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Potential evidence for slab detachment from the flexural backstripping of a foredeep: Insight on the evolution of the Pescara basin (Italy)

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Abstract
The discrepancy between the size of the Apenninic chain and the depth of the Adriatic foredeep is investigated using 2D flexural backstripping on well-constrained depth-converted cross-sections in the Pescara basin (Central Italy). The procedure consisted of removal, uplift, unfolding and unfaulting of the Pliocene–Pleistocene foreland deposits to produce a palaeogeographic map of the basin at the end of the Messinian and to constrain sedimentary rates since the Miocene. Results are found to support the contribution of an external load to the foreland evolution together with the Apenninic chain load. The interplay of the two types of loads resulted in spatial and temporal variations of the foredeep evolution that are quantified by palaeogeographic maps and sedimentation rates obtained through backstripping. Results are interpreted as representing the effects of a southward-migrating wave linked to slab detachment beneath the Adriatic foredeep. This procedure can be useful to investigate similar problems on other chains worldwide.

1 | INTRODUCTION

The Adriatic Sea is the modern foreland of the Apenninic chain, a complex geodynamic region whose evolution is linked to westward subduction of the Adriatic plate. Similar to other chains worldwide (e.g. Gogus et al., 2017 and references therein), geological, geophysical and geochemical evidence suggests that the evolution of the Apenninc system is related to large-scale removal of the underlying lithosphere (e.g. Buiter et al., 1998; Doglioni et al., 1998; Faccenna et al., 2003; Karner & Watts, 1983; Lort, 1971; Malinverno & Ryan, 1986; Patacca et al., 1990; Pauselli et al., 2006; Royden & Karner, 1984; Scrocca et al., 2005; Wortel & Spakman, 1992 and references therein). The removal of the lithosphere could be controlled by several mechanisms including roll-back of a subducting slab (e.g. Doglioni, 1991; Elter et al., 1975; Royden et al., 1987; Scandone, 1980), lateral propagation of slab detachment (e.g. Benoit et al., 2011; Buiter et al., 1998; Channell, 1986; Channell & Mareschal, 1989; Chiarabba et al., 2014; Wortel & Spakman, 1992) or the eastward shifting of an asthenospheric rising plume (e.g. Decandia et al., 1998; Lavecchia, 1988; Lavecchia et al., 2004).

The Pescara Basin (PB), located partly onshore and partly offshore in the central Adriatic Sea (Figure 1), represents one of the main interesting sectors of the Adriatic foreland because it contains one of the main depocenters of the Pliocene–Pleistocene Adriatic foredeep. Thickness variations of the PB sediments are locally controlled by faulting and folding (Figure 1) (e.g. Cazzini et al., 2015; CNR, 1991; Mancinelli et al., 2015).

Despite the significant thickness of the Plio-Pleistocene PB foredeep sediments, which locally can reach ~9 km (Figure 1; CNR, 1991), the maximum topographic expression of the Apenninic chain is only ~2 km, which is insufficient to explain the observed foredeep depth (e.g. Royden & Karner, 1984; Royden et al., 1987). Considering that in the entire area major delta systems are missing (Colantoni et al., 1989; Scrocca et al., 2005), this point has significant implications for understanding the evolution of the Apenninic chain, suggesting the existence of additional loads not linked to crustal

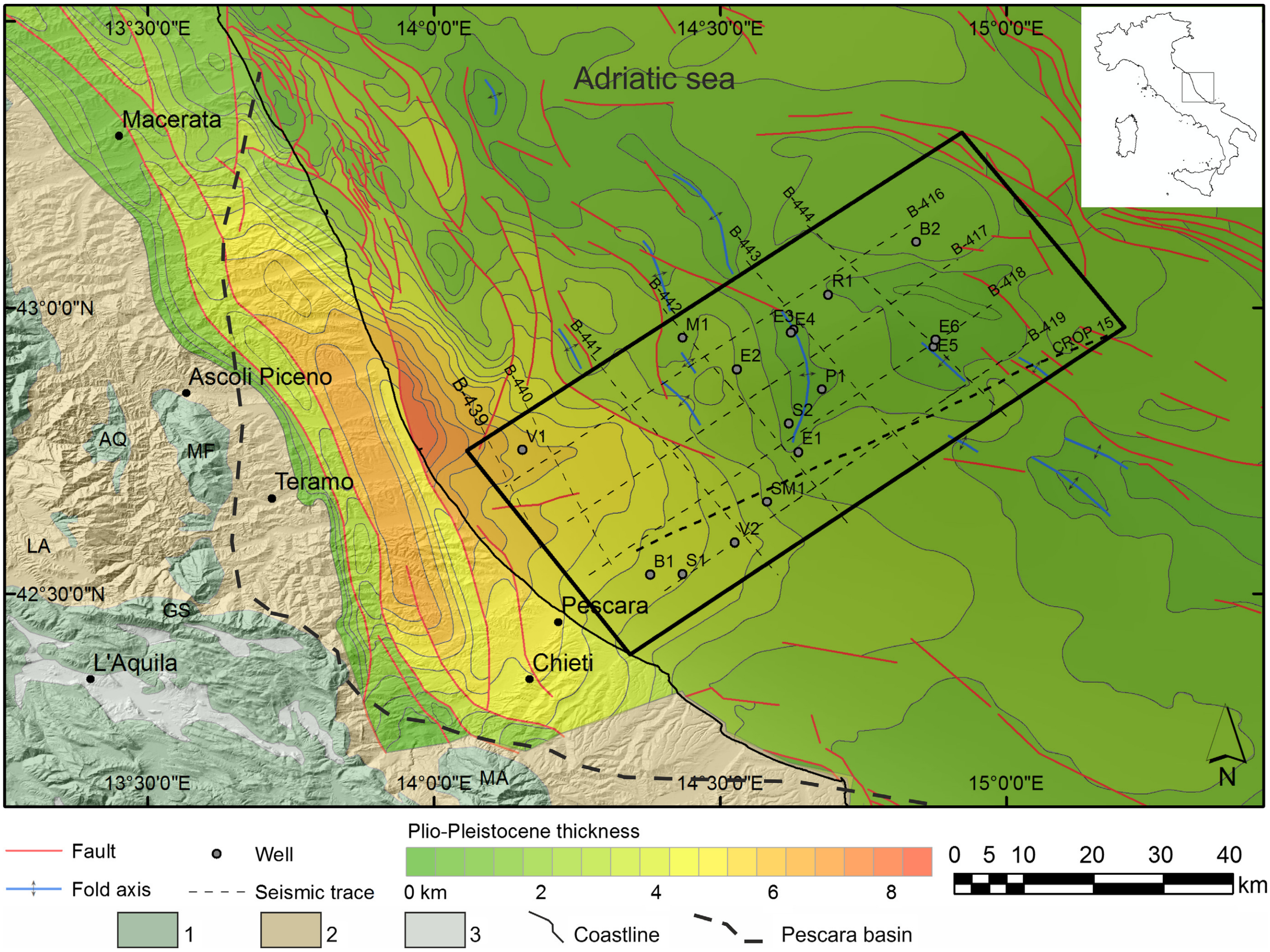

FIGURE 1 Geology of the study area shaded with the thickness of Plio-Pleistocene deposits. 1: Jurassic–Palaeogene carbonate multilayer; 2: Miocene–Pleistocene turbidites and molasse; 3: Pleistocene undifferentiated continental deposits. AQ: Acquasanta; MF: Montagna dei Fiori; LA: Laga; GS: Gran Sasso; MA: Majella. Faults and fold axes, traced as red and blue lines, respectively, refer to the Plio-Pleistocene deposits. Wells and seismic data are described in Table 1. For a complete description of the deposits and units the reader is referred to the Structural Model of Italy (CNR, 1991). Black square delimitates the study area in the Pescara Basin (PB). The PB boundary is drawn after Scrocca et al. (2005)

thickness and isostatic topography. The origin of these missing loads remains a topic of ongoing discussion (e.g. Simpson, 2014). In terms of the relations between the foredeep evolution and additional external loads, the Apennines may be compared with other similar chains (e.g. Eastern Carpathians, Royden & Karner, 1984).

The Apenninic foredeep has been the focus of several investigations to understand its geometry and subsidence history. Many of these studies have been based on forward flexural modelling (e.g., Buiter et al., 1998; D'Agostino & McKenzie, 1999; Royden, 1988). Other authors adopted inverse modelling based on backstripping procedures applied to the Mirandola fault region in the northern Apennines (Scrocca et al., 2005), or on recent (≤400 ka) deposits in the central Adriatic (Maselli et al., 2010). However, a 2D backstripping of the Plio-Pleistocene deposits was never attempted across the entire Adriatic foredeep.

The aim of this work is to model and understand the evolution of the foredeep in the PB using 2D flexural backstripping based on interpreted seismic reflection lines constrained by well data. This enables us to reconstruct palaeogeographic maps for the end of the Messinian (ca. 5.3 Ma) and to evaluate subsidence and sedimentation rates considering decompaction. This approach could advance comprehension of the relations between the orogenic chains, subducting slabs and their foredeeps.

2 | DATA AND METHODS

All data analysed in this study was collected from the VIDEPI database (VIDEPI Project, see Data S1). Data compilation, interpretation of seismic reflection lines and the 2D flexural backstripping procedure were performed with the MOVE 2016 software (© Midland Valley Exploration Ltd). The study area inside the PB was chosen because the Plio-Pleistocene deposits are less faulted and folded than in other regions of the basin, while foreland sediments thicknesses are 1,500–6,500 m (Figure 1).

2.1 | Data interpretation

A total of 10 seismic lines were studied with the interpretation being constrained by 16 wells (Table 1). Interpretation of the seismic lines started with well logs analysis where the main horizons (i.e. the best potential reflectors) were selected, traced and converted to Two Way Time (TWT) with velocities in the ranges given in Table 2 (see Data S1). Once the reflectors were traced, polygons were built (Figure 2) across the entire section which was finally converted in depth with the same velocities used in the previous step (Table 2).

Considering the abundance and distribution of the available wells, the interpretation was constrained to well data on all seismic lines through orthogonal well projection within 2 km of each line. Depth-converted sections were checked by comparison with the original well logs. Offsets at lines' intersections were checked in 3D (Figure 3) and are found to be ≤0.2 km.

Finally, the polygons oriented approximately orthogonally to the Apenninic chain (i.e. sections striking NE: B-416, B-417, B418, B419 and CROP15, Figure 1) obtained after depth-conversion of the seismic lines were backstripped.

TABLE 1 List of wells and seismic lines used in this work

Well (Code in Figure 1)	Total depth (m)	Drilled sequences	PP drilled thickness (m)
Vanessa_001- (V1)	3,330	PP	3,330 – E
Beatrice_001- (B1)	2,200	PP	2,200 – E
Silvana_001- (S1)	5,221	PP – M – OJ	3,520 – E
Veronica_001- (V2)	3,265	PP – M	3,250
Spinello_Mare_001- (SM1)	5,889	PP – M – OJ	2,510 – E
Enigma_001- (E1)	2,228	PP – M –OJ	1,620 – E
Stefania_001- (S2)	1,944	PP – M	1,330 – E
Milli_001- (M1)	1,909	PP – M	1,890
Esmeralda_001- (E2)	3,837	PP – M – OJ	2,240 – E
Patrizia_001- (P1)	1,648	PP – M – OJ	810 – E
Edmond_001_A- (E3)	915	PP – M	790 – E
Edmond_001_TER- (E4)	4,195	PP – M– OJ – T	830 – E
Rigel_001_BIS- (R1)	2,335	PP – M –OJ	977 – E
Edgar_001- (E5)	2,276	PP – M – OJ	700 – E
Edgar_002- (E6)	2,100	PP – M – OJ	660 – E
Bora_001- (B2)	2,500	PP – M – OJ	1,450
Seismic line	**Length (km)**	**Year of acquisition**	
B-416_01-03	77	1967	
B-417_01-03	76	1967	
B-418_01-03	78	1967	
B-419_01-07	72	1967	
B-440_04-07	33	1967	
B-441_02-03	54	1967	
B-442_07-10	51	1967	
B-443_04-05	51	1967	
B-444_04-05	47	1967	
CROP15	83	1995 (CROP Atlas, 2003)	

PP – Plio-Pleistocene sedimentary foredeep infill. M – Miocene sequence encompassing (top to bottom): Messinian evaporites, the Schlier fm. and the Bisciaro fm. OJ – Oligocene–Jurassic carbonaceous sequence encompassing (top to bottom): the Scaglia sequence, the Marne a Fucoidi fm., the Maiolica fm. and the Jurassic carbonatic platform (Calcare Massiccio fm.). T – Triassic, encompassing the Burano formation. Total depths of Vanessa_001 and Beatrice_001 are in middle Pliocene. For detailed description of the formations mentioned here, the reader is referred to the logs of the wells available in the VIDEPI database (see references for a link to the database). Wells with environmental interpretation on log are marked by "E" in the last column. See Figure 1 for location of wells and seismic lines.

2.2 | Backstripping procedure

Using the MOVE software (© Midland Valley Exploration Ltd), 2D flexural backstripping (e.g. Watts, Karner, & Steckler, 1982; Roberts, Kusznir, Yielding, & Styles, 1998—see Data S1 for a description of the backstripping method) was performed on the Plio-Pleistocene and Miocene sequences to isolate the tectonic contribution to subsidence of the Adriatic plate in the PB since the Miocene.

We applied backstripping along with unfolding and unfaulting to uncover the first calcareous record in the stratigraphic sequence (i.e. the Scaglia group—Figure 4a–e) under the Neogene–Quaternary sequences. After this procedure, in cases where the Scaglia group (upper green polygon in Figure 4d–f) was (partly) eroded as evidenced by reduced present-day thicknesses, it was re-drawn to the original thickness of the undisturbed unit as observed on the depth-converted seismic line or on well logs.

The first two steps of the backstripping (Figure 4a,b) considered a thickness of the water layer of 200 m, whilst the water depth was assumed to be zero during the removal (Figure 4c) of the Miocene

TABLE 2 Seismic velocities used for depth-conversion of the interpreted seismic lines

Unit or sequence	Seismic velocity (m/s)
Pleistocene	2,000$^{(1,\ E1)}$–2,300$^{(S1)}$
Pliocene	2,300$^{(2,\ E1)}$–2,600$^{(1,S1)}$
Miocene turbidites and Marly Scaglia	3,500$^{(1,\ 2,\ E1)}$–4,000$^{(1,\ S1)}$
Cretaceous–Tertiary calcareous Scaglia	4,500$^{(E1)}$–5,000$^{(1,\ 2,\ S1)}$
Jurassic and lower Cretaceous calcareous sequence	5,000$^{(1,\ S1)}$
Calcare Massiccio carbonate platform	6,000$^{(1,\ 2,\ S1)}$

Interval velocity values used for the modelling of the sections are derived from: [1]Bally et al. (1986), [2]Barchi et al. (2003), E1 is Enigma_001 well and S1 is Silvana_001 well (see Figure 1 for wells' location).

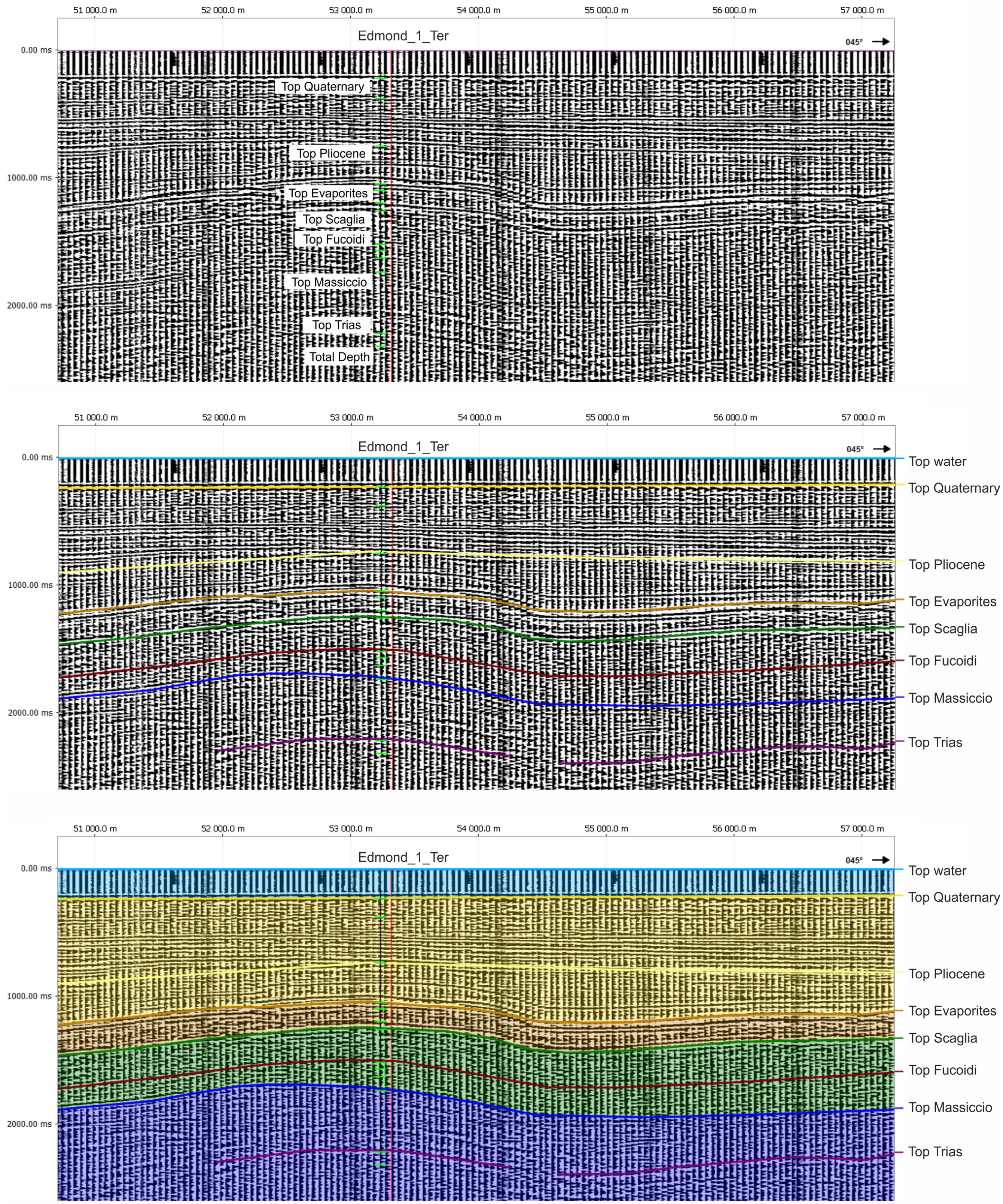

FIGURE 2 Portion of the line B-416 showing the interpretation procedure constrained to well data. Top: main horizons from wells are converted from depth to time using velocities given in Table 2 and are used to interpret the seismic line in time (centre) and trace polygons across the section (bottom). Green ticks mark the horizons as found in the well log and converted in time, red vertical line indicates the intersection between lines B-416 and B-443. The sequence shown here is representative of the stratigraphic relation between the units mentioned in the text. The reader is referred to the well logs for a detailed description of the lithology and microfossil content of the units. See Figure 1 for the location of the seismic line and the well in the study area

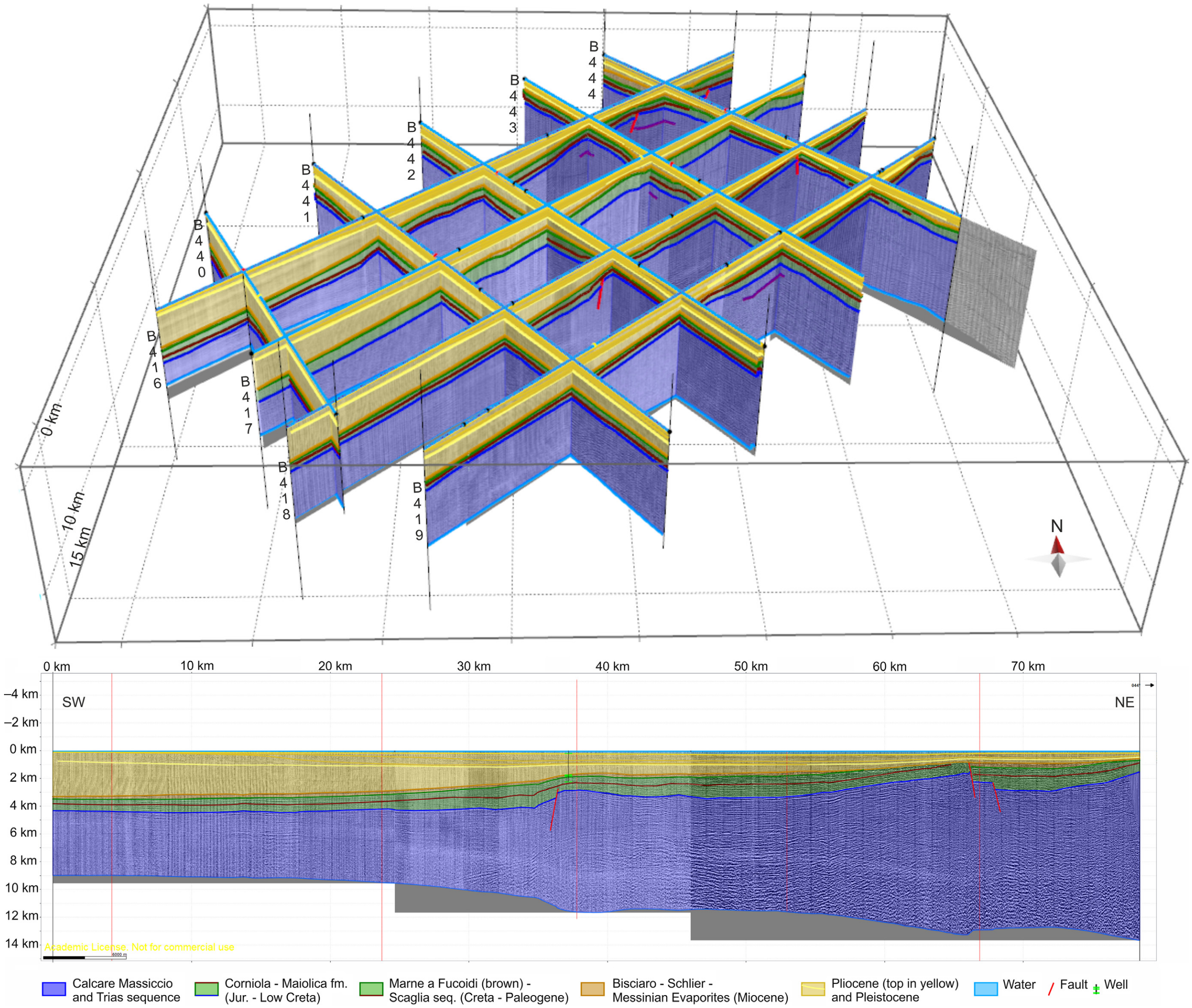

FIGURE 3 Perspective 3D view of the commercial seismic dataset once interpreted and converted to depth (top). Final result after interpretation and depth-conversion for line B-418 (bottom). See Data S1 for the result after depth-conversion for each section

(see Data S1). Finally, the unfolding was targeted to a horizontal surface defined by the depocenter of the decompacted unit (Figure 4c, d). Parameters used for the backstripping procedure are given in Tables 3 and 4.

3 | RESULTS

Section B-418 (Figure 4) shows that after backstripping, the top of the Scaglia sequence in the south-western parts of the section is reconstructed from a depth of +3,500 m to a depth of ca. +1,980 m, with an uplift of +1,520 m, about 43% of its initial depth. This value is comparable with values obtained from the other sections. In fact, on section B-416 backstripping resulted in an uplift of the top of the Scaglia of ~38% (from a depth of +4,180 m to +2,630 m), on section B-417 the uplift is ~37% (from +3,770 m to +2,400 m), on CROP15 it is 41% (from +3,400 m to +2,000 m) and on section B-419, it is ~39% (from +3,250 m to +2,000 m). In all these sections, after the removal of the Plio-Pleistocene deposits, the main depocenter was found in the SW domain of the sections—i.e. the more internal area, proximal to the Apenninic chain. It should be noted that these values referred to the top of the Scaglia sequence are temporally representative of the late Messinian stage because they are calculated after the removal of the Pliocene and Pleistocene deposits thus generating the top of the Scaglia at the beginning of the Pliocene.

Results of the backstripping confirm that the Adriatic plate subduction and loading related to the adjacent Apenninic chain was already active in the Late Miocene, in agreement with previous works (e.g. Gueguen et al., 1998; Robertson & Grasso, 1995). However, is it also possible that at least parts of the subsidence already

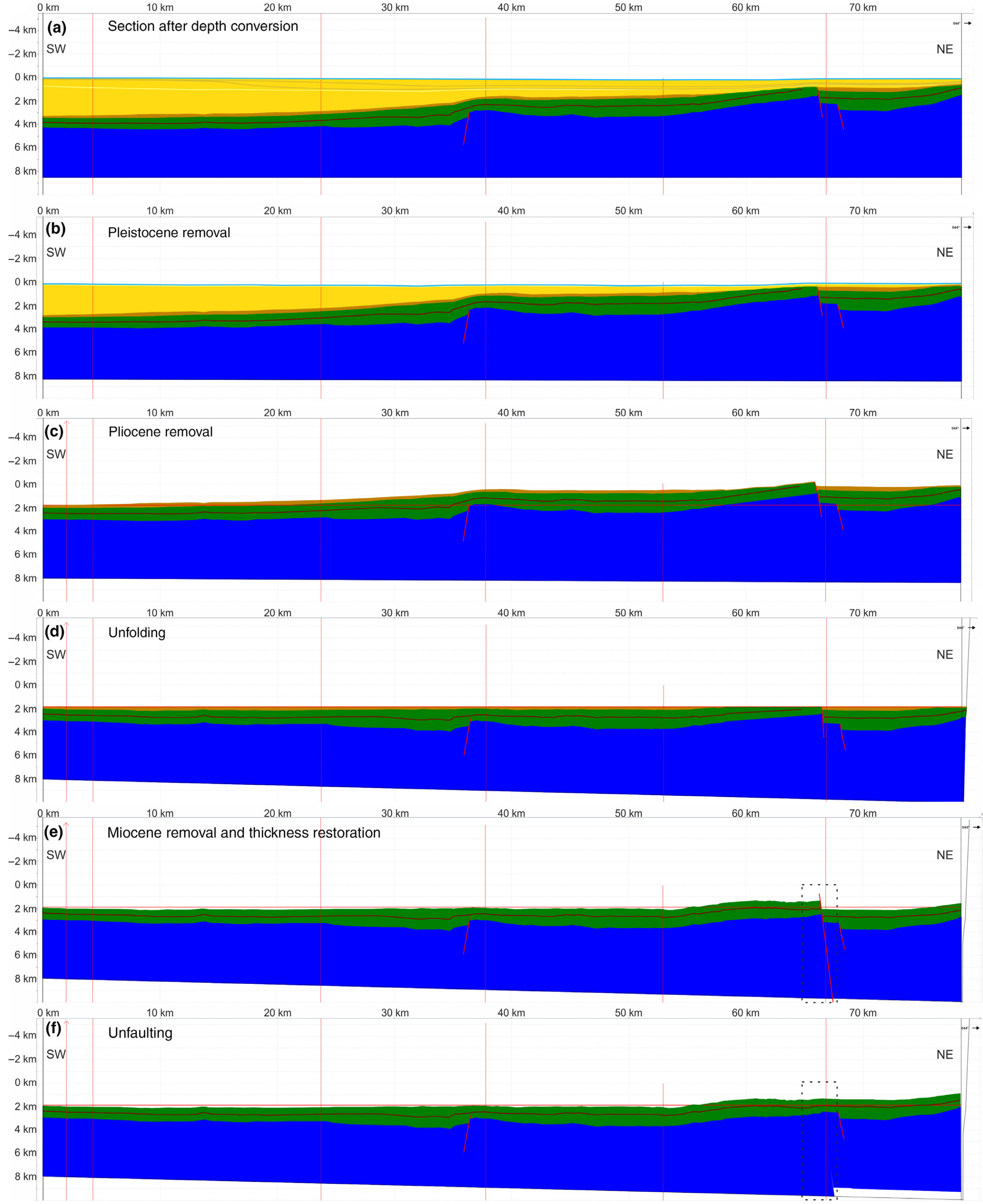

FIGURE 4 (a) Backstripped results of section B-418 after depth-conversion. (b) Pliocene is decompacted due to Pleistocene removal. (c) Pliocene is removed and Miocene is decompacted. (d) Section is unfolded to a horizontal surface (red line), vertical red arrow indicates the pin to which unfolding is constrained (i.e. the depocenter after Pliocene removal). (e) Miocene sequence is removed and the Cretaceous–Palaeogene sequence is restored to its original thickness. (e,f) Where the Cretaceous–Palaeogene sequence is faulted, the last step of the backstripping procedure was followed by the restoration of faults displacing the Cretaceous–Palaeogene (black dashed box) sequence using the simple shear algorithm with an antithetic shear angle of ~78° (Figure 4e,f) (Gibbs, 1983; Verrall, 1981; Withjack & Peterson, 1993). Red vertical lines represent intersections with tie seismic lines. In this model, the bulk density used for Plio-Pleistocene is 2,300 kg/m^3. Porosities and coefficients used for decompaction (Table 3) and the elastic and density parameters (Table 4) used in this work were obtained from the literature. Discussion about effects of varying infill density is provided in Data S1. In the following section only results obtained from models with an infill density of 2,300 kg/m^3 will be discussed. In this work the percentage uplift measured after the procedure refers to the initial depth of the horizon (i.e., how much the horizon was uplifted after the removal of the overlying units)

present in the Late Miocene could be the result of earlier crustal thinning and isostatic subsidence.

Results from the modelling of section B-418 are also in agreement with the interpreted palaeo-environment from S1 well log (Table 1, Figure 1) that cuts the Aquitanian-Burdigalian Bisciaro formation between 3,840 and 3,720 m. The log, based on microfossil content, reports that deposition above the Scaglia sequence occurred in a bathyal environment, in agreement with results of Figure 4e,f where the top of the Scaglia in the SW portion of the section is at depths of ~2,000 m.

Figure 5 shows maps related to backstripping to the top of the Scaglia sequence. It is interesting to note that while the trend of the present top of the Scaglia sequence shows an increase in depth (reaching a maximum depth of about 3,800 m) towards the W-SW, backstripping reveals two relative depocenters divided by a relative high located at the SW end of section B-416 and at the SW end of CROP15 (Figure 5b). This trend in the southwestern region of the study area is also observed on the exposed surface representing this epoch (i.e. top of the Messinian evaporites, Figure 5c). The difference between the actual depth of the top Scaglia as obtained from sections after depth-conversion and the top of the Scaglia after backstripping (Figure 5d), represents the uplift values achieved by backstripping the Plio-Pleistocene deposits and therefore they indicate the subsidence achieved by tectonic and sedimentary loading since the Messinian.

This scenario is further confirmed by calculations of decompacted sedimentation rates for the Miocene, Pliocene and Pleistocene sequences (Figure 6). Average sedimentation rates were calculated by dividing the decompacted thickness of each sequence at a location 2 km from the SW end of the sections, by the duration of the reference epoch—i.e. 17.7, 3.5 and 1.8 Ma (Azzaroli et al., 1997; Cohen et al., 2013), respectively. It should be noted that the Pliocene–Pleistocene boundary is 1.8 Ma rather than the actual 2.58 Ma, because it represents the Pliocene–Pleistocene boundary as it was at the epoch in which well logs were compiled (1972–1990) (e.g. Azzaroli et al., 1997). Data shows that the maximum sedimentation rates (0.95–0.57 mm/year) are achieved in the Pliocene for sections B-416–B-419. Sedimentation rates are lower in the Pleistocene than the Pliocene across all the sections (0.26–0.52 mm/year). These results are interpreted to reflect progressive filling of the foredeep depression, which was essentially overfilled by the end of the Pliocene.

4 | DISCUSSION

This study represents the first attempt to exploit the 2D flexural backstripping on several sections to create palaeogeographic maps (Figure 5) and evaluate the resulting sedimentation rates (Figure 6) in the Adriatic foredeep, using an approach previously tested in the central Po basin (Maesano & D'Ambrogi, 2016). Results delineate a spatial and temporal heterogeneity of the evolution of the basin since the Miocene. What could have caused such a variability? Considering the lack of faults acting on these deposits in the study area (Figures 1 and S1 in Data S1), it is unlikely that such results are produced by intra-basin tectonic activity. Moreover, autochthonous and/or allochtonous sedimentary processes have shown little or no variation since the Pliocene, as observed from well logs and the lack of delta systems, respectively. Thus, we interpret these results as caused by external-basin events resulting from the combination of the Apenninic chain load combined with some external contribution. As proposed by previous authors, the external source may be attributed either to slab roll-back (e.g. Doglioni, 1991; Elter et al., 1975; Royden et al., 1987; Scandone, 1980), or to lateral propagation of slab detachment (e.g. Benoit et al., 2011; Buiter et al., 1998; Channell, 1986; Channell & Mareschal, 1989; Chiarabba et al., 2014; Wortel & Spakman, 1992) or to eastward shifting of an asthenospheric rising plume (e.g. Decandia et al., 1998; Lavecchia, 1988; Lavecchia et al., 2004). To definitely understand the nature and the magnitude of such contributing phenomena will require further investigation, possibly requiring an integrated model taking into account all the possible sources, possibly with a 3D approach (Buiter et al., 1998). However, it is clear that, if our interpretation is correct, the external contribution was more intense during the Pliocene.

Our favoured explanation for the observed transient variations in the PB since the Miocene is the slab detachment model proposed by Wortel and Spakman (1992), which was later tested by Buiter et al. (1998). According to this model, a tear in the subducting slab propagates laterally in the Apennine foreland from north to south with time. Prior to the Pliocene, the PB was probably located well south of the tear and thus the basin depth was governed mainly by the static load of the slab. As the tear approached the PB in the

TABLE 3 Porosity and compaction coefficients used in this work (Sclater and Christie, 1980; Scrocca et al., 2005).

Lithology	Surface porosity (φ_0)	Depth-porosity coefficient (c, km^{-1})
Shale	0.63	0.51
Sand	0.49	0.27
Shaley sandstone	0.56	0.39
Chalk	0.70	0.71

TABLE 4 Parameters used for flexural backstripping

Parameter	Value
Young's modulus (E)	8×10^{10} Pa (or N/m^2)
Poisson's ratio (ν)	0.25
Elastic thickness (T_e)	10 km
Mantle density	3,200 kg/m^3
Plio-Pleistocene infill density	2,000–2,300 kg/m^3
Miocene sequence density	2,400 kg/m^3

E, ν, T_e and the density of the mantle were set as constant values as best fitting parameters obtained from previous models on the area (Buiter et al., 1998; Royden, 1988).

Pliocene, the basin experiences enhanced subsidence as the weight of the detached part of the slab is transferred to the undetached portion (see Figure 3 of Buiter et al., 1998). After the Pliocene when the tear has propagated south of the PB, the basin then experiences rebound due to the decrease in slab pull. On the other hand, the Pliocene increase in the PB foredeep filling is not well-explained by a mechanism that homogeneously evolves in space (along strike) and time (such the slab roll-back).

It is interesting to note how the combination of the two models was never tested in the Adriatic Sea. Hypothetically an along-strike asymmetric roll-back whose intensity increases southward, would fit with the regional geodynamic context (e.g. Doglioni, 1991). Such a mechanism could help trigger slab detachment in the northern Apennines (Wortel & Spakman, 2000) and constrain the shortening decrease observed northward (Bally et al., 1986; Doglioni, 1991; Lavecchia et al., 1984, 1988). In this scenario, the PB could locate the transition area between the detachment-dominated region in the north and the roll-back-dominated region in the south. However, to validate this hypothesis will require a well-constrained 3D numerical model that takes into account lateral variations of the rheological properties of the mantle and of the Adriatic lithosphere. Finally, this approach can be generalized to further investigate other chains whose behaviour is known to be similar to the Apennines (e.g. Gogus et al., 2017; Royden & Karner, 1984).

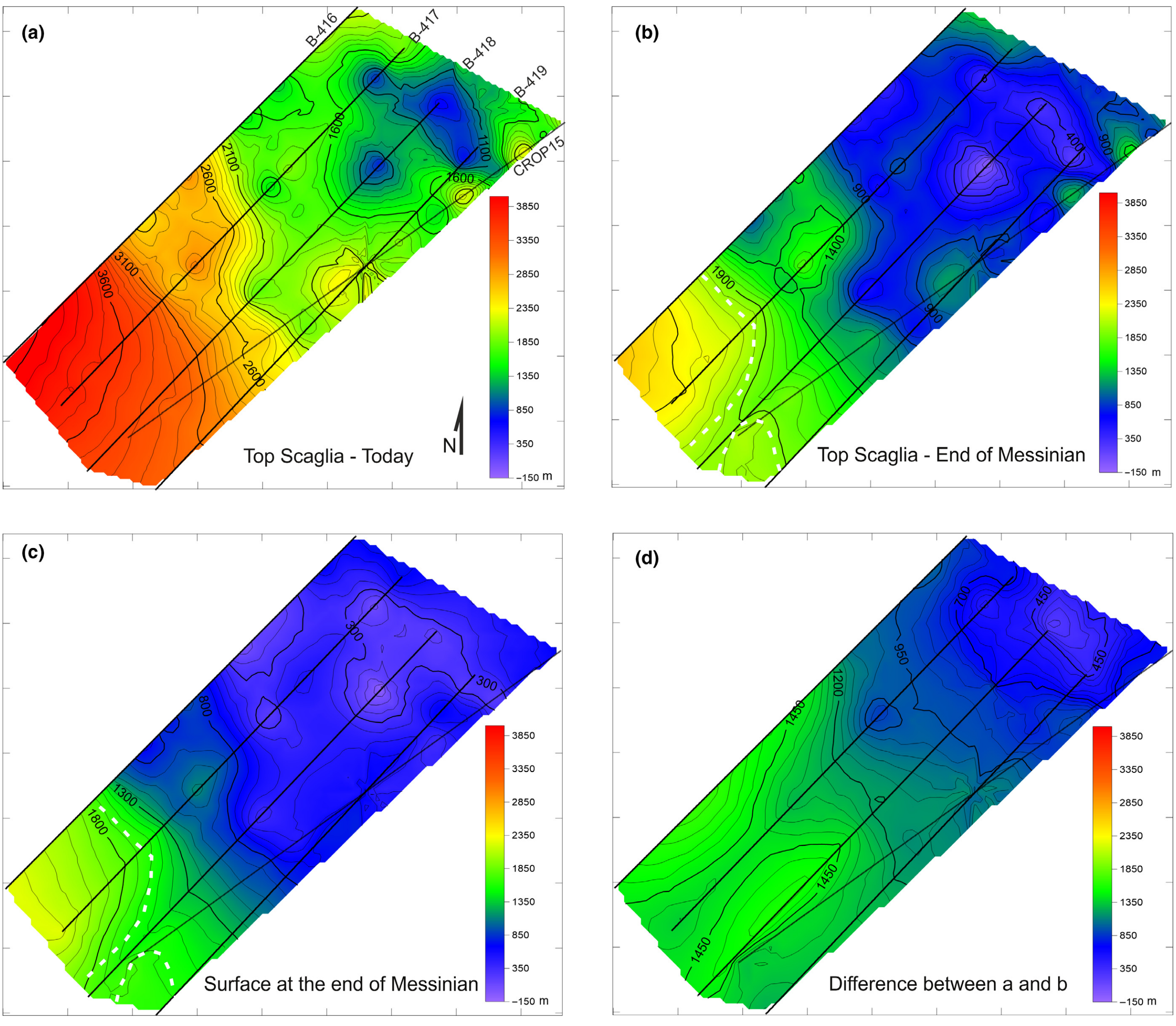

FIGURE 5 (a) Top of the Scaglia sequence as modelled from the interpreted sections after depth-conversion (Figure 4a). (b) Map of the top of the Scaglia sequence after the removal of Plio-Pleistocene deposits (i.e. at the end of Messinian) (Figure 4c). (c) Surface (i.e. top of Evaporites) at the end of the Messinian. (d) Difference between the maps in (a) and (b), representing the values of tectonic- and sediment-induced subsidence since the end of the Messinian. White dashed lines delimit small depressions within the basin (see text). Black lines indicate the seismic lines modelled with backstripping. Contour intervals are 100 m for (a–c) and 50 m for (d)

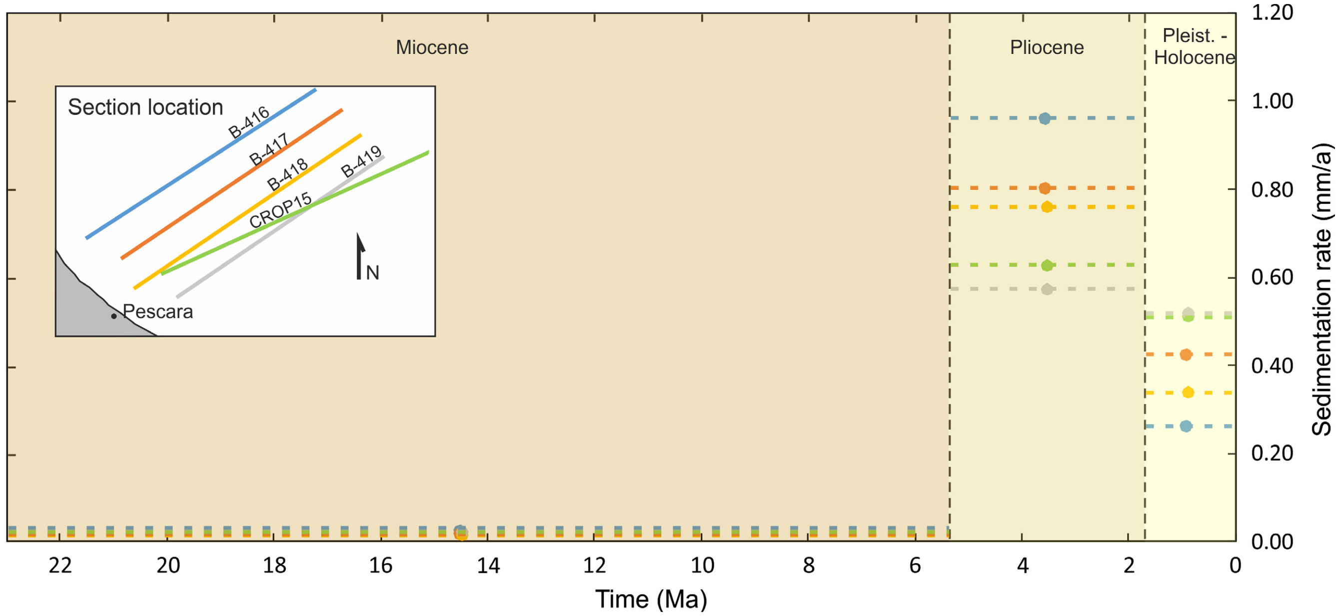

FIGURE 6 Sedimentation rates (corrected for decompaction) for the PB. Values are calculated 2 km from the SW end of each section. Dots represent the average sedimentation rate for the reference epoch. The Pliocene–Pleistocene boundary refers to the epoch of compilation of well logs (1972–1990)

5 | CONCLUSIONS

2D Flexural backstripping was implemented to restore deformation caused by sediment loading and compaction in the PB of the Apenninic foreland (Adriatic Sea). Results of the backstripping procedure indicate that 37%–43% of subsidence was achieved since the Messinian (i.e. in the last 7.2 Ma) with significant spatial variability across the basin. Estimates of average sedimentation rates based on the decompacted Miocene, Pliocene and Pleistocene sequences, show a peak in the Pliocene with maximum values of 0.95 mm/year observed in the more internal area close to the chain. Sedimentation rates decreased (0.26–0.52 mm/year) during the Pleistocene after the basin was nearly completely filled in the Pliocene. These results are interpreted as representative of the effects of a combination of the Apenninic load and a complementary external contribution. The temporal and spatial heterogeneity highlighted in the PB in this work suggests that the external contribution was most likely caused by the southward propagation of a detaching slab, which led to an increase in effective slab pull beneath the PB in the Pliocene as the tear approached, followed by a decrease in slab pull as the tear propagated further southward. However, a contribution from slab roll-back cannot be ruled out. In fact, a combination of the two mechanisms is considered compatible with the outcomes of this and previous works.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

Data S1. More information on Data and Methods, Data Interpretation and Backstripping. Includes Figure S1 (Interpreted cross-sections from figure 3 after depth-conversion).

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