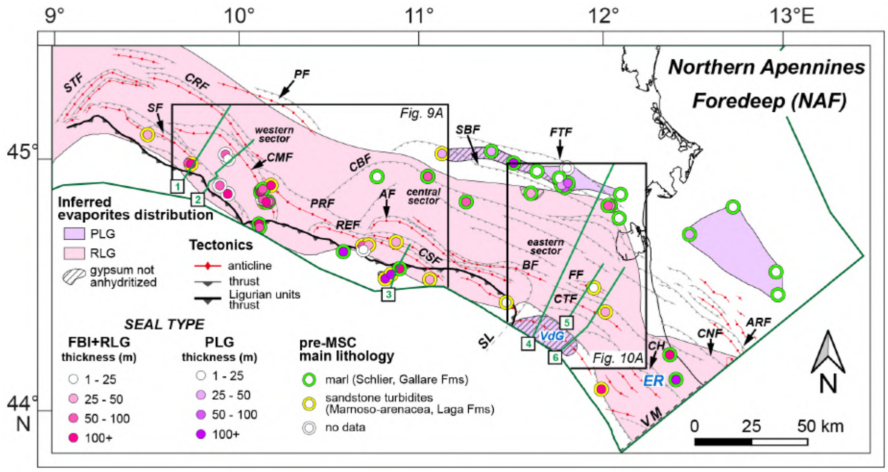

FIGURE 8 Map of the Western and Central (a); Eastern (b) Northern Apennines sectors; the location of the seismic profiles of Figures 9 and 10 is indicated by green traces. For each available borehole the internal circles provide information of the thickness of the evaporite seal (distinguished between PLG, Primary Lower Gypsum, and RLG, Resedimented Lower Gypsum) whereas the outer donuts provide information about the pre-evaporitic lithologies. The areas where the gypsum has not been transformed into anhydrite are also shown. Main thrust Fronts: AF, Albareto; ARF, Arabella; BF, Budrio; CBF, Cavone-Bova; CMF, Cortemaggiore; CNF, Canopo; CRF, Cremona; CSF, Crespellano-Spilamberto; CTF, Cotignola; FF, Fusignano; FTF, Ficarolo-Tresigallo; PF, Piadena; PRF, Parma; REF, Reggio Emilia; SBF, Sabbioncello; SF, Salsomaggiore; STF, Stradella. Other tectonic structures: CH, Cesena High; SL, Sillaro Line; VM, Val Marecchia Line. Main Basins: VdG, Vena del Gesso; ER, Eastern Romagna.

(Regional Agency for Prevention, Environment and Energy of the Emilia-Romagna Region, Italy), 2020) due to the presence of gas in the Pliocene sandstones; whereas, little attention has been paid to the evaporitic and pre-evaporitic units.

4.3.1.2 | *Central sector (NAF-C)*

In this sector, tens of m-large blocks of PLG (Levizzano 001 and Levizzano 002 boreholes) are sandwiched between thrust splays of Ligurian and Epiligurian units (Cremonini & Ricci Lucchi, 1982; Ghielmi et al., 2013; Rizzini, 2005; Rossi et al., 2015); overthrusting a Oligo-Miocene autochthonous succession containing chaotic RLG facies, in turn deformed by the Spilamberto thrust (Figure 9b). Unfortunately, the possible presence of tectonic traps is not confirmed by direct information from boreholes.

4.3.1.3 | *Eastern sector (NAF-E)*

The sector located eastward of the Sillaro line (Figures 2, 8, and 10) is characterized by the absence of allochthonous Ligurian unit and by the presence of a thick autochthonous succession. In Miocene times, this area was filled by the Marnoso-arenacea Fm turbidites (Cremonini & Ricci Lucchi, 1982; Dondi et al., 1982a, 1982b, 1982c; Ricci Lucchi, 1986), wedging toward the NE against the foreland ramp. The Messinian primary evaporites were deposited in the more elevated structural settings: the well-known succession of the Vena del Gesso outcrops in its wedge top-basin, whereas in the foreland basin these deposits are buried below the Po plain in an E-W elongated area between the Sabbioncello and Ferrara thrust fronts (Figure 10a,b). In the Vena del Gesso basin, the PLG rest above a pre-evaporitic shale unit above the Marnoso-arenacea Fm. In the northern area the evaporites rest above the marls of the Gallare or Schlier Fm. On the other hand, in the central portion of the foredeep the evaporites are represented by the RLG and FBI deposits, resting above the Marnoso-arenacea Fm turbidites (Sarsina_001 borehole; Figure 11); in this area the gypsum has been transformed into anhydrite which, at outcrop exposure was re-hydrated back into microcrystalline gypsum. This succession is deformed by three main thrust fronts (Figure 10; Ghielmi et al., 2013; Rizzini, 2005; Rossi et al., 2015), named from the south: Cotignola (CTF), Fusignano (FF) and Ravenna-Alfonsine (RAF). The presence of a thin evaporitic interval above the Marnoso-arenacea Fm. has been confirmed by boreholes drilled on the CTF (42.5 m-thick; Russi_001 dir; Figure 11) and on the FF (5 m-thick); no data exist for the RAF. The sparse available data do not allow to verify the lateral continuity of the evaporitic seal. The older deposits involved in these thrust fronts belong to the Marnoso-arenacea Fm. To the south these deposits are now outcropping due to the uplift of a deep structure involving the Mesozoic units (Cesena high, CH; Farabegoli et al., 1991; Manzi et al., 2005); thus, offering the possibility of a good surface analog. The three main thrust fronts host depleted gas fields in the lower Pliocene sandstones (sandstones belonging to the

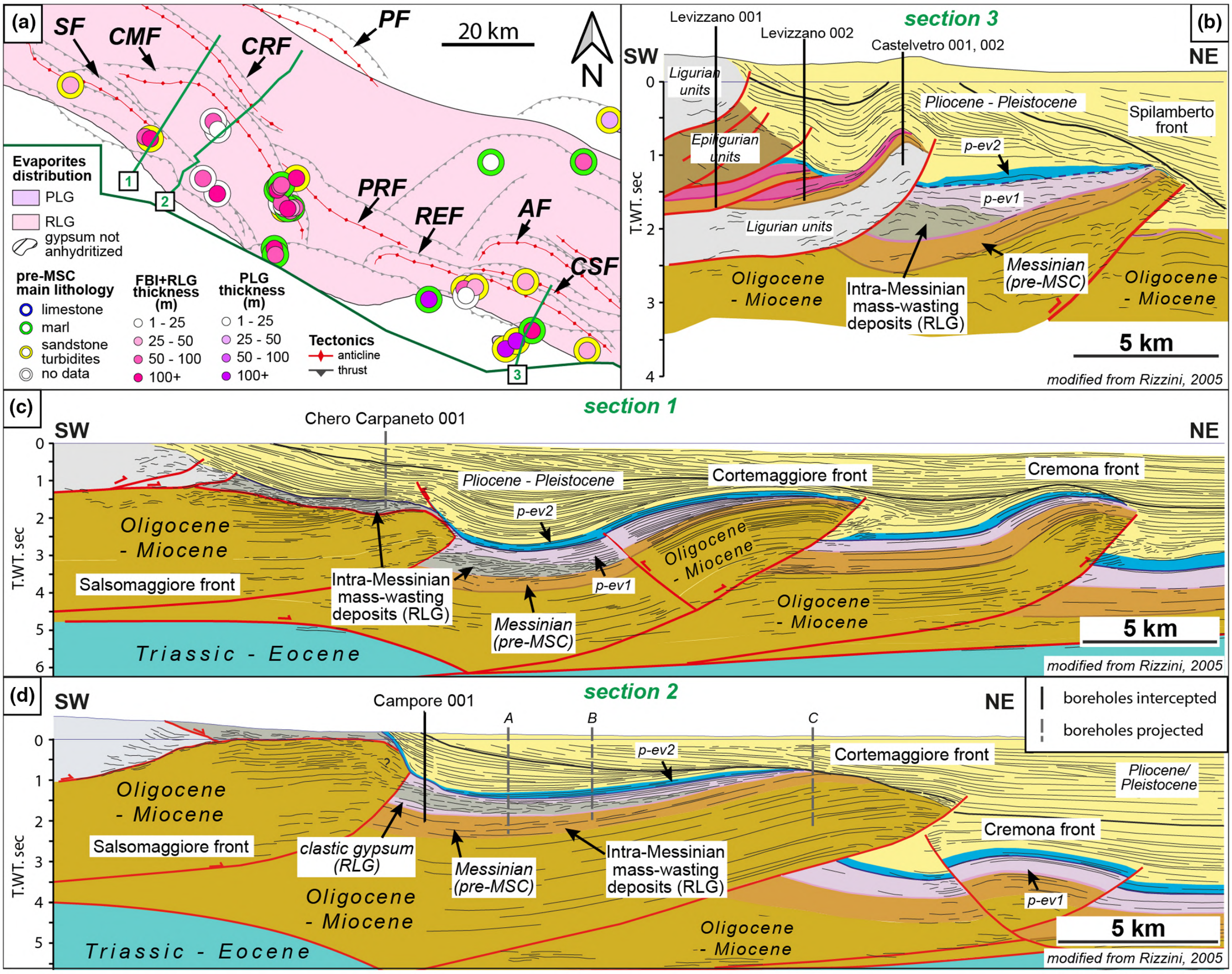

FIGURE 9 Seismic profiles representative of the Western and Central sectors of the Northern Apennines. (a) Enlargement of map in Figure 8 with location of the seismic lines. (b) Line drawing of seismic profile crossing the potential reservoirs of the Spilamberto thrust front (Central setor; modified after Rizzini, 2005); (c) Line drawing of seismic profile crossing the potential reservoirs of the Cortemaggiore and the Cremona thrust front in their southern terminations (Western setor; modified after Rizzini, 2005). (d) names A, B, C were used in the original version of Rizzini, 2005 to indicate unpublished borehole. Main thrust Fronts: AF, Albareto; CMF, Cortemaggiore; CRF, Cremona; CSF, Crespellano-Spilamberto; PF, Piadena; PRF, Parma; REF, Reggio Emilia; SF, Salsomaggiore.

Porto Corsini or Porto Garibaldi Fms) that have been recently taken into consideration for natural gas storage in the Emilia-Romagna region (ARPAE-ER, 2020).

4.3.2 | Foreland and Backbulge (FB)

The foreland and backbulge areas are mainly developed from the southern Romagna-northern Marche up to the Abruzzi, Molise and northern Puglia regions. In this sector of the Apennines the foredeep clastic fill, formed by the late Miocene turbidite units, has been completely exhumed and can be observed in outcrop. In the subsurface the pre-MSC deposits are represented by the hemipelagic marls (Schlier Fm) or by shallow-water shelf carbonates (Bolognano Fm); thus, a potential reservoir should be preferably searched into the latter unit because it is characterized by more favorable petrophysical properties. For what concerns the potential seal, the foreland and backbulge areas are characterized by large areas with PLG and RLG evaporites with a good lateral continuity and/or underlying shale deposits (FBI). Three sectors with different evaporitic and pre-evaporitic facies can be described (Figure 12).

4.3.2.1 | *Northern sector (FB-N)*

The northern sector is characterized by the exclusive presence of pre-evaporitic hemipelagic deposits (Schlier Fm) covered by the RLG evaporite unit (Tavullia_001 borehole; Figure 11) in the western portion and by the PLG unit in the more external portion of the Adriatic

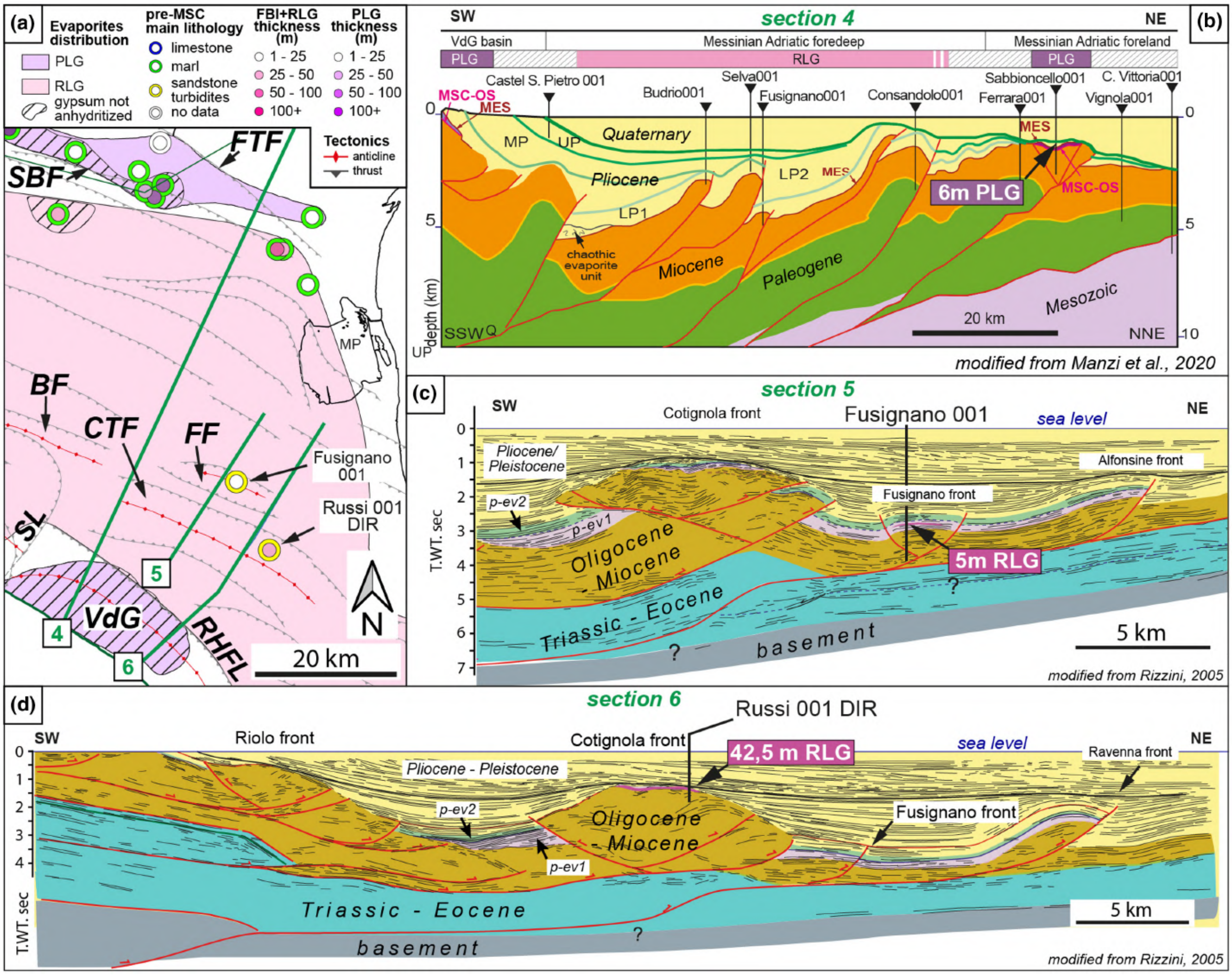

FIGURE 10 Seismic profiles representative of the Eastern Emilia-Romagna area. (a) Enlargement of map in Figure 8 with location of the seismic lines. (b) Basin-wide geological cross section obtaining from merge of multiple seismic profiles (modified after Fantoni & Franciosi, 2010; Manzi et al., 2020; Masetti et al., 2012; Roveri et al., 2003). (c) Line drawing of seismic profile crossing the potential reservoirs of the Cotignola anticline and the Alfonsine thrust front (modified after Rizzini, 2005). (d) Line drawing of seismic profile crossing the potential reservoirs of the Cotignola anticline and the Fusignano and Ravenna thrust fronts (modified after Rizzini, 2005). Main thrust Fronts: BF, Budrio; CTF, Cotignola; FF, Fusignano; FTF, Ficarolo-Tresigallo; SBF, Sabbioncello. Other tectonic structures: RHFL, Riolo high – Forlì line; SL, Sillaro Line. Main Basins: VdG, Vena del Gesso.

offshore (Figure 13a). The main thrust fronts are detached from the basement and involve all the Mesozoic and Paleogene carbonate succession (Figure 13b,c), which is characterized by the absence of siliciclastic turbidites. A variable thickness (few tens of meters) of RLG and FBI units is found on top of the Canopo thrust front (CNF; Figure 13c), whereas the more external Cornelia thrust front (CLF; Figure 13b) is sealed by a thick (>100 m) PLG unit, with apparent good lateral continuity. A potential reservoir has been recognized in the core of the hanging-wall anticline in the Marne a Fucoidi and Maiolica Fms, and sealed by a thick hemipelagic succession (Scaglia, Bisciaro and Schlier Fms) (Proietti et al., 2022, 2023). In the case of brittle deformations locally affecting the latter units, and producing a fracture-related porosity, the Messinian evaporites alone could represent an efficient seal, as more than 100 m of PLG are crossed by the borehole drilled at the top of the anticline (Cornelia_001 borehole; Figure 13b).

4.3.2.2 | *Central sector (FB-C)*

The central sector of the Adriatic offshore is characterized by the presence of a continuous PLG horizon commonly ranging from 50 to more than 100 m in thickness (Figure 14a,b), resting above a pre-evaporitic succession of hemipelagic marls. Locally, due to tectonic deformations involving the pre-MSC units, older carbonate deposits

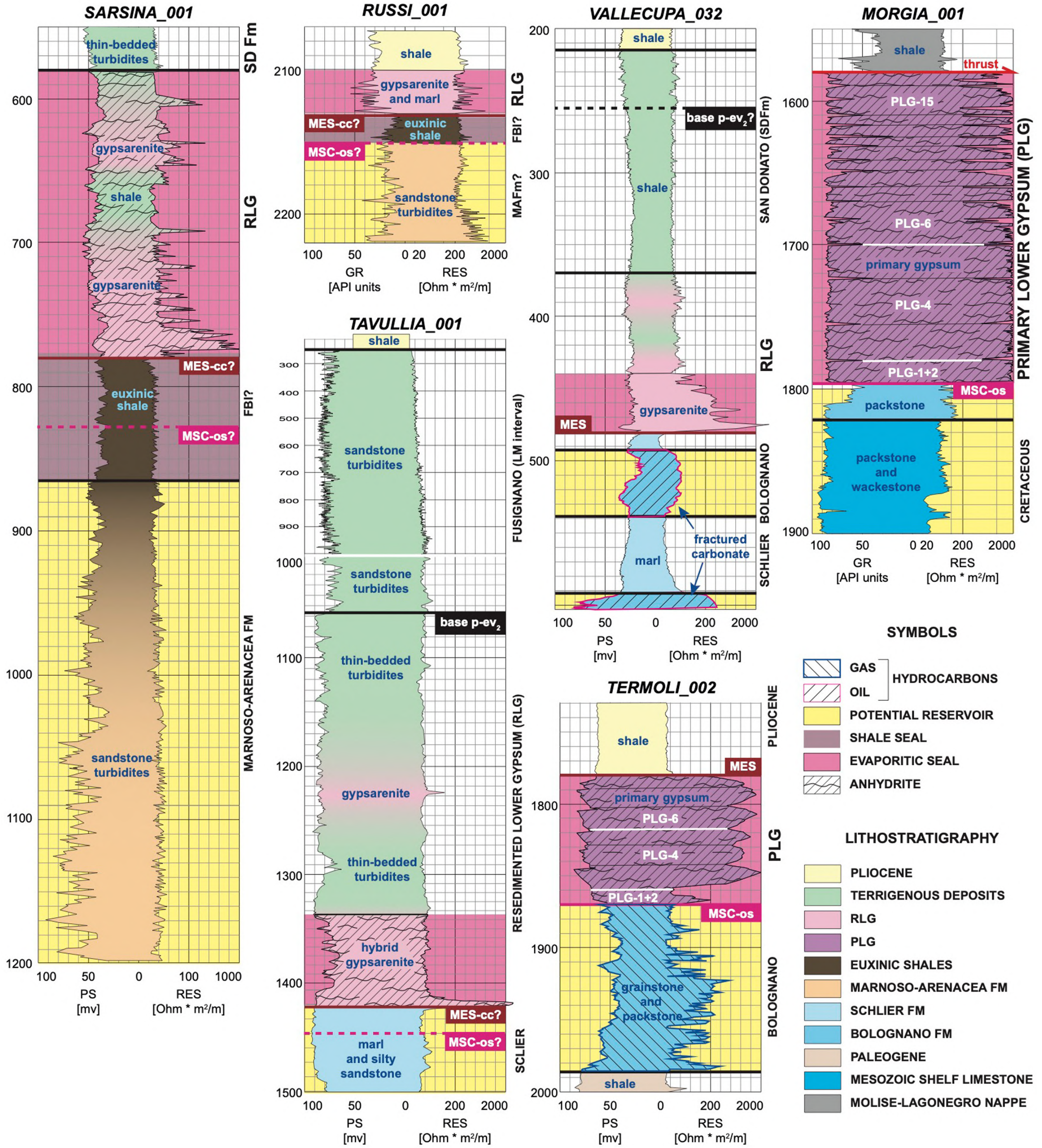

FIGURE 11 Examples of boreholes (see location in Figure 6) crossing the late Miocene succession highlighting the different types of evaporitic seal (primary or clastic gypsum) and of the possible reservoir unit (Miocene turbiditic sandstones, fractured limestones or shelfal packstones and wackestones and/or Mesozoic carbonates). The occurrence of hydrocarbons is also indicated an undirect evidence of good reservoir properties. PLG, Primary Lower Gypsum; PLG1 + 2, PLG-4; PLG-6. PLG-15; cycles of the PLG units, RLG. Resedimented Lower Gypsum; MSC-os, onset surface of the Messinian salinity crisis; MES, Messinian erosional surface; MES-cc correlative conformity of the Messinian erosional surface; FBI, Foraminifer Barren Interval (Manzi et al., 2018); SD Fm, San Donato Formation; p-ev$_2$, post-evaporitc unit 2 (Roveri et al., 2001) largely corresponding with the LM (Lago Mare) interval (stage 3,2 of the MSC; Roveri, Flecker, et al., 2014, Roveri, Lugli, et al., 2014).

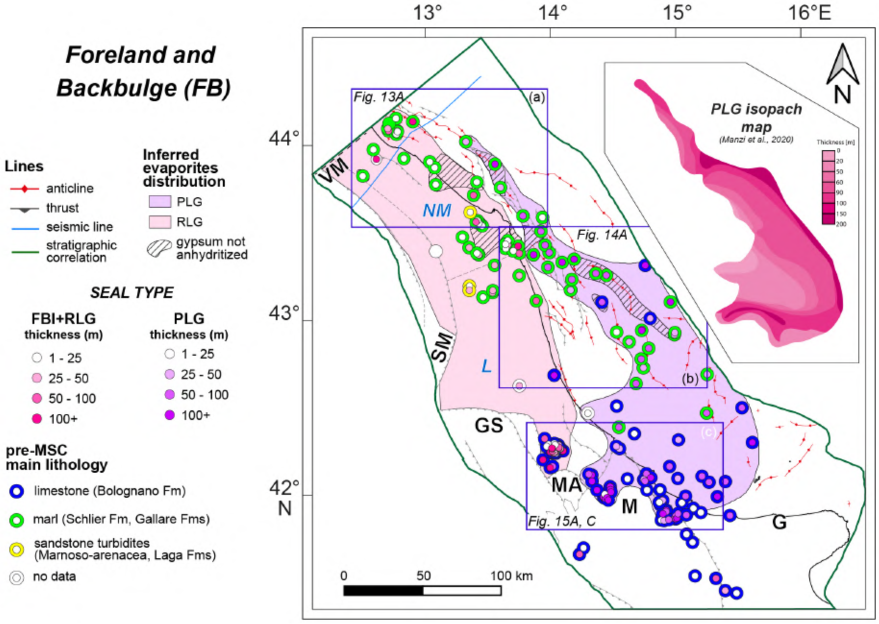

FIGURE 12 Map of the Foreland and Backbulge area with indication of the three areas of interest; Northern sector (a); Central sector (b); Southern sector (c) and location of the seismic profiles of Figures 13–15. For each available borehole the internal circles provide information of the thickness of the evaporite seal (distinguished between PLG, Primary Lower Gypsum, and RLG, Resedimented Lower Gypsum) and the outer donuts provide information about the pre-evaporitic lithologies. The areas where the gypsum has not been transformed into anhydrite are also reported. In the inset the isopach map is obtained from the interpolation of borehole data (after Manzi et al., 2020). Main thrust fronts: GS, Gran Sasso; MA, Maiella; SM, Sibillini Mountains. Other tectonic structures: M, Murge High; Gargano high; VM, Val Marecchia Line. Main Basins: NM, Northern Marche; L, Laga.

(Lower Miocene Bryozoan limestone, in Edmond_001 ter; Eocene wackestone, in Daniel 001 and Dante_001; Upper Cretaceous Scaglia Fm, Rigel_001bis) are sealed by the PLG unit. In the central part of this sector, thrust faults and halokinetic structures rooted in the Triassic units are responsible for the shallower depth of the PLG deposits that were not transformed into anhydrite, according to borehole description. However, gypsum may have been partially dehydrated, further improving the sealing properties.

4.3.2.3 | *Southern sector (FB-S)*

Differently from the previous sectors, widespread late Miocene shallow water carbonate deposits of the Bolognano Fm are present in this sector and capped by a thick PLG horizon (Figure 15a). The thickness of such a carbonate unit ranges from a few meters up to more than 100 m (Figure 15c); above the Bolognano Fm, the thickness of the PLG is slightly less variable, commonly exceeding 100 m. The general tectonic structure is represented by a large-scale antiformal structure, with the Mesozoic shelfal carbonate at its core, and the Bolognano Fm and PLG units lying conformably above (Figure 15e,f). At a local scale, two anticlines involving the Bolognano Fm can be inferred (Morgia and Vasto Mare) by observing the variation of the depth of the Bolognano-PLG boundary reported in the VIDEPI boreholes (Morgia_001 and Termoli_002; Figures 11 and 15c). Unfortunately, the stratigraphic control on the age of these deposits is not good. However, due to its position above the Apulian platform, the Bolognano Fm may probably show similar petrophysical characteristics as observed in outcrop (Brandano et al., 2016; Trippetta et al., 2020), making this unit a potential good reservoir; this could be confirmed by the local occurrence of trace of gas (e.g., Termoli_002 borehole; Figure 11). Potentially interesting additional reservoirs could be provided by Mesozoic shallow-water carbonates found below the Bolognano unit. Finally, the thick horizon of secondary anhydrite in the PLG unit could provide an effective seal.

A smaller area, located to the NW, is instead characterized by the presence of clastic evaporites (RLG) resting above marly limestones that could possibly be ascribed to the outer ramp facies of the Bolognano Fm, thus, less suitable as reservoir. The RLG unit above it is characterized by a strongly variable thickness and due to a shallower burial did not undergo the transformation into anhydrite. However, the local occurrence of oil (Vallecupa_032 borehole; Figures 11 and 15d) may suggest the presence of good reservoir rocks.

5 | DISCUSSION

The identification of potential sites for gas storage needs the concomitant recognition of suitable reservoirs and effective

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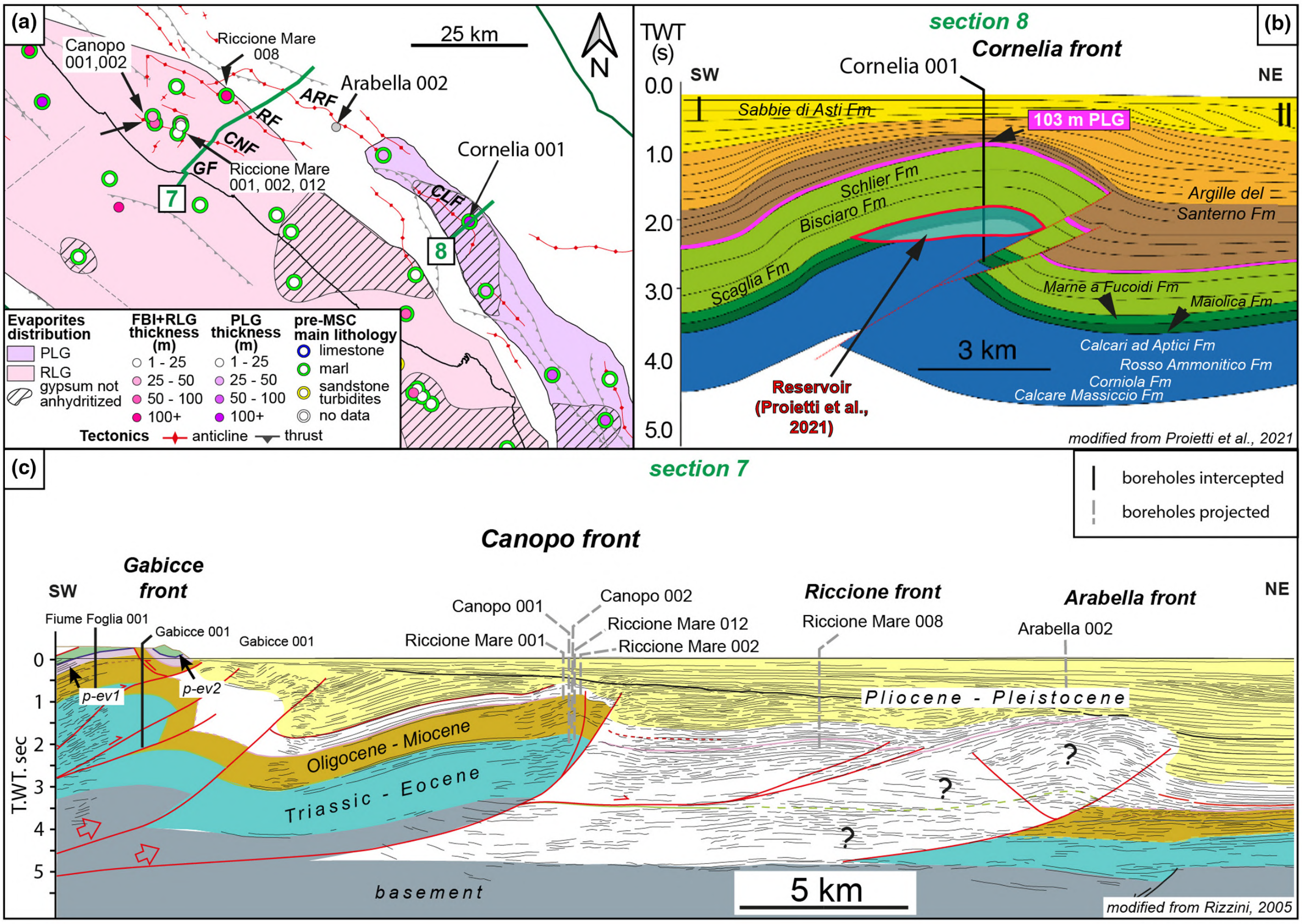

FIGURE 13 (a) Seismic profiles representative of the Northern sector of the FB; see location in Figure 1) Enlargement of map in Figure 12 with location of the seismic lines. (b) Seismic profile crossing the Cornelia reservoir (modified after Proietti et al., 2022). (c) Seismic profile crossing the Canopo potential reservoir (modified after Rizzini, 2005). Main thrust Fronts: ARF, Arabella; CLF, Cornelia; CNF, Canopo; GF, Gabicce; RF, Riccione.

seals. At this regard, Late Tortonian-Early Messinian porous rocks can be found capped by the Messinian evaporites, which are low permeability rocks that constitute efficient seals (Espinoza & Santamarina, 2017), in the stratigraphic succession of the Adriatic Foredeep. Our preliminary qualitative analyses highlight the occurrence of interesting geological settings that may deserve further investigations regarding textural (effective porosity, permeability, diagenesis and cementation), sedimentological (facies changes, facies associations), stratigraphic (thickness, lateral continuity, stacking patterns) and structural features (current depth, type of deformations, deformation depth of reservoir and seal, deformation pattern and intensity distributions) to be addressed in future studies.

5.1 | Identification of potential reservoir

As for the reservoir, the distribution of the Late Miocene deposits suggests that two main types of potential reservoir rocks could be found (Table 1), respectively represented by the deposits belonging to the Marnoso-arenacea and Bolognano Fms.

- *Siliciclastic porous rocks reservoir* (*SR*)—potentially interesting sites in the sandstone turbidites of the Marnoso-arenacea Fm are buried under the Po plain. In outcrops, these deposits are locally characterized by coarse-grained and relatively well sorted facies deposited by flows confined within erosional features in wedge-top basins, whereas finer-grained deposits are expected in the main foredeep (Mutti et al., 2002; Roveri et al., 2002) where, however, the deposition of coarse-grained facies cannot be excluded due to the migration of the main depocenters. As an example, primary porosity obtained in the late Serravallian Marnoso-arenacea Fm (inner stage) outcropping along the Santerno valley, broadly range from ca. 1% to 10%, with higher values characterizing massive crudely laminated facies (Lucca et al., 2024; Ogata et al., 2017).

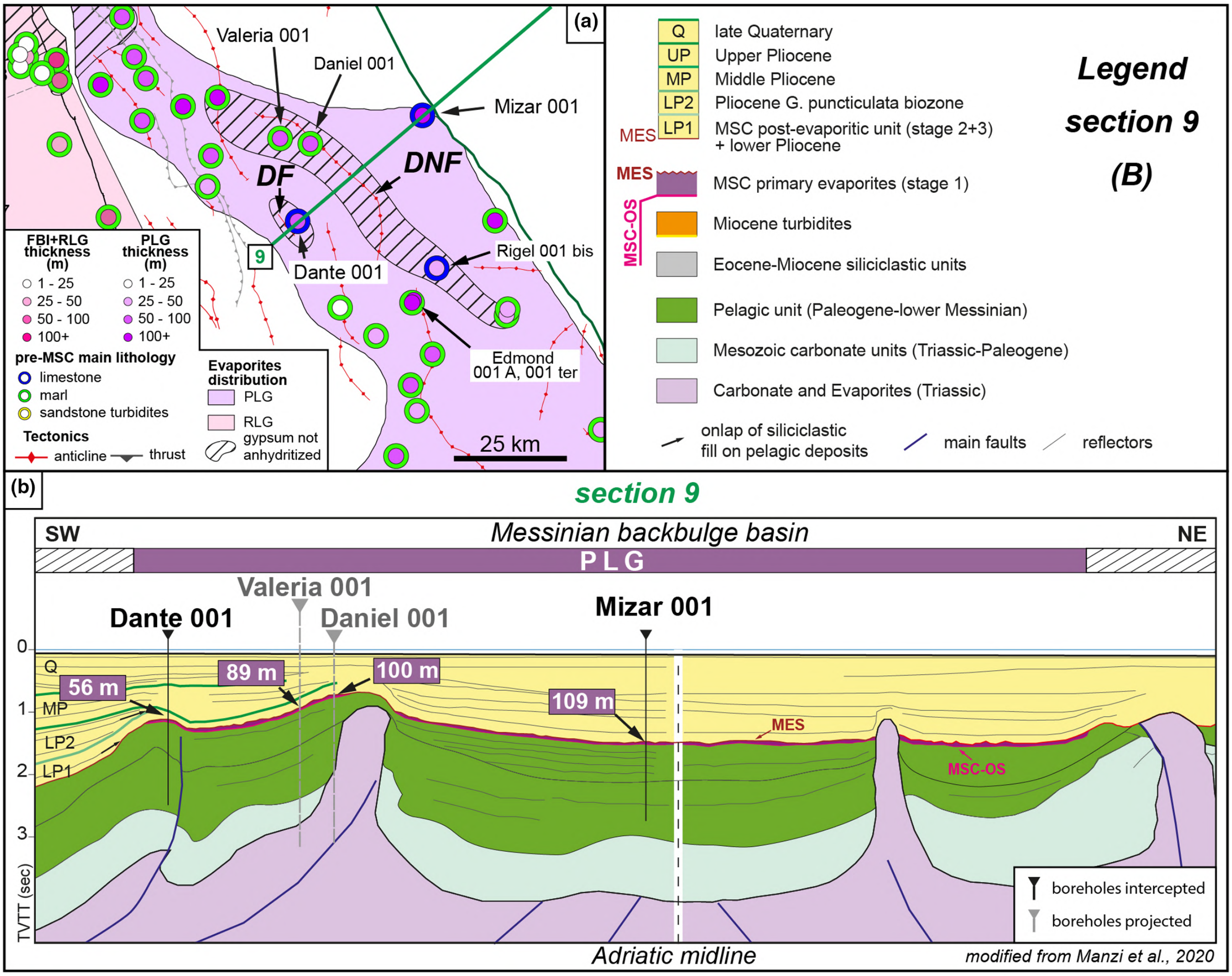

FIGURE 14 (a) Map of the Central adriatic sector reporting the ditribution of the Messinian evaporites and the underlying deposits. Main thrust fronts: DF, Dante; DNF, Danies. (b) Seismic profile crossing the central part of the Adriatic platform with the main boreholes crossing the PLG unit (modified after Manzi et al., 2020).

Moreover, the presence of bed-confined and thoroughgoing fracture systems in such multi-facies successions (Lucca et al., 2024; Storti et al., 2022) further enhances the porosity and storage potential of these siliciclastic rocks.

- *Carbonate porous rocks reservoir* (*CR*)—in this case, interesting sites could be found in the shelf carbonate deposits of the Bolognano Fm that is present in the central Adriatic area (Abruzzo, Molise and Northern Puglia onshore and offshore). In outcrop (Maiella basin), these shallow water carbonates are known to be formed by granular deposits with reduced amount of matrix (Brandano et al., 2016); thus, they may be regarded as good reservoir rocks. In the subsurface south of Pescara a large area characterized by similar deposits has been recognized. The thickness of the Bolognano Fm. here is variable, but a 3000–3500 km^2-large laterally continuous area showing tens of meters thickness has been identified (Figure 15c,e,f).

5.2 | Identification of effective seals

In the identification of the seal it is very important that the role of impermeable barrier is homogeneously maintained in the area of interest. Accordingly, there are some very important aspects that must occur in the evaporitic unit: (i) very reduced or absent lateral facies changes; (ii) scarce presence of non-evaporitic deposits; (iii) absence of porous deposits; (iv) constant (and significant) thickness; (v) very low primary porosity; (vi) ductile behavior and absence of brittle deformations. On these basis, three main types of evaporitic seal can

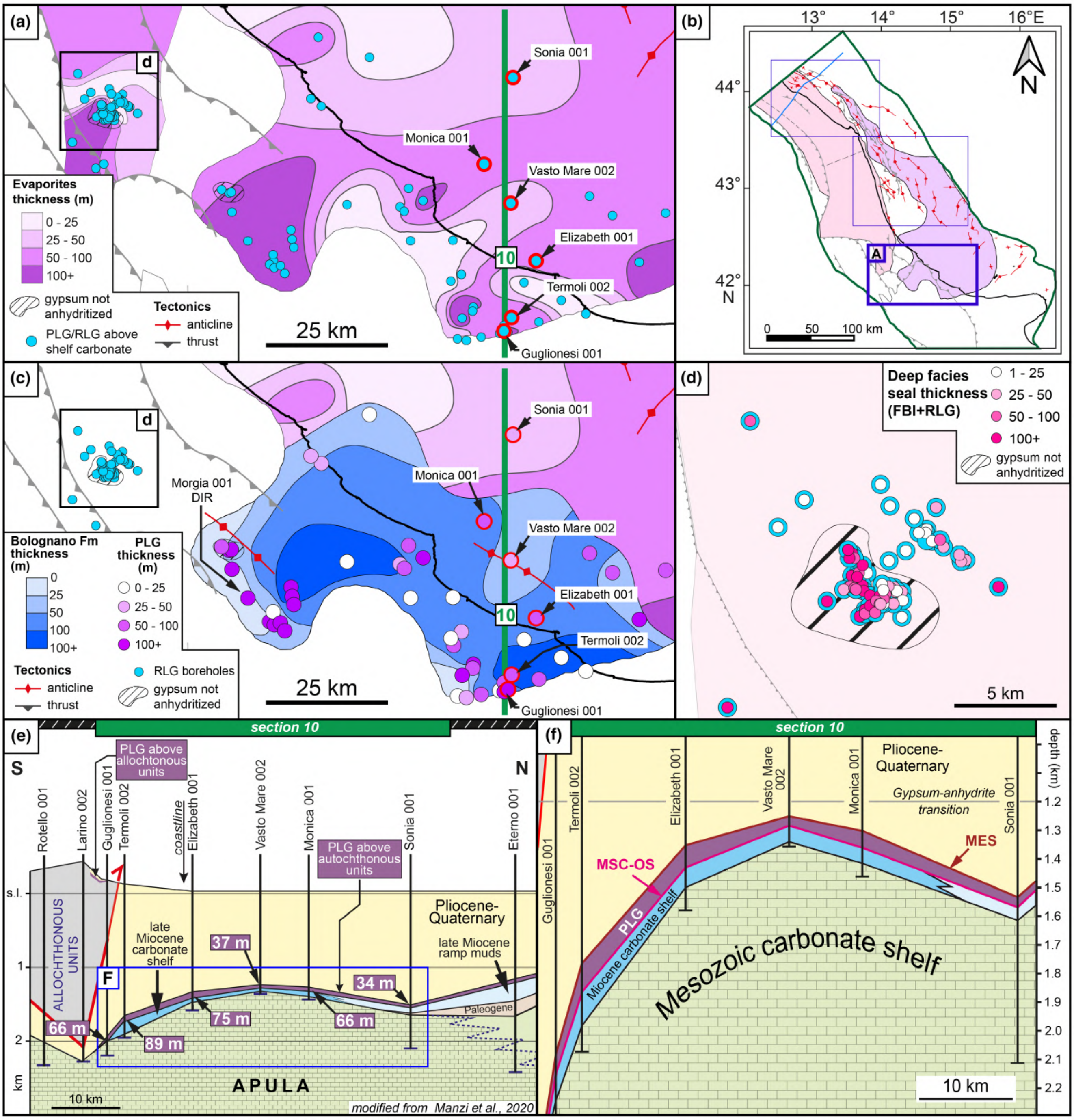

FIGURE 15 Seismic profiles representative of the southern sector of the FB see location in Figure 8. (a) Enlargement of map in Figure 12, with location of the cross sections in E and F, reporting the isopach map of the evaporitc top seal (PLG unit) and presence of the underlaying Bolognano Formation for each available borehole. (b) Location map. (c) Enlargement of map in Figure 12, with location of the cross sections in E and F, reporting the isopachs curve for the potential reservoir unit (Bolognano Formation) below the evaporites and the thickness of the overlaying evaporitic seal for each available borehole. (d) Enlargement of A with indication of the thickness of the evaporitic seal for each available borehole. (e) Borehole correlation crossing the southern part of the Adriatic evaporitic platform (modified after Manzi et al., 2020). (f) Enlargement of (e) showing the presence of an antiformal structure including in its core shelfal carbonate units deposited above Apula (Mesozoic—late Miocene), representing potential reservoir, capped by a thick PLG unit as a possible top evaporitic effective seal.

be found in the Messinian evaporites (Table 2); their original properties could underwent local deformative and diagenetic modifications.

- *Very good efficiency evaporitic seals* (*ES1*) are characterized by reduced/absent shale/carbonate intercalations, tabular unit geometries, good lateral continuity,

TABLE 1 Main characteristics of the two types of porous reservoir rocks found below the Messinian evaporites.

Type of porous rock reservoirs	SR—siliciclastic porous rock reservoir	CR—carbonate porous rocks reservoir
Porous-rock composition	Siliciclastic	Carbonate
Grain-size	Coarse-medium sandstone	Grainstone
Clast sorting	Moderate	High
Primary porosity	Moderate	High
Cementation	Low-moderate	Low-moderate
Unit geometries	Tabular (lobe deposits)/lenticular (channelized deposits)	Wedge
Lateral continuity	Good-moderate	Moderate
Deformations	Low/high	Low/high
Behavior	Brittle/ductile	Brittle/ductile
Facies	Turbiditic lobes and channels	Carbonate ramp
Stratigraphic unit	Marnoso-arenacea Fm. /Laga Fm.	Bolognano Fm.
Depositional setting	Inner foredeep	Foreland

thickness exceeding 100 m, almost complete gypsum to anhydrite transformation. These are potentially found in a large onshore and offshore area south of Pescara where the PLG unit was deposited and then underwent strong post-depositional subsidence.

- *Good efficiency evaporitic seals* (*ES2*) show: discrete lateral continuity, thickness between 50 and 100 m, gypsum only partially transformed into anhydrite. ES2 are expected in those areas where the RLG unit has been deposited and underwent moderate post-depositional subsidence. The local presence of gypsum-bearing mass-wasting deposit and of overlying thick clay deposits may locally increase the seal properties.
- *Moderate efficiency evaporitic seals* (*ES3*) are represented by evaporitic units with reduced lateral continuity, thickness below 50 m and gypsum not transformed into anhydrite. They could be present in outer the Adriatic foredeep areas that are characterized by thin evaporite deposits, minor subsidence and possibly associated with the presence of structural highs.

5.3 | Occurrence of additional seals

The occurrence, above and below the evaporites, of by fine-grained terrigenous deposits with low permeability provides additional seals. Two main areas can be identified, which show different stratigraphic successions:

•*Uplifting and tectonic highs*, e.g. the Vena del Gesso thrust-top basin and the Adriatic foreland. Here, the PLG unit is commonly found directly above the shallow marine carbonates (Bolognano Fm) directly, or with a thin hemipelagites interbed (Schlier Fm). It is truncated on top by the MES a feature that may have caused a reduction of its expected thickness (>200 m). However, such a reduction would not be a problem because, commonly, hundreds of meter-thick low permeability hemipelagic deposits are found above it (Santerno Clays Fm; Pliocene).

- *Tectonic lows*, e.g. in the main foredeep above the evaporites are represented by the RLG unit resting directly, or with a thin organic-rich shale interbed (euxinic shale unit), above siliciclastic turbiditic deposits. The evaporites, in turn, are commonly overlain by thick complex Messinian units (San Donato/Colombacci/Fusignano Fm) made up by shale and turbiditic intercalations which may show variable permeability.

5.4 | Tectonic deformations, structural settings, reservoir depth

Creation of structural traps may be mainly related to (i) thrusts propagation into the main foredeep, related to the progression of orogenic contraction, or (ii) folding and fracturing associated with stretching imparted by flexural tectonic deformations in the forebulge. In both the cases, brittle tectonic deformations can produce secondary porosity in the reservoir, but, at the same time, they can reduce the efficiency of the seal. In the case of sulphate evaporites, it is worth noting that the transformation from gypsum to anhydrite may reduce or hamper the possibility to produce brittle deformations in the evaporitic seals. As

TABLE 2 Main characteristics of the three types of evaporitic seal provided by the Messinian evaporites.

	ES1	ES2	ES3
Type of seal			
Expected efficiency	Very good	Good	Moderate
Evaporitic unit	PLG	RLG	RLG
Characteristics of the evaporitic seal unit			
Evaporitic facies	Mainly primary	Clastic	Clastic
Shale/carbonate	Reduced/absent	Moderate	High
Facies changes	Low	Moderate	High
Unit geometry	Tabular	Lenticular	Highly irregular
Lateral continuity	Very high	Moderate	Low
Anhydritization	Pervasive	Minor	Absent
Lower boundary	Sharp	Sharp/erosional	Erosional
Upper boundary	Erosional	Transitional	Transitional
Thickness	>100 m	50–100 m	<50 m
Deformations	Absent/low	Moderate	Intense
Behavior	Ductile	Ductile	Brittle
Depositional setting	Foreland	Inner foredeep	Outer foredeep
Paleo depth	0–200 m	200–1500 m	200–1000 m
Post-depositional subsidence	>1000 m	500–1000 m	< 500 m
Present-day depth range	−4308/+343 m asl	−4766/+492 m asl	−4766/+492 m asl
Characteristics of the underlaying additional seal unit			
Expected efficiency	Moderate	Low	Moderate
Unit	Euxinic shales	FBI/euxinic shales	FBI/euxinic shales/Schlier
Age	Tortonian-Messinian	Messinian	Tortonian-Messinian
Type deposits	Hemipelagic shales	Dolomitic shales/thin-bedded-turbidites	Hemipelagites
Thickness	50–100 m	<50 m	<50 m
Characteristics of the overlaying additional seal unit			
Expected efficiency	Moderate/good	Moderate/low	Moderate/low
Unit	Santerno clays Fm	San Donato/Colombacci/Fusignano Fm	San Donato/Colombacci/ Fusignano Fm
Age	Pliocene-recent	Messinian-recent	Messinian-recent
Type deposits	Hemipelagic shales	Shales/turbidites	Shales/thin-bedded turbidites
Thickness	>100 m	>500 m	>50 m

described before, the increase of the temperature related to burial depth of up to ca. 1 km (anhydritization depth in the Apennines; Rossi et al., 2021) cause the dehydration of gypsum and the transformation into anhydrite, thus, favoring ductile (i.e viscous) deformations and limiting the development of brittle fractures. Anhydrite can be preserved also at shallower depth because the rehydration to gypsum occurs only at the end of the exhumation phase, when the anhydrite approaches the surface and is reached by meteoric waters.

According to the literature (Bachu et al., 2007; Kovscek, 2002) the optimal conditions for CCS of are obtained with $T > 31.1°$ and $p > 7.38$ MPa when CO_2 behaves as a supercritical fluid; corresponding to depth >800 m in the Apennine foredeep (Buttinelli et al., 2011; Proietti et al., 2022, 2023). Moreover, a maximum depth of 2.4–2.7 km is suggested by a costs/benefits analysis (Bachu et al., 2007; Iglauer, 2018). The potential sites for CCS described in paragraph 4.3 fall into this depth window. This optimal depth window for CCS matches very well the field of stability of the anhydrite; thus, the better efficiency conditions of the seal can be expected.

6 | CONCLUSIONS

Our revision of many published data, integrated with unpublished boreholes and seismic data allow to recognize the presence, in the late Miocene succession of the Adriatic foredeep, of reservoir rocks and evaporitic seal systems that can be considered of potential interest for the storage of natural and synthetic gas.

Two potential reservoir types can be found:

SR: it consists of coarse-grained, mainly channel and lobes facies, siliciclastic turbidites of the Marnoso-arenacea and Laga Fms; they are mainly exposed in the inner portions of the foredeep but are also buried below the Po Plain.

CR: it includes the shelfal carbonate grainstones of the Bolognano Fm; which are outcropping around the Maiella Massif and also occur in the subsurface of the southern Adriatic area, both onshore and offshore.

Locally, the reservoir properties can be enhanced by the occurrence of brittle deformations associated with folding and subsequent exhumation (Lucca et al., 2024; Ogata et al., 2017).

These porous rocks can be capped by three types of evaporitic seals defined based on their facies, thickness, and diagenesis:

ES1: very good efficiency seals are represented by thick (>100 m) tabular units of primary gypsum facies (PLG) largely converted into anhydrite, associated with reduced terrigenous or carbonate deposits and affected by weak deformations, which occur in the foreland at depth often exceeding 1 km.

ES2: good efficiency seals are provided by tabular to slightly lenticular unit of clastic gypsum deposits (RLG) with reduced terrigenous intercalations and overall moderate thickness (50–100 m), which occur in the inner foredeep settings.

ES3: moderate efficiency seals are represented by highly irregular-shaped evaporitic units made up of clastic sulphates with reduced (<50 m) thickness and moderate deformations, mostly occurring in the outer foredeep settings.

Locally the efficiency of the seal can be reduced (occurrence of brittle tectonic deformations) or improved (presence of additional pre-, sin- or early post-evaporitic shale seals deposits).

Our results highlight the importance of the Messinian evaporitic sulphates as effective reservoir seals and allow to provide a preliminary zonation based on the qualitative assessment of the sealing properties, namely lateral continuity, thickness, and type of evaporites. We suggest that two main reservoir and evaporitic seal systems could provide previously overlooked potential sites of storage in the Adriatic foredeep:

- *SR reservoir + ES2/ES3 seal systems* can be found when the coarse grained turbiditic deposits of the Marnoso-arenacea Fm are involved in the thrust folds buried below the Po Plain (Northern Apennine foredeep) and are capped by clastic evaporites (RLG).
- *CR reservoir + ES1seal systems* can be found where the Bolognano carbonate units are involved in forebulge deformations and capped by thick (>100 m) primary evaporites (PLG).

These geological settings, that are of potential interest in the definition of gas storage in the Adriatic foreland basin system, deserve further field analog investigations aimed to the petrophysical, sedimentologic and stratigraphic characterization of the different evaporitic facies and the reservoir porous rocks and to the definition of the more efficient seals, which can be addressed in future studies.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in ViDEPI at https://www.videpi.com/videpi/videpi.asp. These data were derived from the following resources available in the public domain: Pozzi, https://www.videpi.com/videpi/pozzi/pozzi.asp.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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