Restored topography of the Po Plain-Northern Adriatic region during the Messinian base-level drop - implications for the physiography and compartmentalisation of the paleo-Mediterranean basin

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ABSTRACT

The Messinian Salinity Crisis (MSC) involved the progressive isolation of the Mediterranean Sea from the Atlantic between 5.97-5.33 Ma and a sea-level fall whose timing, modalities and magnitude remain actively debated. At that time, the central Mediterranean was undergoing strong tectonic activity due to the rollback of the Adria slab and eastward migration of the Apenninic belt. The combined effects of the post-evaporitic MSC sea-level drop and morpho-structural changes (due to the Intra-Messinian phase) resulted in a regional...
unconformity, which shows erosive markers and conformable relationships with the Messinian and Mio-Pliocene boundary in the Po Plain and Northern Adriatic Foreland. Here, we produce a paleo-topographic reconstruction of the Po Plain-Northern Adriatic region (PPNA) during the Messinian peak desiccation event based on such regional unconformity. We mapped this surface through wells and 2D seismic data from Eni’s private dataset. The unconformity shows V-shaped incisions matching present-day southern Alpine valleys and filled with Messinian post-evaporitic and Pliocene deposits, suggesting that the modern drainage network is at least of late Messinian age. The Messinian unconformity has been restored to its original state through flexural-backstripping numerical modelling. The resulting landscape suggests a maximum sea-level drop of 800-900 m during the MSC peak and is consistent with stratigraphic and sedimentologic data provided by previous works. The modelled shoreline separates the subaerially eroded land from an elongated basin composed by two ca. 400 and 1000 m deep depocenters during the maximum sea-level drop. These results suggest that the Mediterranean was split in at least three sub-basins subject to independent base-levels, fresh water budgets and flexural responses during the maximum lowstand.

INTRODUCTION

The Messinian Salinity Crisis (MSC) is one of the most extreme and debated Cenozoic environmental changes (Rouchy & Caruso, 2006; Roveri et al., 2014a, b; Vai, 2016 and reference therein). Diagnostic evaporitic deposits (Selli, 1960; Hsü et al., 1973, 1977; Müller & Mueller, 1991; Allen et al., 2016) and erosional unconformities across the entire Mediterranean (Lofi et al., 2005; Bertoni & Cartwright 2006; Lofi et al., 2011a, b) enable to date this event between 5.33-5.97 Ma (Krijgsman et al., 1999; Manzi et al., 2013). Many of the erosional unconformities merge into a single polygenic surface (usually referred to as the Margin Erosional Surface – MES, Lofi et al., 2005; CIESM, 2008, Lymer et al., 2018) in the upstream of deep marginal and intermediate basins (Roveri et al., 2014b; Lymer et al., 2018), thereby providing evidence for
erosion in the Mediterranean margin. Many of the key depositional units and erosional markers of the MSC, however, are buried underneath km-thick sedimentary units and currently located offshore (Lofi et al., 2011a, b; Urgeles et al., 2011; Gorini et al., 2015; Thinon et al., 2016), while accessible outcrops are strongly deformed by late-Cenozoic tectonics (e.g. Sicily, Butler et al., 1995; Caruso et al., 2015). Therefore, assessing the magnitude of the drawdown and the resulting paleogeography of the Mediterranean area during the MSC acme is still difficult (e.g. Hsü et al., 1977; Cita & Corselli, 1990; Blanc, 2006; Meijer & Krijgsman 2005; Jolivet et al., 2006; Bache et al., 2012; Roveri et al., 2014a, b; Vai, 2016; Sternai et al., 2017). Previous numerical modelling produced quantitative estimates regarding sea-level and salinity variations, as well as the flexural response at the Mediterranean scale (Meijer et al., 2004; Meijer & Krijgsman 2005; Gargani & Rigollet, 2007; Govers, 2009). Given the regional length scales, these studies used relatively low-resolution Messinian key-horizons with minor geological control on the palinspastic retrodeformation or lithofacies record. Although the separation between the western and eastern Mediterranean basins by the Sicily sill is accepted (Gargani & Rigollet, 2007; Ryan, 2009; Micallef et al., 2018), uncertainties exist regarding the central Mediterranean and, particularly, its northernmost sector, the Po Plain and Adriatic basin. During the Messinian, this sector of the Mediterranean was a complex puzzle of fragmented carbonate platforms, basins and outcropping Apennines which is challenging to restore at a regional scale (Jolivet et al., 2006; Patacca & Scandone 2007; Mantovani et al., 2014; Matano et al., 2014). Within this scenario, the possibility that smaller basins and their connections during the MSC has not been taken into account by previous numerical modelling studies.

We model the sea-level drop of the Po Plain-Northern Adriatic foreland basin (PPNA) during the Messinian based on its detailed stratigraphic record in order to better understand its connectivity with the rest of the Mediterranean Sea during the MSC. To this aim, we analyse public and private (courtesy of Eni Upstream) subsurface data and carry out a 3D reconstruction of the subaerial and submarine landscape of the Po Pain and Adriatic foreland during the MSC desiccation peak, i.e., after the MSC stage 1 according to the chronostratigraphy.
by Roveri et al. (2014a, b, 2016). We take advantage from high-resolution stratigraphic data (e.g. sedimentological, paleontological and geochemical data) and detailed geological constraints (e.g. seismic-based and well logs) for the study region also provided by recent works (Ghielmi et al., 2010, 2013; Rossi et al., 2015; Rossi, 2017; Rossi et al., 2018). We are able to (1) provide the paleotopography of the PPNA, which improves our understanding of the basin evolution and its relationships with the broader Mediterranean paleogeography during the MSC, and (2) recognize V-shaped valleys filled with Messinian post-evaporitic and Pliocene deposits in the seismic data along the southern Alps, which imply a syn-MSC or older age of the present-day southern Alpine river drainage pattern.

**GEOLOGICAL SETTING**

Tectonic shortening affected the PPNA at different times and with variable directions during the Cenozoic (e.g. Toscani et al., 2016). Since the middle-late Miocene, the thrust front of the Northern Apennine thrust-fold-belt bounds to the southwest the Po Plain and Northern Adriatic Foreddeep Basins (Fantoni & Franciosi, 2010; Ghielmi et al., 2013; Rossi et al., 2015). The Western and Southern Alps bound the Western Po Plain foredeep basins to the north, while the PPNA is connected to the northeast to the Venetian-Friulian Basin (Fig. 1a).

During the Messinian, the whole Apennine thrust belt experienced a period of strong tectonic accretion, defined as Intra-Messinian phase (Ghielmi et al., 2010, 2013; Mantovani et al., 2014; Matano et al., 2014). The PPNA was marked by a strong sedimentary and tectonic reorganization related to combined effects of the MSC drawdown and morpho-structural reshaping, resulting in an angular unconformity overlaid by post-evaporitic Messinian prograding systems or transgressive Pliocene deposits (Ghielmi et al., 2010, 2013; Rossi et al., 2015, 2018; Rossi, 2017). In seismic profiles on the basin margins, this unconformity shows erosive markers (truncation of the MSC lower evaporates or pre-MSC succession) at the base of forced regressive deltaic systems and predominantly conformable relationships basinward through the entire Messinian sequence and Mio-Pliocene boundary (Fig. 1c). Unlike the Western
and Eastern Mediterranean offshore (Lofi et al., 2011a, b), the PPNA region was not a fully evaporative basin during the MSC (Ghielmi et al., 2010, 2013), as suggested by the absence of halite and potassium-rich salts deposition in the entire Adriatic foreland (Ryan, 2009). Geophysical investigations in the Po Plain led Ghielmi et al. (2010, 2013) and Rossi et al. (2015) to reconstruct syn- and post-evaporitic lithofacies associations distribution maps (i.e. continental vs marine shelf-to-basin sediments), showing evidence for a thick coastal wedge where the complete Messinian succession is preserved, included pre-evaporitic deposits. Instead, in the northern and eastern Adriatic foreland, Messinian sediments are poorly preserved or lacking (Fig. 2a). In detail, cyclic gypsum and anhydrite deposits (maximum thickness in well ~250 m) are observed only in marine foreland shelves (along the northern margin of the PPNA) and hypersaline piggy-back basins on the Northern Apennine belt, overlain by post-evaporitic Messinian brackish sequences (Artoni et al., 2007, 2010; Ghielmi et al., 2010, 2013; Rossi et al., 2015; Pellen et al., 2017). In the deep part of the basin, the sedimentary sequence is only composed of siliciclastic deposits, also during the MSC post-evaporitic maximum desiccation phase (Ghielmi et al., 2010). According to this geological setting, the Po Plan-Adriatic basin can be defined as intermediate basin sensu Lymer et al. (2018). Lymer et al. describe intermediate basins as located between peripheral shallow basins (with presence of lower evaporates only overlain by Pliocene deposits) and deep basins (with presence of thick halite), covering a wide range of both bathymetries and MSC deposits.

Late Messinian incised valleys in the Venetian-Friulian Basin onshore and offshore (Donda et al., 2013; Toscani et al., 2016; Zecchin et al., 2017) led to suggest a maximum relative sea-level drop in the Northern Adriatic region of more than 100-200 m during MSC acme, but not exceeding 900 m (Ghielmi et al., 2013). This is in divergence with previous interpretations from Roveri et al. (2014a, b, 2016) based on modeling submarine dense water cascading from the shelf areas producing canyons without the need of significant drawdown. Roveri et al. extended the proposal of a relatively minor MSC sea-level drop (100-200 m) to the entire Mediterranean, in contrast with other estimates suggesting between 1300 and 2000 m of sea-
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adjustment (after Sternai et al., 2012). The top of the pre-collisional carbonate basement is an important surface for hydrocarbon because it corresponds to the top of a deep oil play and the major seismic marker for the related structure interpretation (Turrini et al., 2014, 2016).

The restoration of the regional paleo-topography during the maximum MSC drawdown was obtained following the workflow outlined in figure 4a and using the TISC software (Garcia-Castellanos, 2002; Garcia-Castellanos et al., 2003). We account for sediment decompaction and for the 2D (planform) flexural isostatic adjustment associated with unloading by the removal of post-Messinian sediments and the missing water column during the MSC acme (Fig. 4). In summary the workflow involves: (i) removal of the shallowest stratigraphic unit and calculation of the flexural-isostatic response, (ii) decompaction of the underlying sedimentary units, (iii) removal of the water layer and calculation of the corresponding flexural-isostatic response. This is a standard methodology in subsidence basin analysis (Allen & Allen, 1990; Bell et al., 2014). Decompaction is conducted by calculating near-surface porosity, decay constants and bulk densities for lithologies observed in wells and also using the relationships provided by Sclater & Christie (1980) (see Tab.1). We assigned uniform surface porosity, bulk density and porosity-depth exponential coefficient to the analysed volumes. We disregard gradual sediment compaction because the model is time-independent and we are not interested on the evolution of subsidence but on the total amount of post-Messinian subsidence. We also disregard non-uniform grain size or sediment facies distribution because of lack of deep wells with pre-MSC detailed data covering the entire region. Following previous numerical models on MSC river erosion and water/evaporation budget, we assume that the sea-level before the MSC was close to the present-day one (Loget et al., 2005; Blanc, 2006; Gargani & Ricollet, 2007; Miller et al., 2005). The most representative lithologies within the Paleogene-late Messinian sediments (volume to be decompacted) are marine marls (i.e., Scaglia Formation and Gallare Group) and sandstones (i.e., Gonfolite Group and latest Tortonian-syn-evaporitic Messinian turbidites of Bagnolo Formation) with an averaged lithology-type of 75% shale and 25% sand (Tab. 1). The
The upper volume to be removed is mostly represented by km-thick Plio-Pleistocene turbidites (variable in clay content) and fine-grained foreland deposits (i.e. Zanclean marine shales). The averaged lithology-type is similar to the "Shaley Sandstone" defined by Sclater & Christie (1980 (Tab. 1). The density of both the removed seawater and the remaining water volume during the MSC drop is assumed to be 1030 kg/m$^3$ like the current average seawater density at the surface (Beicher, 2000). Finally, the basement density was set to 2850 kg/m$^3$ (Ebbing et al., 2001).

The restoration of the tectonic deformation of the basin was carried out removing the vertical component of the main Pliocene-Pleistocene thrusts and anticlines of the Northern Apennines and Western and Southern Alps, according to published uplift data (Scrocca et al., 2007; Toscani et al., 2014; Maesano et al., 2015; Bresciani & Perotti, 2014; Tab. 2) (Fig. 5a). In performing this operation, we neglect horizontal deformation given that previous works suggest between 10 and 20 km of average horizontal shortening (~10% with respect to the basin width) along the Northern Apennine front in the Po basin since the late Messinian (Fig. 5b) (Perotti, 1991; Bigi et al., 1995; De Donatis, 2001; Toscani et al., 2014), which translates into minor strain at the basin scale. This is also in agreement with the regional-scale Apennine eastward migration (since ~5 Ma up to present position) reconstructed by Carminati et al. (2010). We assume such limited shortening does not affect the modeling.

RESULTS

The depth-converted late Messinian unconformity of the PPNA with 500 m contouring is shown in Fig. 6. The overall northern margin of the PPNA appears incised by ca. N-S and NW-SE trending valleys. In detail, in the Southern Alpine sector the incisions show steep V-shape morphologies (Figs. 6, 7), cutting upslope Oligocene-Late Miocene sediments (Fig. 7c). These canyons are filled with Messinian post-evaporitic fluvial conglomerates of the Sergnano Fm and Plio-Pleistocene turbidites (Fig. 7c). The volume to be removed is mainly composed by km-thick Plio-Pleistocene turbidites, dominant with respect to the late Messinian deposits. From the
Alpine land outcrops to the deep Po Plain, the Messinian succession appears incomplete, which is likely due to erosion and forced regression of the fluvio-deltaic systems during base-level lowering, as also pointed out by Rossi et al. (2015, 2018). In the eastern Adriatic foreland ramp, late Messinian sediments are poorly preserved or completely lacking (Fig. 2a). From 3D depth-reconstruction, these fluvial incisions have propagated at least 50 km inland, with the maximum depth reaching ~1 km in the central Po Plain (Figs. 6, 7a, b).

**Parametric Study for the backstripping analysis**

In order to test the sensibility to the input parameters (Tab. 3) and investigate different scenarios, we run a series of flexural-backstripping calculations looking for the best fit model with respect to the constrains provided by the data described in section Datasets and methods. In particular, in this section, we explore the sensitivity of model predictions in terms of the restored palaeo-shoreline position and the fit to the geological constraints to input parameters such as:

i) the amount of sea-level lowering, i.e., -200/-850/-1500 m to account for previously proposed MSC scenarios (e.g.; Ryan & Cita, 1978; Gargani, 2004; Manzi, 2005; Urgeles et al., 2011; Ghielmi et al., 2013; Roveri et al., 2014a, b),

ii) the lithospheric elastic thickness, Te, i.e., 10, 20, 45 km to account for plausible rheological conditions of the Adriatic continental basement (Moretti & Royden, 1988; Royden, 1988; Kruse & Royden, 1994; Kroon, 2002; Barbieri et al., 2004) and

iii) different lithologic characteristics of the sediments, in order to test how different sand-clay proportions affect the basement isostatic response.

The effect on the lithospheric post-Messinian vertical motions by the sea-level drop and elastic thickness variations appear as the most relevant (Fig. 8), while, varying only the porosity of the pre- and post- Messinian sediment volumes imply variations in the estimates by less than 100 m (Tab. 3). The estimated coastline location also depends primarily on the morphology of the
basin and its slope. In the Adriatic foreland, the horizontal position of the shoreline shifts by up to ~150 km for sea-level drop >1km (Fig. 8c) due to the low basin slope. The steeper northern basin margin implies limited migration of the shoreline if the sea-level drop is ≤800-900 m, while a significant basinward migration of the coastline is observed for imposed drawdown > ~1.5 km (Fig. 8c, d, e). We remark that, overall, sea-level changes smaller than 50 m do not significantly affect the results of the backstripping analysis. For this reason, model predictions for each sea-level drop can be extended within a ±50 m interval.

Preferred Model

Our preferred reconstruction of the late Messinian unconformity within the PPNA basin accounts for an 850 m sea-level drop, Te equal to 20 km, decompacted sediments made of 75% clay and 25% sand and bulk density of volume to be removed of 2115 kg/m$^3$ (Tab. 1 and Fig. 9). These input parameter values are supported by previous studies or direct analysis on the region. For instance, the selected northern Adria plate lithospheric elastic thickness is consistent with results from Moretti & Royden (1988), Royden (1988) and Barbieri et al. (2004) and the lithology parameters are averaged from the deepest drilling and log analyses. The imposed amount of drawdown improves the fit between the modelled shoreline and sedimentologic constrains, i.e., coastal wedge position, fluvial drainage network, erosional surface (Fantoni et al., 2001, Ghielmi et al., 2010, 2013; Rossi et al., 2015; Rossi, 2017; Rossi et al., 2018) (Figs. 2, 9b, c) and continental vs marine shelf-to-basin facies boundary from the facies associations distribution map of the post-evaporitic sequence published by Ghielmi et al. (2010, 2013) (Fig. 9a). In addition, the output is consistent with the maximum base-level lowering of 900 m, as estimated by Ghielmi et al. (2013) through local investigations within the Po-Plain onshore (but never extended throughout the Po Plain western sector and Northern Adriatic offshore).
According to our preferred model, the PPNA region was a narrow basin with two definite submarine depocenters during the maximum Messinian drawdown. In the western Po Plain, the depocenter was nearly 400 m deep, while a wider WNW-ESE trending and ~1000 m deep depocenter was located to the east, where the maximum isostatic uplift occurred (~995 m, Fig. 10). Terrigenous turbidite deposition was enhanced in both sub-basins during Messinian time by the exposure of the pre-Messinian shelf (Fig. 9c) and by the accelerated erosion of the surrounding belts. To the NE, the Venetian-Friulian Basin is subaerially exposed during the maximum Messinian sea-level drop, a result that agrees with the proposed fluvial origin of the incised valleys and dendritic drainage network in the present-day onshore and offshore subsurface (Donda et al. 2013; Ghielmi et al. 2010, 2013; Toscani et al., 2016; Zecchin et al., 2017) (Fig. 9b). Further to the east, a vast portion of the Mesozoic Istrian-Dalmatian platform, located in present-day Croatia region (Fig. 1a) and the Adriatic Sea, were subaerially exposed, which is also in agreement with previous works (Velić et al., 2015) (Figs. 2a, 9a).

DISCUSSION

The timing of the end of the Southern Alpine tectonic deformation is well defined by seismic reflection profiles and exploration wells showing that Messinian post-evaporitic deposits (i.e., fluvio-deltaic forced regressive systems, Sergnano Fm.) and early Pliocene turbidite units are mostly undeformed (Pieri & Groppi, 1981; Fantoni et al., 2001, 2004; Livio et al., 2009; Rossi, 2017) (Fig. 7c). Additionally, the good fit between the subsurface incised valleys and the present-day river network flowing into the Po River alluvial plain reveals that the southern Alpine drainage pattern ~6 million years ago was very similar to the modern configuration (Fig. 7). Moreover, the equivalent spatial fit in the alluvial plain might possibly be due to the differential subsidence between the siliciclastic- and mud-filled incised valleys and their interfluves (Fig. 7c). One may interpret that the erosional features recognized below the central Southern Alps (Figs. 6, 7) testify that the margin underwent subaerial erosion as the base level dropped by hundreds of meters during the MSC. The Alpine rivers carved V-shaped
valleys up to 1 km deep across the modern Po Basin and incised at least 50 km far into the Alps. Regressive erosion due to the Messinian drawdown shaped the cryptodepressions (sensu Bini et al., 1978) that today confine the glacial Alpine lakes of Northern Italy (e.g. Maggiore, Lugano, Como, Iseo and Garda lake) as first suggested by Bini et al. (1978), Finckh, (1978), Rizzini & Dondi, (1978). Similarly, several canyons that underlie current valleys have been documented all around the Mediterranean marginal regions, such as in the Nile, Rhone, Var Valleys, Alboran sill and the Ebro River (Chumakov, 1973; Barber, 1981; Clauzon, 1982; Loget et al., 2005, 2006; Urgeles et al., 2011).

The main features of the restored late Messinian landscape of the PPNA region are two major depocenters subject to turbiditic deposition throughout the Messinian, rimmed by exposed marine shelves and localized hypersaline basins, in agreement with previous studies by Artoni et al. (2007, 2010) and Rossi et al. (2015) (Fig. 2, Fig. 9). The proposed ~850 m drop is significantly lower than the 1300-2000 m drawdown suggested by several authors. Among them Ryan (1976), Blanc (2000), Gargani (2004), Meijer & Krijgsman (2005), Gargani & Rigollet (2007), Sternai et al. (2017) sustain a kilometer sea-level drop on the basis of numerical modelling. Although Ryan & Cita (1978), Stampfli & Hocker (1989), Clauzon et al. (1996), Maillard & Mauffret (2006), Bache et al. (2009), Urgeles et al. (2011), Cameselle & Urgeles (2016) have revealed depositional processes associated with emersion of continental margins (e.g. Gulf of Lions, Valencia-Ebro margin) compatible with ~1500 m base-level fall, also by morphological evidences from seisms and well data.

Thus, we support the PPNA region as a restricted elongated foreland basin physically disconnected from the rest of the Mediterranean during the MSC post-evaporitic acme and subject to an independent hydrological balance in a way similar to that discussed by Blanc (2006) and Bache et al. (2012). This imposed a geomorphological base level in our study region shallower than that in the west and east Mediterranean sub-basins. Regarding the location of the morphological high separating the PPNA basin from the rest of the Mediterranean, the Adria foreland offshore offers a complex distribution of carbonate platforms and tectonic
deformations suitable to sustain the hypothesis of at least one major paleo-sill in the area. For instance, in the central Adriatic Sea there is an important alignment of structural highs deformed during the Oligo-Miocene accompanied by halokinetic activity (Pikelj et al., 2015) (also known as the Mid-Adriatic Ridge), although growth strata above Messinian evaporates show higher uplift activity during Plio-Pleistocene time (Scisciani & Calamita, 2009; Del Ben et al., 2010). The region of the Apulian platform in the southern Adriatic Sea, however, is probably the best candidate for the location of the barrier separating the Apennine foredeep during the MSC desiccation peak from the rest of the Mediterranean. Cita & Corselli (1990), Clauzon et al. (2005), Bache et al. (2012), Santantonio et al. (2013), and Pellen et al. (2017) inferred that a divide was probably located between the present-day Gargano-Pelagosa region in the southern Adriatic Sea. Seismic data and well log analysis of southern Italy onshore and offshore (de Alteriis, 1995; Scrocca, 2010; Santantonio et al., 2013; Pellen et al., 2017) reveal a submarine high carbonate structure (cropping out in the Puglia region) with a stratigraphic hiatus and an erosive surface on Messinian evaporites, that further supports the paleogeographic reconstruction published by Vai (2016).

Although the timing of closure and re-opening of the southern Adriatic sill during the late Messinian is beyond the purpose of this work, the presence of marine bio-events (e.g. the first occurrence of Turborotalita multiloba and the Neogloboquadrina acostanesis sx/dx coiling change) in the pre-MSC sequences (Sierro et al., 2001; Blanc-Valleron et al., 2002; Gennari et al., 2013; Caruso et al., 2015), the reconstruction of the near Tertiary Piedmont Basin (TPB) (Fig. 1a) based on the Lower Evaporites gypsum (Dela Pierre, 2011) and the quasi-uniform $^{87}$Sr/$^{86}$Sr values of the Lower Evaporites throughout the Mediterranean (Roveri et al., 2014b; Schildgen et al., 2014) suggest that the Po-Adriatic basin was connected to the rest of the Mediterranean at least during the pre-evaporitic and syn-evaporitic phases. The isolation of the PPNA basin from the Mediterranean occurred only after the deposition of the Lower Evaporites, that is during the maximum sea-level drop correlated with the TG12 or both TG12 and TG14 glacial intervals (Krijgsman & Meijer, 2008; Cosentino et al., 2013) is still consistent with our preferred model.
This, however, implies an abrupt change in the integrated balance between river discharge, precipitation, evaporation and uplift rate to explain the rapid base level change. A positive freshwater budget may prevent salt saturation, explaining why halite or other high soluble K-rich salts did not accumulate in the entire Adriatic region during MSC. The PPNA syn- and post-evaporitic Messinian deposits may indeed reflect a complex equilibrium between high freshwater input provided by the large rivers draining the Alpine belt and the progressive increase in salinity due to the MSC. This would cause precipitation of gypsum and anhydrite only in restricted basins in the Northern Apennine, like the Tertiary Piedmont basin, piggy-back basin, and very localized sectors of the Po Plain-Northern Adriatic shelf (Rossi et al., 2002; Artoni et al., 2007, 2010; Dela Pierre, 2011; Ghielmi et al., 2013; Rossi et al., 2015), coeval with siliciclastic deposition in the residual, deep depocenters (Ghielmi et al., 2010, 2013; Rossi et al., 2015).

**CONCLUSIONS**

The restored landscape of the PPNA region during the maximum MSC sea-level drop (Fig. 9) allows outlining the following conclusions.

- The flexural-backstripping modelling best matches the available subsurface stratigraphic and facies distribution data when an 800-900 m drawdown is imposed; thus, the sea-level fall related to the MSC maximum lowstand in the study area is smaller than what was inferred for the eastern and western Mediterranean (1300 m or more), but also significantly larger than what was proposed by Roveri et al. (2014a, b, 2016) for the entire Mediterranean area (about 200 m).
- This result implies that, at a broader scale, during maximum sea-level fall, the Mediterranean was divided into at least three sub-basins (the two major Western and Eastern Mediterranean Basins and PPNA) with independent base-level evolutions and water budgets. The separation from the rest of the Mediterranean can partly explain the lack of halite and potassium-rich salts in the Po Plain area and Adriatic Sea.
The present-day fluvial network flows directly above buried incised valleys into the Southern Alpine basement below the Po Plain. The match in the flat plain is probably due to differential compaction of sediments between incised valley fills and interfluves. This suggests that the present fluvial network draining the Southern Alps can be dated back to at least the late Messinian.

Finally, based on our results, we suggest that caution should be used in performing analyses addressing the amount of drawdown during the MSC at the whole Mediterranean scale and support, for this purpose, the generation and use of high-resolution stratigraphic data (e.g. sedimentological, paleontological and geochemical data) and/or models (i.e. seismic-based constrained by well log data).

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FIGURE CAPTIONS

FIGURE 1
A: Tectonic map of the study area.
B: Geological section (a-a’) along profile, modified from Toscani et al. (2014). See Fig. 1a for location.
C: Seismic profile in TWT (b-b’) (see Fig. 1a for location) from Eni dataset from the Northern Apennines thrust-fold belt to the Southern Alps. Seismic data has European normal standard. Grayscale Amplitude in the range of ±18.00.

FIGURE 2
Cross correlation panel by well log analysis. PS (Spontaneous Potential), RES (Resistivity).
A: Red stars are wells from ViDEPI project showing the extended erosion and the complete lack of Messinian deposits. From NW to SE: Ornella 1, Glenda 1 and Alessandra 1 wells. See Fig. 1a for location.
B: White stars are wells from Eni private database showing late Messinian depocenter filled with post-evaporitic turbidites of the Fusignano Fm. overlying a syn-evaporitic sequence (gypsum and/or anhydrite) thinning towards the NE Adriatic foreland ramp. Note that electric logs data for the second well to the SW does not reach the bottom of the Plio-Pleistocene but the stratigraphic column includes 33 m of Messinian brackish fine deposits and 17 m of evaporites. See Fig. 1a for location.

FIGURE 3
A: Study area and complete dataset. Red lines correspond to the ENI seismic grid, while yellow lines correspond to the seismic profiles by public ViDEPI dataset. Black squares are drillings from both private and public database.
B: Area where the dataset has been integrated with observations from Fantoni et al. (2004), Mosca (2006), Bigi et al. (1992), Rossi (2017).
C: Area where the dataset has been integrated with observations from Toscani et al. (2016).

D: Area where the dataset has been integrated with observations from Fantoni et al. (2001).

FIGURE 4
A: Work flow used to restore the Messinian landscape during the maximum sea-level draw down.
B: Conceptual model of the backstripping procedure applied to the basin.

FIGURE 5
A: Current position of the main late-Messinian Northern Apennines and Southern Alps thrusts buried in the Po Plain (solid black lines) and Plio-Pleistocene thrust fronts (dashed black lines). Symbols and code name refer to the location of the main Plio-Pleistocene structures vertically restored (see Tab. 2).
B: Black lines show the current position of main late-Messinian Northern Apennines and Southern Alps thrusts buried in the Po Plain subsurface, compared with their restored late-Messinian position (red lines), according with shortening rates from the bibliography (see text for detail).

FIGURE 6
Map of the reconstructed MES with 500 m contouring with respect to the modern topography.

FIGURE 7
A: Map of the reconstructed MES in the central Southern Alps, zoom from figure 6, with 500 m contouring with respect to the modern topography. Blue lines show the present-day fluvial network.
**B:** Profile (in depth domain) along the trace a-a’. The black line is the present-day topography (vertically exaggerated) and the red line is the MES. Note the match between the locations of valleys on the modern topography and the MES.

**C:** Seismic profile along b-b’ trace is from Eni private dataset. It shows some details of two canyons in the bedrock below the Po Plain. Note the good fit between the present-day Serio river location and the Messinian incision (MES) directly below. The green line (TES, as Top Erosion Surface) is a successive erosional phase (base Zanclean) that removed the most of the post-evaporitic fluvial gravels delta system (with high amplitude reflector facies). Only some remnants were preserved at the bottom valley and on top of interfluve. The paleo-valley is then sealed by Plio-Pleistocene turbidites. Blue line corresponds to the Intra-Zanclean Unconformity (I-ZU). Pre-Messinian deposits refer to the Oligo-Miocene succession.

**FIGURE 8**
Paleogeography obtained by modelling two extreme scenarios involving the same $Te$ (20 km) and lithologic properties but (A) 200 m and (B) 1500 m MSC sea-level drawdown. Red contour lines are the corresponding calculated flexural uplift.

**C, D, E:** Shoreline migration produced by imposing different magnitude of sea-level drop and $Te$ values. For these models, fixed lithologic properties were considered.

**FIGURE 9**

**A:** Restored late Messinian landscape, with 200 m contouring applying, from our preferred model accounting for a 850 m sea-level drop. The dotted black line shows the continental vs marine shelf-to-basin facies boundary by Ghielmi et al. (2010, 2013).

**B:** TWT amplitude colour map of the MES showing a subaerial drainage network (after Ghielmi et al., 2010).

**C:** Seismic map (TWT) of the Messinian unconformity showing the dip morphological seismic attribute (after Ghielmi et al., 2010, 2013 and Rossi, 2017). The pre-evaporitic shoreline break is
highlighted in the northeast. Some NE-SW Pliocene incisions with retrogressive slump scars can be observed.

**FIGURE 10**
Map of the estimated isostatic uplift for our preferred model ($Te$ 20 km and MSC sea-level drop of 850 m). White lines show the restored position of the main Northern Apennine and Southern Alpine thrust fronts during the late-Messinian.

**TABLE 1** - Parameters for different lithologies from BasinMod2014 software and used for decompaction and uplift calculation.

**TABLE 2** - Structure code-name and location in figure 5 from Maesano et al. (2015); geometric features of the fault and the vertical component considering the age interval of the tectonic activity (see Fig. 5a for location).

**TABLE 3** - Table of maximum uplift variations under different input parameters: sediments porosity, $Te$ and sea-level drops.
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Coast lines modeled with equal Te and different sea level drops

-200 SEA LEVEL DROP

-1500 SEA LEVEL DROP

Coast lines modeled with different Te and different sea level drops

-200 m
-850 m
-1500 m

marine/continental facies limit (Ghielmi et al., 2013 and Rossi et al., in press)