The Messinian salinity crisis in the Adriatic foredeep: Evolution of the largest evaporitic marginal basin in the Mediterranean

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ABSTRACT

The recent release of a large number of subsurface geological data by the Italian Minister of Economic Development, including boreholes and seismic profiles, provided the occasion for a new assessment of the deposits associated with the Messinian salinity crisis (MSC) in the Adriatic foreland basin system and a new integration with the outcropping successions of the Apennines. In particular, the study of the Messinian evaporites allowed to reconstruct a new detailed palaeogeographic and palaeobathymetric framework for all the stages of the crisis.

We identified the largest evaporitic marginal basin ever described for the Mediterranean hosting the precipitation of the primary shallow-water gypsum deposits (PLG, Primary Lower Gypsum) during the first stage of the crisis. During the second and third stages of the crisis, the PLG basin underwent uplift and erosion and the evaporite accumulation moved to the deeper part of the basin and was characterized by the deposition of the Resedimented Lower Gypsum unit including clastic evaporites, recycling the PLG ones, primary halite and terrigenous deposits.

The distribution of the different evaporitic facies, was the basis for an improved reconstruction of the upper Miocene tectonic evolution of the Apennines thrust belt. Our results show a clear separation between shallower depocenters, located in the wedge-top and in the Adriatic foreland basins and characterized by MSC stage 1 PLG deposition, and deeper-water ones, located in the Adriatic foredeep and close to the Calabrian Arc, where MSC stage 2 terrigenous and gypsum-bearing clastic deposits and primary halite accumulated.

1. INTRODUCTION

The distribution of the Messinian salinity crisis (MSC) related deposits in the Apennines and in the Adriatic foredeep basin has been matter of several studies during the last decades, mostly based on outcrop data (Roveri et al., 2001, 2004, 2006, 2014b). Recently, the Ministry of Economic Development of Italy (*MISE, Ministero dello Sviluppo*

Economico), through the project entitled “Visibility of petroleum exploration data in Italy” (*ViDEPI, Visibilità dei dati afferenti all'attività di esplorazione petrolifera in Italia*) has released a large amount of subsurface data filed since 1957 and covering the whole Italian territory. The ViDEPI database includes a large number of boreholes and industrial seismic profiles for hydrocarbon investigation. A great part of these boreholes crossed the Messinian deposits, especially in the offshore areas. Their analyses made it possible to recognize the subsurface equivalents of the deposits cropping out in the Apennines and to provide a detailed reconstruction of the distribution of the MSC-related deposits all along the Apennines foredeep.

2. THE MESSINIAN SALINITY CRISIS (MSC): A BRIEF OVERVIEW

The Messinian salinity crisis (MSC; 5.97-5.33 Ma) is one of the more dramatic palaeoceanographic and biological event in the Earth’s history, during which huge volumes of evaporites accumulated on the Mediterranean seafloor because of the reduced connections with the Atlantic Ocean, due to the interplay between tectonic uplift in the Gibraltar area and glacio-eustatic changes (Krijgsman et al., 1999). The largest part of the evaporites deposited during the MSC is now buried below the deep Mediterranean seafloor but the large number of outcrops has allowed the reconstruction of a very-high resolution stratigraphic framework through the integration of bio-, magneto- and cyclostratigraphic data (Clauzon et al., 1996; Krijgsman et al., 1999; Hilgen et al., 2007; CIESM, 2008).

2.1 MSC stages

A large consensus has been reached during the last decade by the scientific community in subdividing the MSC into three evolutionary stages, each of them well time-constrained and characterized by peculiar evaporite deposits and palaeohydrological conditions (CIESM, 2008; Roveri et al., 2014a,b). Controversies still persist on what actually occurred during these three stages, especially for what concerns the variations of the Mediterranean sea level.

Stage 1 (5.97-5.60 Ma) - According to Roveri et al. (2008) and Lugli et al. (2010), shallow-water (< 200m) bottom-grown primary evaporites (PLG, Primary Lower Gypsum; accumulated only in marginal silled basins, whereas organic- and dolomite-rich foraminifer-barren shales sedimented in deeper water (Manzi et al., 2007; FBI, Foraminifer Barren Interval, *sensu* Manzi et al., 2018). Up to 16 shale-gypsum cycles were deposited under a strong astronomical control to form up to 200 m-thick evaporite successions (Vai, 1997; Hilgen et al., 2007; Lugli et al., 2010). According to other authors, based on the interpretation of seismic data, PLG deposition has also occurred in deeper waters (Ochoa et al., 2015) or has been replaced by halite (Meilijson et al., 2018, 2019).

Stage 2 (5.60-5.55 Ma) - It represents the MSC acme. The marginal basins that hosted the PLG deposition during stage 1 underwent uplift and deep erosion. In this stage evaporite deposition shifted to the deeper settings and was characterized by both clastic (derived from the dismantlement of the PLG unit) and primary evaporites (cumulate deposits of gypsum, halite and K-Mg salts) deposits, grouped into the Resedimented Lower Gypsum unit (RLG; Roveri et al., 2008a). The connections with the Atlantic were further reduced but still sufficient to allow accumulation of marine water-derived salt. This stage was marked by a widespread tectonic activity and by a sea level drop for which timing (before, during or after halite deposition; see discussion in Roveri et al., 2014b) and magnitude (from 100-200 m; according to Roveri et al., 2016; Manzi et al., 2018; up to 800 m according to Druckman et al., 1995; Amadori et al., 2018; up to more than 1500 m according to Lofi et al., 2005; Bache et al., 2009) are still lively debated.

Stage 3 (5.55-5.33 Ma) - This is the last and probably the less known stage of the MSC. The deposition of primary evaporites was limited to the southern and eastern portion of the Mediterranean Sea (Sicily, Cyprus, Crete) and completely absent in the Apennines foredeep. The peculiar Lago-Mare fossil associations, including hypohaline mollusk, ostracod and dinocyst (Rouchy et al., 2001; Bertini, 2006; Orszag-Sperber et al., 2006; Cosentino et al., 2007; 2012; Gliozzi et al., 2007; Grossi et al., 2008; Pellen et al., 2017, Roveri and Manzi, 2006; Roveri et al., 2008c; Ruggieri, 1967), suggests the development of hypohaline conditions possibly related to the input of Paratethyan water in the Mediterranean basin. However, on the basis of the occurrence of marine fossils (fishes; Carnevale et al., 2006; dinocysts, Popescu et al., 2009; Pellen et al., 2017; long-chain alkenones, Vasiliev et al., 2017), possible oceanic incursions during the last stage of the crisis have been envisaged (Bache et al., 2009; 2012). Marine waters may have provided the ions needed for the precipitation of the Upper Gypsum evaporites during insolation minima (Manzi et al., 2009). Depleted Sr isotope values and the increased terrigenous deposits during this stage point to a Mediterranean Sea characterized by hypohaline waters, more humid climatic conditions and enhanced fresh-water input (Roveri et al., 2014a,b). The recognition of the peculiar Sr signature in both shallow and deep settings (Roveri et al., 2014a; Gvirtzman et al., 2017; Manzi et al., 2018) suggests the persistence of water connections between the Mediterranean subbasins also during the stage 3 that were likely filled by a unique water body. However, other authors hold that, at least at the beginning of stage 3, the Mediterranean basin was almost desiccated, based on the occurrence of inferred fluvial deposits above the stage 2 halite in the Levantine Basin (Madof et al., 2019).

2.2 MSC surfaces

This MSC stratigraphic framework is based on the recognition of some key-surfaces (Roveri et al., 2019; and their Fig. 3):

onset surface (OS) – It marks the MSC onset placed in the 4th precessional cycle above the Gilbert chron at 5.97 Ma (Manzi et al., 2013). It is associated with the sudden disappearance of the foraminifers. It can be found indistinctively at the base of the PLG unit or at the base of the FBI (Manzi et al., 2007; 2018);

evaporites onset surface (EOS) - It is a diachronous surface flooring the PLG, only locally coinciding with the OS; The Messinian deposits laying above the EOS belongs to stage 1 and are younger than 5.97 Ma;

Messinian erosional surface (MES ≡ ***base of the p-ev$_1$ unit) -*** It is a widespread unconformity surface (Cita and Corselli, 1990) locally associated with angular discordance and local subaerial exposure (Vai, 1988). It can be traced from the top of the PLG unit in the marginal basins up to the base of the RLG unit in the deep ones. It has been recognized offshore along the Mediterranean basin margin (Ryan and Cita, 1978; Lofi et al., 2005; Roveri et al., 2014b and references therein). In the deeper portion of the basins the MES pass to its correlative conformity surface (MES-cc; Roveri et al., 2008b; 2019). The MSC deposits laying above the MES belongs to stage 2 or 3 and are always younger than 5.60 Ma; this surface marks the dismantlement of the PLG deposits and their resedimentation in the foredeep lows (Roveri et al., 1998; 2006; 2008c).

ash layer (al) – A rhyolitic volcaniclastic key-bed dated at 5.53 Ma (Roveri et al., 1998; Trua et al., 2010; Cosentino et al., 2013) found in the whole Adriatic foredeep and locally in Calabria and Sicily, roughly marking the base of stage 3, is often found at the top of the RLG unit;

base of p-ev$_2$ – dated at 5.42 Ma, this surface can be regarded as a maximum regressive surface in the MSC succession (Roveri et al., 2008b) marking a change from regressive to transgressive trend in the post-evaporitic succession. In the marginal settings this surface commonly is found at the base of fluvio-deltaic deposits, whereas, in deeper settings, it marks the base of coarser-grained turbiditic deposits. Above this surface a higher diversity hypohaline biota is commonly present (“Lago-Mare” *sensu stricto;* Roveri et al., 2008c).

Miocene/Pliocene or Messinian/Zanclean boundary (M/P) – this surface marks the Messinian-Zanclean boundary placed at 5.33 Ma 5 precessional cycles below the base of the Thvera magnetic event (Van Couvering et al., 2000) and marked by the return to fully marine conditions in the Mediterranean; in the Apennines, it is commonly associate with a black shale organic-rich horizon (Roveri et al., 2006).

3. GEOLOGICAL SETTING

The study area includes different portions of the Apennines that have been historically considered as worlds apart. We try here to limit the Apennines subdivision into two main paleogeographic domains, autochthonous and allochthonous that were deposited respectively in the outer and in the inner portion of the Apennines fold and thrust system. We focus on the late Miocene-early Pliocene terms of the stratigraphic succession (Fig. 1).

3.1 Autochthonous domains (AD)

All the sedimentary successions deposited in basins resting on the undeformed portions of the foredeep and foreland above Adria and Apula that experienced only minor tectonic translations after the MSC are grouped in this domain.

3.1.1 Northern Apennines

The northern area includes the foredeep basin formed above the Umbro-Marchean (UM) units characterized by a thick Triassic-Jurassic shallow water carbonate succession (Burano Anhydrites, Calcare Massiccio, Calcari a Posidonia, Rosso Ammonitico units) followed by Cretaceous-Paleogene hemipelagic carbonate and marls (Maiolica, Fucoidi marls, and Scaglia Fms). While the inner Umbro-Marchean unit (IUM; Fig. 1a) was involved in the Apennines orogenesis, the outer Umbro-Marchean unit(OUM; Fig. 1a) was characterized, since the Langhian, by the deposition of a thick Alpine-derived siliciclastic fill extending for hundreds of km along the Adriatic foredeep from the Emilia-Romagna to the Umbria region (Ricci Lucchi, 1986; Argnani and Ricci Lucchi, 2001).

During the late Tortonian an important tectonic phase affecting the whole Apennines caused the eastward migration of the foredeep (Ricci Lucchi, 1986), the formation of the Vena del Gesso wedge-top basin (VdG; Roveri et al., 2003) and the segmentation of the main foredeep into minor basins (ER, Eastern Romagna; NM, Northern Marche; L, Laga; Fig. 1).

In the inner sectors of the foredeep, affected by tectonic segmentation, turbidite deposition stopped during the late Tortonian while their deposition continued during the whole MSC and in the Pliocene in the undeformed foredeep (e.g. the Laga basin; Ricci

Lucchi, 1975; 1986). The turbidites were deposited in the more subsiding portions of the Adriatic foredeep. Conversely, in wedge-top basins or in the foreland ramp, that were not reached by the turbiditic flows moving along the foredeep axis, the pre-MSC succession commonly consists of hemipelagic deposits (Euxinic shale and Schlier Formations), showing a well-developed cyclic pattern given by the alternation of sapropels, marls and diatomite, the deposition of which is strictly controlled by variation of Earth orbital parameters (Vai, 1997; Krijgsman et al., 1999). These deposits are characterized by a large fossiliferous content (foraminifers, nannofossils, and locally mollusks); their sedimentation rate is quite reduced as the last 1.2-1.5 Ma preceding the MSC onset have been recorded by less than 50-60 m (Manzi et al., 2007; 2018).

During the MSC the sub-basins of the foredeep were characterized by different stratigraphy. During stage 1, the primary evaporites (PLG) were deposited only in shallow basins, like the thrust-top VdG basin (Roveri et al., 2003) and in the foreland (Roveri et al., 1986; 1992; 2005; Rossi et al., 2015); in the deeper basin of the Romagna and Marche this interval is characterized by the deposition of an organic-rich and dolomite-rich foraminifer-barren shale unit (FBI; Manzi et al., 2007; 2018). During stage 2, the VdG basin was uplifted, the PLG unit was eroded and resedimented in the adjoining basins to form the RLG unit (Manzi et al., 2005). The stage 3, in this sector, is characterized by the absence of evaporites and by the deposition of Apennine-derived terrigenous deposits (San Donato, Colombacci, Laga units; Bassetti et al., 1994; Ricci Lucchi, 1975; 1986; Ricci Lucchi et al., 2002; Roveri et al., 2001; Milli et al., 2007) containing peculiar hypohaline biota and showing strong thickness variability, from few meters in the VdG basin up to more than 1 km in the deeper buried portions of the foredeep (Fusignano Fm; Cremonini and Ricci Lucchi,1982). The return to the fully marine conditions at the base of the Zanclean was sharp and marked by a black, organic-rich horizon (Roveri et al., 2004; 2006).

The OUM is limited to the south by the Gran Sasso thrust front (GS) involving the carbonate units of the Lazio-Abruzzi platforms (LAP), the front of the Molise-Lagonegro nappe (MLN), and bounded to the east by the Apulian Platform, including the Gargano high (G; in red in Fig. 1a) that originated mostly in the Late Miocene-Pliocene (Argnani et al., 2009).

In the most elevated portions of the Lazio-Abruzzi platform, the carbonate deposition continued until the MSC. In the Maiella area the *Lithothamnion* limestone facies, representing the younger term of the Bolognano Fm., was deposited until the lower Messinian (Brandano et al., 2012; Cornacchia et al., 2017); in its upper part, this unit passes gradually to marl deposits containing *T. multiloba*, whose distribution zone (6.34-5.97 Ma; Sierro et al., 2001; Manzi et al., 2007) is quite close to the onset of the MSC. Around the Gargano high, on top of the Apula platform, the pre-MSC late Miocene succession is incomplete and poorly age-constrained; it includes shallow water limestone deposits (breccias and calcarenites), the deposition of which is supposed to have been continued until the early Messinian. No evaporites crop out in this area. The pre-crisis unit is capped unconformably by the Gravina calcarenites, a Pliocene unit which age is not strongly constrained.

Moving southward, the Messinian deposits of the OUM continue into the Bradanic Trough (BT). They are buried under the allocthonous Molise-Lagonegro Nappe (MLN), that was emplaced during the Plio-Pleistocene (Patacca and Scandone, 2007; 2011). The only information about MSC deposits in the BT derives from boreholes and seismic data and their place into the stratigraphic framework is still lacking.

3.2 Far-travelled Allochthonous domains (TD)

This domain includes all the semiallochthonous geological terranes that during the late Miocene were located in the more inner (western) position of the foredeep and that during the Plio-Pleistocene translated in their present position above the AD (Fig. 1).

3.2.1 Northern Apennines

In the Northern Apennines the Emilia and the Val Marecchia Epiligurian units were deposited over a late Jurassic-lower Eocene Ligurian complex translating (north)eastward over the Tuscany and Umbro-Marchean-Romagna domains. These Epiligurian satellite basins are characterized by Messinian successions similar to those of the VdG basin (Manzi, 2001; Gennari et al., 2013), with thick PLG unit eroded on top and sealed by the uppermost portion of the Lago-Mare unit and by the Pliocene marine clay unit. The PLG lays conformably on a shelf shale succession (Termina, Ca' i Gessi formations; Ruggieri, 1970; Roveri et al., 1999; Gennari et al., 2013) the base of which is locally marked by late Tortonian sandstones (Termina Fm) and conglomerates (Acquaviva Fm), in the Emilia and in the Val Marecchia, respectively. During the Messinian the Epiligurian basins were located in a more internal position with respect to the VdG basin; they reached their current position during the middle Pliocene.

3.2.2 Southern Apennines

In the southern Apennines two main translated domains can be distinguished: the Molise and Lagonegro nappe and the Calabrian Arc.

The MLN (Fig. 1) represents the accretionary wedge of the Calabrian Arc (e.g., Argnani, 2005; Casero, 2004; Vitale and Ciarcia, 2013) and consists of a Triassic-lower Miocene tectonic complex including slabs of deep basinal (shale and cherty limestone) and flyschoid deposits (carbonate or siliciclastic turbidites). These units are capped by a relatively less deformed late Miocene-early Pliocene succession (Matano et al., 2005); it is formed by i) a pre-MSC unit including the Faeto flysch and Toppo-Capuana marls; ii) an evaporite unit (Monte Castello Fm) capped by terrigenous unit (Anzano molasse, Torrente Fiumarella unit) and by the Pliocene shallow marine to deltaic deposits (Ariano unit). The evaporites crop out discontinuously but they are well exposed in three localities, Cervaro River, Monte Ferrara and Scampitella quarries (Matano et al., 2007) where, on the basis of gypsum facies (massive, banded and branching selenite) and Sr signature (within stage 1 range) an incomplete PLG succession, up to 50 m-thick, can be recognized. The base of the PLG is poorly exposed but is assumed to be conformable. Conversely, its top is unconformable and overlain by terrigenous deposits containing scarce hypohaline ostracod and mollusk that can be assigned to the stage 3. A reduced succession is found in the outer portion of the Molise allochthonous both in outcrop and subsurface, including blocks of PLG unconformably capped by the Lago-Mare deposits (Cosentino et al., 2018).

The Calabrian Arc (Van Dijk, 2000; Fig. 1) consists of pre-Triassic metamorphic and intrusive units in places with Alpine metamorphism, originally located close to Corsica-Sardinia, were translated south-eastward because of the opening of the Tyrrhenian Sea since the late Tortonian (e.g., Argnani 2005; Cipollari et al., 1999; Kastens et al., 1988). The Ionian side of the Calabrian Arc is characterized by a late Miocene-Pleistocene succession resting unconformably on the crystalline basement and its Mesozoic-Cenozoic sedimentary cover, or on the Mesozoic-Paleogenic terrigenous units accreted in front of the Calabrian Arc (Van Dijk, 2000; Roveri et al., 2008; Zecchin et al., 2003). The MSC units rest on a late Tortonian-early Messinian marine unit consisting of thin-bedded turbidites, marl and diatomite (Ponda Fm) resting in turn on a fluvio-deltaic conglomerates succession (San Nicola unit) derived from the dismantlement of the crystalline and metamorphic basement. In the Crotone and Rossano basins, the MSC deposits consisting of a lower clastic carbonate and gypsum deposits (Roveri et al., 2008; Manzi et al., 2011) belonging to the RLG unit resting unconformably above the pre-crisis units and floored by the MES. Locally an organic-rich evaporitic-free unit barren of foraminifers, representing the deep time-equivalent of the stage 1 evaporites, is preserved. Above the resedimented gypsum unit a hybrid (gypsum, carbonate and siliciclastic) unit including halite lenses is present (detritico-salina unit; Roda, 1964), in turn capped by a fluvio-deltaic unit with Lago-

Mare faunal associations including conglomerate lenticular bodies (Carvane unit, Roda, 1964). The end of the MSC is marked by the deposition of lower Pliocene open marine marls (Cavalieri marls) followed by the siliciclastic deposits of the Belvedere Fm (Roda, 1964; Van Dijk, 2000).

4. METHODS

In this work we have considered 1341 boreholes belonging to the offshore zones of the Adriatic and Ionian Sea (offshore zones A, B, D, F) and the onshore Autochthonous Domain. An extended version of the methods is provided in the supplementary document. We focused of the late Tortonian-early Pliocene stratigraphic interval in order to reconstruct the distribution of the deposits associated with the Messinian salinity crisis along the Adriatic foredeep. The studied boreholes have been grouped on the basis of encompassed stratigraphic interval (tab. S1).

5. THE OUTCROPPING MSC UNITS

Here we will briefly describe the main physical and sedimentological characters of the different Messinian evaporitic units as they appear in outcrop; these features can be useful in the interpretation of evaporites on borehole log.

5.1 Primary bottom-grown gypsum (PLG unit; stage 1)

Due to its peculiar characters the PLG unit is easily recognizable in the field. The complete succession, forming large-scale tabular bodies with a thickness of 200 m or more (Fig. 2a,b), includes up to 16 gypsum beds separated by thin (typically 1-3 m) intervals of dark euxinic shales (Fig. 3a). Its internal organization, that is maintained over large distances, is characterized by (Lugli et al., 2010; Fig. 3a): i) two lowermost thin (<10m) gypsum beds (PLG1-2) with giant crystals massive selenite showing a lateral transition to limestone (Manzi et al., 2013); ii) three intermediate very thick (up to 35 m) and very lateral persistent gypsum beds (PLG3-5) with massive and banded selenite facies; iii) up to 11 thick (10-15 m) gypsum bed (PLG6-16) showing the presence of branching selenite in the upper part of the beds. Despite the variation in absolute thickness, the relative thickness of the gypsum beds remains rather constant in the different basins and the presence of the intermediate cluster formed by the thickest beds (PLG3-5; Fig. 13 in Lugli et al., 2010; Fig. 2b, 3a) can be easily identified, thus, representing a key horizon useful for stratigraphic correlations.

The gypsum facies, are characterized by a different resistance to weathering that provides a characteristic erosional profile. PLG1-5 gypsum beds being made up by coarse and interlocked gypsum crystals (massive and banded facies) are characterized by a massive aspect with sharp upper and lower boundaries. The gypsum beds of the upper cycles (PLG6-16) may show relatively smoother tops due to the presence of the more erodible branching selenite facies containing a greater amount of limestone and/or shale (Fig. 3b).

The PLG deposits rest conformably on hemipelagic or shelf shale and are erosionally cut on top by the MES.

5.2 Gypsum and hybrid clastic deposits (RLG unit; stage 2)

The RLG unit is floored by the MES; it rests unconformably on pre-MSC deposits but locally, in the basinal areas where the MES pass down basin to its correlative conformity surface, a barren organic-rich shale interval (FBI) is present below the RLG (Manzi et al., 2007). The RLG evaporites form tens of m-thick lenticular or tabular bodies (Fig. 2c) characterized by a great variability of clastic facies that can be grouped as follows (Manzi et al., 2005; 2011).

5.2.1 Mass wasting gypsum-bearing deposits (RLG1)

This group includes mass-wasting deposits, submarine glides, slides and slumps, cohesive flows (facies R0, R1 of Manzi et al., 2005). These deposits include heterometric PLG-derived gypsum block and chaotic shale. They are characterized by individual lenticular beds, with irregular bases and tops, forming wedge-shape bodies close to the main tectonic slopes, e.g. the large slope complex found close to the structural high boarding the VdG basin (Roveri et al., 2003) similar PLG-bearing chaotic bodies are described in seismic also at the front of the Ligurian nappe close to Reggio Emilia (Rossi et al., 2002).

5.2.2 gypsum-bearing turbidites (RLG2)

This group includes the gypsum-bearing gravity flow deposits (granular flows and high- to low-density turbidity currents; facies R2 to R7 of Manzi et al., 2005) commonly consisting of m-thick composite graded beds showing a lower coarser-grained (rudite or arenite) gypsum-bearing division capped by a finer-grained one mostly composed by gypsiltite or shale (Fig. 3c). Commonly these beds show a good lateral persistency and limited thickness (Fig. 2c). Carbonate and terrigenous sandstone clasts recycled from older deposits may be found in the coarser-grained interval. The base of these beds is commonly sharp and the top is smooth due to the normal gradation and the transition to the shale interval.

5.3 Primary halite and gypsum deposits (RLG unit; MSC stage 2)

These deposits can only be observed where diapirs crop out or in mines in Calabria (Crotone basin), Sicily (Caltanissetta basin) and Tuscany (Volterra basin) otherwise they are absent in the rest of the Apennines. Halite forms lenticular bodies with local thickness up to 600 m due to intense halotectonics. Internally they consist of dm-thick beds separated by thin anhydrite or shale horizons; thin K-Mg rich salt beds are locally found in the middle part of the halite bodies (Lugli et al., 1999; Manzi et al., 2012).

5.4 post evaporitic deposits (Lago-Mare unit; MSC stage 3)

The primary gypsum deposits of the Upper Gypsum unit (UG; Manzi et al., 2009) occur only in the Caltanissetta basin (Sicily), capping the RLG unit. In the Calabrian arc and in the rest of the Apennines the RLG is capped by thick terrigenous fine-grained deposits including a rhyolitc volcaniclastic key-bed described in paragraph 2 and showing a coarser-grained upper portion (p-ev_2 unit) including conglomerates (Cusercoli Fm, Romagna, Roveri et al., 1998, 2006; Carvane unit, Crotone basin, Calabria, Roda, 1964), sandstones and thin limestone layers (Colombacci Fm). The Lago-Mare biota are mostly distributed in the p-ev_2 unit and in its time equivalent, upper half, portion of the Upper Gypsum unit. The end of the MSC is marked everywhere by the sudden transition to fully marine deposits, commonly preceded by a dark shale horizon (Roveri et al., 2006).

6. THE MSC UNITS IN THE SUBSURFACE: DISTINGUISHING CRITERIA FOR LOG INTERPRETATION

The different lithologic units belonging to the late Tortonian-early Pliocene interval crossed by the boreholes are listed in tab. S2 with their typical characteristics observed from the geophysical logs, gamma ray (GR), resistivity (RES) and sonic (Δt). The evaporites can be easily distinguished from the siliciclastic and hemipelagic deposits not only directly (cuttings analysis) but also indirectly on the basis of geophysical logs especially for the higher resistivity, lower Δt and lower gamma-ray (with the exception of the K-Mg salts). Among the Messinian evaporites a further distinction between primary gypsum, clastic gypsum and halite deposits can be obtained on the basis of the different values and vertical pattern observed in the gamma ray, resistivity and sonic logs.

A main subdivision of the MSC-related deposits includes three main group of rocks.

6.1 Evaporite-free intervals

These intervals consist mostly of clay or marl deposits containing minor sandstone or carbonate horizons devoid of evaporites. The intervals are commonly characterized by very low (<10 Ωm) resistivity, relatively high gamma ray (50-100 API units) and Δt (60-200

μs/ft**)**. The presence of sandstone or carbonate can be highlighted by small increase of resistivity and decrease of gamma ray and Δt. The pattern of geophysical logs has commonly a monotonous trend, local spikes are recorded where thin sand or carbonate layers are crossed.

6.2 Gypsum-rich intervals

Gypsum-rich intervals are characterized by high resistivity (200-600 Ωm), low gamma ray (0-10 API units) and low Δt (45-50 **μ**s/ft**)**. Among them the primary deposits (PLG) can be easily distinguished from the clastic ones (RLG) based on the log patterns:

6.2.1 Primary Lower Gypsum intervals (PLG)

The PLG unit is characterized by a peculiar blocky pattern obtained by thin spikes of low resistivity/high gamma ray that punctuate a high resistivity/low gamma ray base line, that reflect the lithological composition of the succession (Lugli et al., 2010; Sampalmieri et al., 2008; 2010). These features allow the recognition and count of the cycles from the geophysical logs that can be used for stratigraphic correlations. In particular the typical stacking pattern can be recognized from logs (e.g. Patrizia_001, Fiona_001, Morgia_001 boreholes; Fig. S1): two thin (< 10 m) lowermost cycles (PLG1-2), three very thick and massive cycles (PLG3-5) and up to 11 medium (10-15 m) cycles (PLG-6-16). In the geophysical logs, PLG-1-5, consisting of massive and banded selenite facies only, show commonly both sharp bases and tops, whereas PLG-6-16 beds, due to the presence of the branching selenite, may show a sharp base but a smoother top.

6.2.1 Resedimented Lower Gypsum intervals (RLG)

The RLG unit (e.g. Thurio_001 and Dalila_001 boreholes; Fig. S1) is characterized by a (finely) spiky pattern obtained from a thin alternation of spikes with high resistivity/low gamma ray (gypsum) and spikes with low resistivity/high gamma ray (clays). As shown in the previous paragraph the clastic gypsum beds are thinner with respect to the PLG beds.

6.3 Salt-rich intervals

A very high resistivity (~10000 Ohm.m) identifies the salt-rich interval (e.g. Thurio_001 borehole; Fig. S1). The alternation of thin halite, gypsum and clay may result in a spikey pattern whereas massive halite may produce a blocky one. Halite is commonly characterized by low gamma ray values (0-10 API units) whereas K-salts can be highlighted by higher values (100-200 API units). Δt is commonly low (60-75 **μ**s/ft**)**.

7. RECONSTRUCTION OF THE ADRIATIC EVAPORITIC BASIN

The boreholes of the ViDEPI dataset that have been used in this work are those crossing the MSC interval, that can be represented by sediments or by hiatus. Two main groups can be distinguished (Fig. 4a):

The Adriatic foreland units - These deposits resting on the Autochthonous Domain and covered by the Plio-Pleistocene succession are found in the more external domains that were only partially involved in the Apennine deformation, the foredeep and foreland ramp basins (below the Adriatic Sea).

In the Southern Apennines these units include deposits that rest on the Autochthonous Domain (Fig. 1b) , and in particular on the Apulian Platform domain, but are tectonically overlain by the units of the Translated domains. The Adriatic foredeep and foreland units have been found in the Southern Apennines and were reached below the MLN allochthonous units. The post-MSC succession above the MSC is absent or reduced because of the allochthonous thrusting; it becomes progressively more complete toward the external zones on the foredeep, allowing the reconstruction of TD migration during the Pliocene (Patacca and Scandone, 2007; Bigi et al., 2013).

Translated MSC units – These deposits resting on the Far-travelled Allochthonous and covered by the Plio-Pleistocene succession are found in the buried basins of the Calabrian Arc and in the north-eastern portion of the MLN.

A reconstruction of the early Tortonian-Messinian stratigraphy obtained by the analysis of the boreholes data is here proposed separated into three time intervals (Fig. 4 b,c,d):

Pre-MSC (Tortonian-Messinian; 8.50-5.97 Ma; Fig. 4b)

The large part of the pre-MSC deposits of the Autochthonous Domain is characterized by the deposition of fine-grained (marls and sapropels) hemipelagic deposits whereas the deposition of the Tortonian-Messinian siliciclastic turbidites is limited to the western portion of the northern Apennines foredeep and in the outer Marnoso-arenacea and Laga basins. Shelf carbonate deposits are found in a small area extending in a WNW-ESE direction from the Gran-Sasso-Maiella area to the northern Gargano (between Pescara and Foggia). Interbedded hemipelagic and shelf terrigenous deposits (clays with sandstone lobes) were deposited in the eastern basins of the Calabrian Arc (Roda, 1964; Roveri et al., 1992).

Stage 1 (5.97-5.60 Ma; Fig. 4c)

During the first stage of the MSC the deposition of PLG unit is limited to: i) the wedge-top basins of the Authocthonous Domain, ii) the wedge top basins translating above the Ligurian and Molise-Lagonegro nappes and ii) to the Adriatic foreland basins (Fig. 1).

The best example in the wedge-top basins of the AD is found in the Vena del Gesso basin (Roveri et al., 2003) where the reference section for the evaporites of the stage 1 is present (Monte Tondo section; Lugli et al., 2010). In the satellite basins developed above the allochthonous units, three main areas can be distinguished: Marecchia river valley, Irpinia and Molise. In the Marecchia river valley (Gennari et al., 2013) and in Irpinia (Matano et al., 2005) the PLG unit rests conformably above a pre-MSC shelfal shale succession. Conversely in the Molise area Cosentino et al. (2018), having observed that the PLG unit rests indistinctly above the Varicolored Clays (Cretaceous-Paleogene) or the Faeto flysch (Aquitanian-lower Messinian) deposits, suggested the presence of an unconformity at its base. In the area south-west of Termoli, between the Saccione and the Trigno rivers, 13 boreholes crossed an evaporite unit that can be assigned to PLG on the basis of the analogies in term of thickness and trend of the geophysical logs with that drilled a few km to the north resting above the Autochthonous Domain. It is worth noting that 5 out of the 13 boreholes reached the PLG on the top of the Apulian succession below the allochthonous units. As correctly reported by Cosentino et al. (2018) the PLG above the Molise-Lagonegro Nappe is commonly found resting above a clayey succession of not well-defined age. However, considering that the PLG unit crops out in small isolated blocks at the front of the MLN (e.g. Stingeti and Gessaro; Cosentino et al., 2018) and that it is present in the foreland below the MLN, a different interpretation could be suggested. The PLG could have been accreted at the front of the MLN when the allochthonous units translated over the foreland, where the PLG unit rests conformably above the AD; in this view the base of the PLG cannot be considered an unconformity.

The MSC succession in the Adriatic foreland is characterized by a main depocenter located in the Adriatic offshore between the Gargano and the Conero Riviera (Ori et al., 1986; Roveri et al., 2005; Corcagnani, 2017). Here, several boreholes crossing the PLG unit allowed the reconstruction of 6 correlation panels (Fig. 5) and 4 isopach maps (Fig. 6).

The PLG commonly overlays hemipelagic deposits, but in the Gran-Sasso-Maiella area it rests above shelf carbonates developed since the early Miocene; thus, suggesting the presence of shallow-waters environment well before the MSC onset. In the other areas no PLG are found. Based on outcrop (Northern Apennines, Manzi et al., 2007; Conero Riviera, Iaccarino et al., 2008; Calabria, Roveri et al., 2008d) and subsurface data in the Northern Adriatic foredeep (Rossi et al., 2015) an organic-rich, dolomitic-rich, foraminifers-barren shale unit can be found in the area where the PLG unit is absent (Fig. 4b).

The peculiar pattern of the PLG successions observed in outcrops and described in the previous paragraphs, allows the recognition in the offshore of the individual cycles in this offshore area from boreholes. The correlations between the boreholes showing the best geophysical logs (see Fig. 5) have been traced along three NW-SE-oriented panels (sections 1, 2 and 3) and three panels perpendicular to the previous ones (sections 4, 5 and 6) in order to show the internal variations of the unit. The cluster formed by the thickest cycles, PLG3-5, can be easily recognized; it is continuous all along the sections providing a helpful tool for stratigraphic correlations. The lowermost cycles PLG1-2 have been detected in several sections; thus, confirming the conformable character of the base of the PLG. Conversely, the unit appear truncated on top by the MES and sealed by the Lago-Mare or directly by the Pliocene deposits; the latter become younger eastward, as described in the Conero area (Ori et al., 1986; Roveri et al., 1986; 2005). Because of this upper truncation the entire PLG succession is rarely preserved. The most complete successions are found in the southern area (Morgia-001 dir, Bomba-001 and Fontemaggiore-002 dir boreholes) where up to 16 cycles can be recognized.

The analysis of the variation of the thickness of individual beds can be performed for the lower cycles only. In fig. 6 it is possible to appreciate the variation of the thickness of PLG1+2, PLG3 and PLG4, each one up to 40 m-thick. The thickness decreases northward, close to the Abruzzo coastline where the Apulian platform deepens (Santantonio et al., 2013; Trincardi et al., 2011c) below the Pescara basin (Ori et al., 1986), filled in mostly during the Plio-Pleistocene. Unfortunately, no boreholes are available in this area and thus it is possible to follow the PLG further to the west only on the seismic lines. In the Conero Riviera (Roveri et al., 1986; 2005) the unit ends eastward against a structural high that has been subsequently incorporated in the Conero thrusts. In general, it is possible to recognize a decrease in thickness of the beds, in section 2, in the western-central part of the basin. Conversely, the larger thicknesses are mostly found in the southeastern part. This suggest that the bed thickness is decreasing with the paleodepth as suggested by Lugli et al. (2007; 2010).

Close to the Adriatic midline, the PLG cycles remain relatively thick. Unfortunately, no boreholes are available beyond the midline, and consequently it is not possible to see how the thickness of the unit and of its individual beds vary further eastward.

The lateral continuity of the PLG is deduced from the analyses of seismic profiles and mapping (Roveri et al., 2005; Trincardi et al., 2001; 2011a-e; Corcagnani, 2017) that show the absence of major tectonic structures and an almost horizontal bedding. Thus, it makes sense to use the thickness obtained from the boreholes for the reconstruction of the isopach maps (Fig. 6b, c, d). The PLG1+2 beds are relatively thin and have been grouped together. PLG3 and PLG4 have been considered in separate maps. No map has been

reconstructed for the overlying beds because they are not continuous all along the study area due to erosion on top.
The preservation of the complete succession in the southwestern area comprises between the Gran Sasso and the Gargano can be explained in terms of evolution of the foredeep. During the pre-MSC this area was shallow, and shelf carbonate deposits accumulated, while at the same time hemipelagic deposits were deposited more to the north. During stage 2 and later this area experienced a rapid subsidence that can be related to the flexure of the foreland ramp due to the load of the eastward migrating Apennine chain; thus the present-day depth of the PLG unit has been reached long after their deposition.

Within the PLG succession, the upper cycles are characterized by a slightly attenuated log response with respect to the PLG3-5 cycles. This can be related to the presence of branching selenite facies that contains shale and/or limestone, making the upper portion of the upper cycles, less resistant to the erosion with respect to the lower cycles. These differences may have implications in the production of the resedimented evaporites after the erosion of the PLG unit; the upper cycles are more suitable to provide sand-sized detritus whereas the lower cycles provide more easily large blocks (Manzi et al., 2005). We infer that the erosion of the upper cycles may have provided a detritus with a grain-size suitable to be transported and redeposited by turbiditic flows in the deeper portion of the foredeep.

Stage 2+3 (5.60-5.33 Ma; Fig. 4d)

These two stages are considered together because the stratigraphic resolution of the logs does not allow to define with precision the boundary between the two stages.

During stage 2 the previously deposited PLG unit were eroded and resedimented in the deeper portions of the foredeep (Marche and Laga basins), in the Bradanic Through and in the wedge-top basins of the Calabrian Arc.

In general, the resedimented gypsum that is present at the base of the MSC succession resting unconformably above Tortonian-early Messinian shale deposits can be assigned to stage 2, the presence of halite lenses intercalated with clastic gypsum has been recognized only in boreholes drilled above the allochthonous units of the Calabrian Arc (fig. 4d). The only exception is found in a small area in the Basilicata region, described below.

Evaporite-free deposits containing typical hypohaline biological association are comprised between the clastic evaporites, below, and the Pliocene, above, can be assigned to stage 3. The Lago-Mare biota could be present also in the stage 2 deposits but become more abundant in the stage 3 (Roveri et al., 2008c); the direct recognition in boreholes indicate a relatively high abundance of biota, thus, suggesting an assignment to stage 3 rather than to stage 2.

8. THE MESSINIAN APENNINES

8.1 Distribution of the MSC deposits

The distribution of the different evaporitic facies in the Adriatic foredeep led to depict more clearly the geological evolution of the Apennines after the MSC. The integration of outcrop and borehole data has been the base for the reconstruction of two borehole-based regional-scale geological sections (Fig. 7) extending from the Tyrrhenian to the Adriatic sides of the Apennines.

A geological section (Fig. 7a) extending S-N from the Salerno gulf up to the Central Adriatic Sea shows the relationships between the Allochthonous units of the Apennine orogenic wedge and the Autochthonous Domain. According to the boreholes stratigraphy, along this section the TD is a tectonic accretionary complex consisting of undifferentiated Miocene deposits including varicolored shale (Sicilids), quartzarenite (Numidian Flysch), cherty limestone, late Tortonian-early Miocene marls and minor thin layers of clastic gypsum and carbonate. The precipitation of the primary bottom-grown gypsum during the stage 1 occurred in the more elevated structural settings: in the piggy-back basins above the northeastward moving Molise-Lagonegro Allochthonous units and in the Adriatic foreland (Matano et al., 2005; Roveri et al., 2005). The boreholes that reached the Autochthonous Domain below the MLN show that the deposition of the PLG is limited to an area located to the north (fig. 1) characterized by pre-MSC shallow water carbonate deposits. This structural elevated area on the Apula Platform, here called “palaeogargano” and mostly corresponding with the Gargano-Pelagosa paleo sill of Pellen et al., 2017, was located close to the present-day Gargano high (G fig. 6a) and confined the Adriatic PLG basin to the south. To the north of the sill a large Adriatic evaporitic basin hosted the deposition of the PLG (Fig. 4c), from the Termoli area (Guglionesi 001 borehole) up to Adriatic midline (Bora 001 borehole) and even more to the east. This basin, together with the Emilia evaporitic basin, with an impressive area ~30000 km^2 , represents the largest PLG depositional setting ever described in the Mediterranean. The true extension of the PLG basins cannot be reconstructed; however, a rough calculation based on the PLG present-day distribution (Tab. S1) suggests that the areal extent of the deposits may have been greater than the sum of all the other PLG basins of the Mediterranean.

Moving south of the “palaeogargano sill” the MSC deposits disappear for a 50 km-long tract where the Mesozoic carbonates are deeply eroded and capped by Pliocene deposits. In order to find other Messinian deposits, it is necessary to move more to the south, where PLG evaporites are absent and only clastic evaporites of the RLG unit have been reached by boreholes crossing the whole MLN (from Montestillo 001 to Taurasi 001).

The W-E section (Fig. 7b), perpendicular to the previous one, shows more clearly the large subsidence experienced by Apula under the load of the Allochthonous units, where the RLG units are capped by up to 200 m of Lago-Mare deposits (Bellaveduta 001). It is worth noting the direct fault system that lowered the western side of Apula in the Bradanic Trough. The section reports the Irpinia basin where the PLG accumulated, on top of the Allochthonous units. Conversely, below the TA, only clastic evaporites are present (from Bellaveduta 001 to Taurasi 001). The zoom of the allochthonous front, in fig, 7c, shows the deformations of Apula and the stratigraphic hiatus below the Pliocene deposits.

A slightly different situation can be described for the Basilicata area (Fig. 8). Here the evaporites, consisting of clastic gypsum and/or halite (Recoleta 001, Cavone Bernalda 001, S. Basilio 001) are found in the allochthonous units overthrusting the late Pliocene marine deposits. No evaporites are found directly above the Mesozoic carbonates of Apula that are unconformably covered by Pliocene deposits, which are progressively younger (from early to upper Pliocene) moving from Letizia 001 to F. Basento 001). The Messinian evaporites can thus be considered here as foredeep units accreted at the front of the MLN as they have been deposited more to the west and at a greater depth than their present-day location.

We have also reconstructed two regional-scale seismic sections in the northern and central Apennines (Fig.9) in order to better show the distribution of the evaporites in the Adriatic foreland. In the northern Apennines (Fig. 9a) we have reconstructed a seismic section, extending in a SSW-NNE direction from the Vena del Gesso Basin to the Adriatic foreland in the Veneto area, by integration of two published seismic sections (section 5 of Fantoni et al., 2010; section SL-1 of Roveri et al., 2003). The PLG deposits are limited to the more elevated positions, in the wedge-top VdG basin, where they crop out, and in the foreland only in a limited portion beyond the more external thrust involving the Mesozoic succession with its hangingwall anticline is now located below the city of Ferrara. Conversely, the more subsiding area saw the deposition of a thick terrigenous turbidites unit (Fusignano Fm; Cremonini and Ricci Lucchi, 1982), that includes resedimented gypsum deposits at its base, laying unconformably above the late Tortonian-early Messinian deposits or, in the deeper portion of the foredeep, conformably above an organic- and dolomitic-rich shale interval representing stage 1 (PLG time-equivalent deposits; Manzi et al., 2007; Rossi et al., 2015).

In the central Apennines we have reconstructed a second seismic section (Fig. 9c) that integrating two published sections (fig. 1b of Bigi et al., 2011; fig. 6 of Wrigley et al., 2015) and 5 seismic lines available from the ViDEPI database (Fig. 9b). In this section it is possible to appreciate the great extension of the Adriatic evaporitic basin. The integration of seismic and borehole data allows to recognize the conformable base and the unconformable top of the evaporitic unit eroded by the MES. In the eastern side, the PLG unit is limited by a deep thrust belonging to the external Dinaric front and involving the more external portions of the Mesozoic carbonate platform and the Oligo-Miocene succession; more eastward the MSC units are no longer present. Moving to the western termination of the PLG basin a change in the seismic geometries is observed across a thrust fault few km west of the Dante_001 borehole. Beyond this structure the reflector marking the base of the PLG is lacking and the MES cuts down to the pre-MSC units and is onlapped by post-evaporitic deposits which become older to the west up to include the late Messinian terms of the Laga Formation (stage 2 and 3). Gypsum-clastic deposits (indicated with G in Fig. 9b) are found in boreholes at the base of this MES-floored post-evaporitic unit. The MSC units become thicker moving further to the west, in the depocenter of the Laga basin where a 2500-3000 m-thick turbiditic unit was deposited during the whole Messinian (Bigi et al., 2009; Artoni, 2003); around 700 m of this unit was deposited during the post-evaporitic interval (stage 2+3).

8.2 Implication for tectonic reconstructions

The distribution of the MSC evaporites provide some important constraints that can be used for the restoration of the Apennines at Messinian time.

A first constraint comes from the presence of the MSC deposits below the MLN, which implies a restoration of the allochthonous front up to 100 km to the south (fig. 7a) and to the west (fig. 7b), thus a minimum total retreat of the front of the MLN up to 65 km to the SW.

A second important constraint comes from the PLG distribution. At present time the elevation of the PLG above the TD reach more than 750 m above sea level in the Irpinia basins, and around 100 m in the Biferno Valley (Cosentino et al., 2018). In the Adriatic offshore the PLG are at different depths varying from almost 2 km below sea level in the south part of the basin and around 800-1000 m in the northern one. Since the deposition of the PLG occurred in photic environment in shallow water basins (<200 m according to

Lugli et al., 2010), it is possible to reconstruct the palaeobathymetry of the different sectors. This allows to reconstruct the vertical movements that affected the different sectors of the Apennines. For instance, the Irpinia basin have been uplifted of more than 900 m since the PLG time, likely because of the overthrusting of the Molise-Lagonegro nappe above the Apula Platform; the latter, due to the load of the TD subsided rapidly more than 1500 m.

According to paleotectonic reconstructions (Argnani, 2005; 2013) and considering the constraints obtained from the distribution of the MSC deposits we can shoot a picture of the Apennines across the salinity crisis (see the paleogeographic map in Fig. 10). Three main steps in the evolution of the Apennines can be described.

Pre-MSC (8-5,97 Ma)

This interval is very important to understand the evolution of the Apennines because it includes an important phase of tectonic reorganization of the Mediterranean area that is marked by the widespread deposition of coarser grained siliciclastic deposits (Fontanelice member of the Marnoso-arenacea, Fm Northern Apennines, Ricci Lucchi, 1975; Roveri et al., 2003; Laga Fm., Central Apennines, Ricci Lucchi, 1975.; S. Nicola dall'Alto conglomerates, Calabria, Roda, 1974; Terravecchia Fm, Sicily, Ruggieri and Torre, 1984) followed by a phase of tectonic quiescence that preceded the onset of the crisis and that is characterized by the predominant deposition of hemipelagic (Schlier, Tripoli, euxinic shales Fms) and, locally, shelf carbonate deposits.

Stage 1 (5.97-5.60 Ma)

This interval is characterized by the deposition of PLG deposits in shallow-water (<200 m; Lugli et al., 2010), silled basins formed in the fold-and-thrust belt (wedge-top basins) and possibly in the foreland. Compared with the other Mediterranean areas where the unit crops out, the Adriatic basin is much larger (see comparison in tab. S1). Additional smaller occurrences of PLG deposits above the foreland, are found in basins located both onshore (EV basin) and offshore (between Ravenna and the Po river delta)

All these basins containing PLG can be considered to have an average paleo water-depth of 100 m. At the same time, in the deeper poorly oxygenated portion of the basins an organic-rich barren shale unit is found in the northern Apennines (Manzi et al., 2007), Calabria (Roveri et al., 2008d), Sicily (Manzi et al., 2011) and in the Tyrrhenian (Roveri et al., 2014a), Piedmont (Dela Pierre et al., 2011), and Levant basins (Manzi et al., 2018)

Stage 2+3 (5.60-5.33 Ma)

After stage 1, a new important tectonic phase possibly enhanced by a sea level drop, for which magnitude, timing and duration are still debated (see discussion in Roveri et al., 2014b), was responsible for the deep incision of the PLG deposits and their resedimentation in the topographic lows via gypsum-bearing slides, olistostromes and turbidity currents.

This time interval could also be characterized by strong evaporation, possible related to a further restriction of the connections with the Ocean, leading to the formation in shallow-water settings of halite-saturated brines which moved as density currents toward the deep portions of the Mediterranean (Roveri et al, 2014c). All these evaporites, floored by the MES, are included in the RLG unit (Roveri et al., 2008a). It is worth noting that halite is never found in situ above the Apulian Platform, but only above the Calabrian Arc, in those area that were deeper during the pre-MSC and stage 1 (Figs. 4, 10). The halite was deposited in the westernmost portion of the Ionian basin and was then accreted at the front of the Calabrian Arc during the Plio-Quaternary SE migration of the arc.

In the neighborhood of emerging areas, the RLG unit is overlain by thick terrigenous deposits (Fusignano, San Donato, Colombacci, Laga, Carvane Fm) including the typical brackish Lago-Mare biological association in its upper part. Notably, in Sicily, this interval is characterized by the deposition of the Upper Gypsum deposits.

During the uppermost interval of the MSC, the Apennine foredeep has been sometimes considered to be segmented in small perched basins (Bache et al. 2012, Pellen et al., 2017 and reference therein), completely isolated from the Mediterranean by the Gargano-Pelagosa sill. Differently, our reconstruction (Fig. 10) suggests that the Adriatic and Ionian water masses were connected. Our analysis of the ViDEPI dataset allows to define a large area (pink area in Fig. 04 d) where the evaporites are buried below the Molise-Lagonegro Nappe (Fig. 7). On the basis of log patterns, the unit can be interpreted as clastic evaporites (RLG), like those extending from the Romagna to the Laga basin. Conversely, the evaporites found above the MLN belong to the PLG unit and were deposited during stage 1. Moreover, considering that the Gran Sasso units (part of the Lazio-Abruzzi Platform) overthrusts the Messinian deposits of the Laga Fm (Bigi et al., 2011; Calamita et al., 2011;) which includes the clastic evaporites of the RLG unit (Manzi eta l., 2005), it can be inferred that the MLN and the Lazio-Abruzzi platform should be restore westward of their present position. Differently, in the Calabria area, the boreholes of the ViDEPI dataset do not cross the allochthonous terrains of the Calabrian Arc that overthrust the MSC unit deposited in the Ionian Basin. Unfortunately, the boreholes data do not allow to reconstruct the high-resolution stratigraphic framework for the uppermost Messinian (stage 3) that was possible to obtain from the outcropping successions. Thus, the distribution of the Lago-Mare sediments below the MLN can not be defined.

9. CONCLUSIONS

After the public release of the subsurface data obtained for hydrocarbons investigations in Italy, a great number of boreholes and seismic data have been made available. We analyzed and integrated these data in order to reconstruct in more detail the distribution of the MSC evaporites and evaporite-free deposits and to better describe the evolution of the Apennines. The main conclusions of our work are:

- during stage 1 the deposition of the evaporites was limited to the marginal basins located in the Apennines wedge-top and foreland;
- the Adriatic foreland basin represents the largest evaporitic marginal basin of the Mediterranean ever described;
- in the Adriatic foreland the PLG unit rests conformably above hemipelagites or shallow-water carbonates;
- the geophysical logs allow to recognize and count the evaporite cycles from boreholes and to provide a 3D reconstruction of the PLG succession;
- the thicker, more complete and better preserved PLG successions are located in the western portion of the Adriatic basins; they preservation was favored by the subsidence related to the foreland flexure due to the progressive load of the Apennine orogen during the Plio-Pleistocene;
- the PLG unit is truncated on top by the MES, which is in turn sealed by the latest Messinian Lago Mare deposits or by the Pliocene;
- the MES can be followed from the top of the PLG unit toward the base of the Late Messinian-early Pliocene succession; clastic gypsum deposits are locally found above it;
- in the deeper portion of the Apennine foredeep (central and northern Apennines) gypsum is a minor component of the siliciclastic turbidite fill;
- within the orogen halite deposition is limited to small satellite basins above the Calabrian Arc (Basilicata area, Crotone basin) where it is associated to clastic gypsum.

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Figure captions

Fig.1. A) Geological map of the Central and Southern Apennines and, in the inset (B), a schematic structural map of Italy. The map includes: i) the location of the boreholes used for this study; ii) **the main MSC basins**, both outcropping (after Manzi, 2001; Roveri et al., 2003; Manzi et al., 2005; Roveri et al., 2006) and buried under the Po plain (after Manzi, 2001; Roveri et al., 2003; Rizzini, 2005; Ghielmi et al., 2013; Rossi et al., 2015); iii) the extension in the Adriatic offshore of the MSC deposits (modified from CNR map) below the Pliocene units; iv) the main tectonic structures (modified from CNR map); v) the main diapirs of Triassic evaporites and the distribution of the Dalmatian Mesozoic Platform deposit (modified after Wrigley et al., 2015); vi) the extension in the Adriatic offshore of the MSC deposits (modified from CNR map) below the Pliocene units; vii) the location of the boreholes used for this study.

The main **MSC basins**, both outcropping (after Manzi, 2001; Roveri et al., 2003; Manzi et al., 2005; Roveri et al., 2006) and buried under the Po plain (after Manzi, 2001; Roveri et al., 2003; Rizzini, 2005; Ghielmi et al., 2013; Rossi et al., 2015). Two types can be distinguished. **PLG basins** - basins that hosted the deposition of shallow water primary evaporites (PLG unit) during stage 1: Epiligurian (E), Emilia-Veneto (EV), Vena del Gesso (VdG), Val Marecchia (VM), Molise (M), Maiella (MA), Irpinia (I), Adriatic (A). **RLG basins** - those where only clastic evaporites (RLG unit) were deposited during stage 2: Messinian main foredeep (MF), Eastern Romagna (ER), Northern Marche (NM), Laga (L), Bradanic Trough (B), Sibari-Rossano (S), Crotone basins (K), South Adriatic Basin (SAB).

The main **tectonic features** are: Apennines buried thrust front (ABTF), Livorno Sillaro line (LS), Forlì Line (FL), Val Marecchia line (VM), Sibillini Mountains thrust line (SM), Olevano-Antrodoco line (OA), Chienti Line (C), Gran Sasso thrust front (GS), Maiella Rocca Monfina line (MRM), Gargano high (G), Murge high (M), Sangineto line (SG).

The main **tectonic units/domains**: Ligurian units (L), Tuscan unit (T), Macigno-Cervarola unit (MC), Inner Umbro-Marchean units (IUM), Outer Umbro-Marchean units (OUM), Lazio-Abruzzi platforms (LAP), Molise-Lagonegro nappes (MLN), Bradanic Trough (BT), Calabrian Arc (CA), Apulian Mesozoic platform (AP), Dalmatian Mesozoic Platform (DP), Dinaric units (DU).

Fig. 2. Outcrop examples of the MSC evaporites. A) the PLG unit forms an up 200 m-thick tabular body with strong lateral persistence. (Vena del Gesso, between the Sgarba stream and the Senio river). The location of the Monte Tondo quarry and Spes quarry sections, where the reference PLG sections have been measured by Lugli et al. (2010), are reported. Photo, courtesy of Piero Lucci; B) closer view of the Monte del Casino area shown in A, notice the thickest beds of the lower PLG cycles (PLG3 partially covered by the vegetation, PLG4, PLG5, PLG6). Photo, courtesy of P. Lucci; C) example of the RLG unit (left side of the Lese river valley, Crotone basin) consisting of alternation of hybrid carbonate-gypsum clastic turbidites and shale resting on top of the Ponda Fm (badlands). B and C are reported at the same scale to allow the immediate comparison between the PLG showing thicker beds separated by very thin shale beds (B) and the RLG where thinner beds are intercalated by shale intervals of similar thickness (C).

Fig. 3. Outcrop examples of the MSC evaporites. A) a normal fault in the PLG unit close to the Spes quarry (fig. 2) allow a direct comparison between the lower and the upper PLG gypsum beds. Notice the homogeneous aspect of the cycles PLG3-5 made up by the massive and banded selenite facies only. B) Closer view of cycle PLG8 and PLG9 (base; Monte Tondo quarry). Notice that the lower part of the bed consisting of massive selenite is more resistant to the weathering of the upper part of the cycle consisting of branching selenite. C) turbiditic gypsarenite beds (ga) alternated to dark organic-rich shale (s). B and C are reported at the same scale to allow the immediate comparison between the PLG showing thicker beds separated by very thin shale beds (B) and the RLG where thinner beds are intercalated by shale intervals (C).

Fig. 4. A) Location of the ViDEPI boreholes in the study area; in black the available boreholes; in yellow those that cross the MSC deposits; in red the boreholes that are were drilled above the Translated Allochthonous Domain (see the trace of the front of the allochthonous). B) distribution of the different facies deposited during the Tortonian-Messinian interval, preceding the MSC onset. The siliciclastic deposition is limited to two area, one in the northern Apennines foredeep and one above the Calabrian Arc. Elsewhere the hemipelagic deposition is prevalent, Notice the presence of shallow water carbonate in a small area between the Gargano and the Gran Sasso. C) distribution of the

different facies deposited during stage 1. The PLG deposition occurred mainly in the foreland area in the Adriatic offshore. Minor basins were located in the inner foredeep (VdG basin), and in the foreland (now buried below the Po plain). D) distribution of the different facies deposited during the post-evaporitic interval (stage 2 and 3). Notice that the halite was deposited only above the allochthonous units of the Calabrian Arc.

Fig. 5. Cross section of the PLG unit in the Adriatic offshore. The separation line between the different cycles (PLG1-2, PLG3-5 and PLG6-16) has been used for correlation.

Fig. 6. Isopach maps of the PLG unit showing the general distribution in the study area (A) and the detail in the Adriatic offshore focusing on the thickness of the PLG1+2 (B), PLG3 (C) and PLG4 (D) cycles. Notice as the thickness of the single beds increase in the eastern (close to the Adriatic midline) and in the south-western (close to the Molise and Gargano coastline) part of the basin. Modified after Corcagnani, 2017.

Fig. 7. Regional scale cross sections showing the distribution of the MSC deposits in the Adriatic Foredeep and in above the Allochthonous. A) N-S oriented section showing that the areas were PLG (to the north) and RLG (to the south) evaporites were deposited is separated by an area with pre-MSC carbonate deposits. Other PLG deposits are found above at the front of the Allochthonous nappe. B) W-E section showing the RLG unit found below the Allochthonous; its distribution is limited to the east by a tectonic slope affecting the Apula Mesozoic units. These onlap can be better observed in the seismic (C)

Fig. 8. Distribution of the Messinian evaporites in the Basilicata area representing the northernmost extension of the salt deposits. The RLG units including also gypsum is found at the front of the Allochthonous unit only whereas no MSC deposits are found above Apula.

Fig. 9. A) Map of the distribution of the MSC evaporite facies with location of the regional seismic sections (B and C) across the Apennines foredeep. Section B is traced in the Northern Apennines from the Vena del Gesso basin (VdG) to the Veneto foreland (modified after Roveri et al., 2003 and Fantoni et al., 2010; Masetti et al., 2012). Section is traced in the central Apennines from the Laga basin to the Adriatic offshore (Modified from Bigi et al., 2009 and Wrigley et al., 2015). Notice the distribution of the PLG evaporites

during stage 1 limited to the more elevated structural basins in the Apenninc chain and in the foreland.

RA, Riolo Anticline; BST, Budrio-Selva Thrust; TT, Tresigallo Thrust; FT, Ferrara Thrust; AA, Acquasanta Anticline; MTF, Montagna dei Fiori Thrust; BT, Bellante Thrust; CS, Costal Structure. The stage 2 + 3 interval crossed by boreholes may be recorded exclusively by siliciclastic (s) deposits or may include also resedimented gypsum deposits (g), commonly found at the base.

Fig. 10. Paleogeographic map of the Central Mediterranean during the MSC showing the distribution of the paleogeographic domains and the main sedimentary facies. The distribution of the PLG (Stage 1) in the foreland region is also indicated. The dark gray patter in the Adriatic represents a sill separating the southern and central-northern basin. The front of the Apennine accretionary wedge is marked in red (line with triangles), whereas the Apennine front is in black. The tentative route of clastic gypsum transport and the flow of brines are also indicated. Main basins: VdG, Vena del Gesso; A, Adriatic; K, Crotone; T, Tyrrhenian; AP, Algero-Provencal; C, Caltanissetta; H, Hyblean; I, Irpinian; B, Basilicata Ionian. Modified from Argnani 2000; 2005; Manzi et al., 2005; Fauquette et al., 2015.