

# Forebulge migration in the foreland basin system of the central-southern Apennine fold-thrust belt (Italy): New high-resolution Sr-isotope dating constraints

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## Abstract

The Apennines are a retreating collisional belt where the foreland basin system, across large domains, is floored by a subaerial forebulge unconformity developed due to forebulge uplift and erosion. This unconformity is overlain by a diachronous sequence of three lithostratigraphic units made of (a) shallow-water carbonates, (b) hemipelagic marls and shales and (c) siliciclastic turbidites. Typically, the latter two have been interpreted regionally as the onset of syn-orogenic deposition in the foredeep depozone, whereas little attention has been given to the underlying unit. Accordingly, the rate of migration of the central-southern Apennine fold-thrust belt-foreland basin system has been constrained, so far, exclusively considering the age of the hemipelagites and turbidites, which largely post-date the onset of foredeep depozone. In this work, we provide new high-resolution ages obtained by strontium isotope stratigraphy applied to calcitic bivalve shells sampled at the base of the first syn-orogenic deposits overlying the Eocene-Cretaceous pre-orogenic substratum. Integration of our results with published data indicates progressive rejuvenation of the strata sealing the forebulge unconformity towards the outer portions of the fold-thrust belt. In particular, the age of the forebulge unconformity linearly scales with the pre-orogenic position of the analysed sites, pointing to an overall constant migration velocity of the forebulge wave in the last 25 Myr.

## KEYWORDS

central-southern Apennines (Italy), fold-thrust belt, forebulge, foredeep, foreland basin system, strontium isotope stratigraphy

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# 1 | INTRODUCTION

The Apennines are a fold-thrust belt belonging to the Western Mediterranean subduction zone: a narrow, arcuate, low-elevation orogenic system formed by the convergence between African and Eurasian continents, which rims most of the western Mediterranean Basin (Royden & Faccenna, 2018 and references therein) (Figure 1a). This system includes, beyond the Apennines, the Calabria, Maghebride, Rif and external Betic thrust belts, along with associated back-arc and foreland basins. In this framework, the Apennines form the northern limb of the Apennines–Calabria–Sicily orocline, developed because of the SE-ward retreating subduction of the Alpine Tethys (e.g. Carminati & Doglioni, 2012; Doglioni, 1991; Faccenna et al., 1997; Malinverno & Ryan, 1986; Royden et al., 1987).

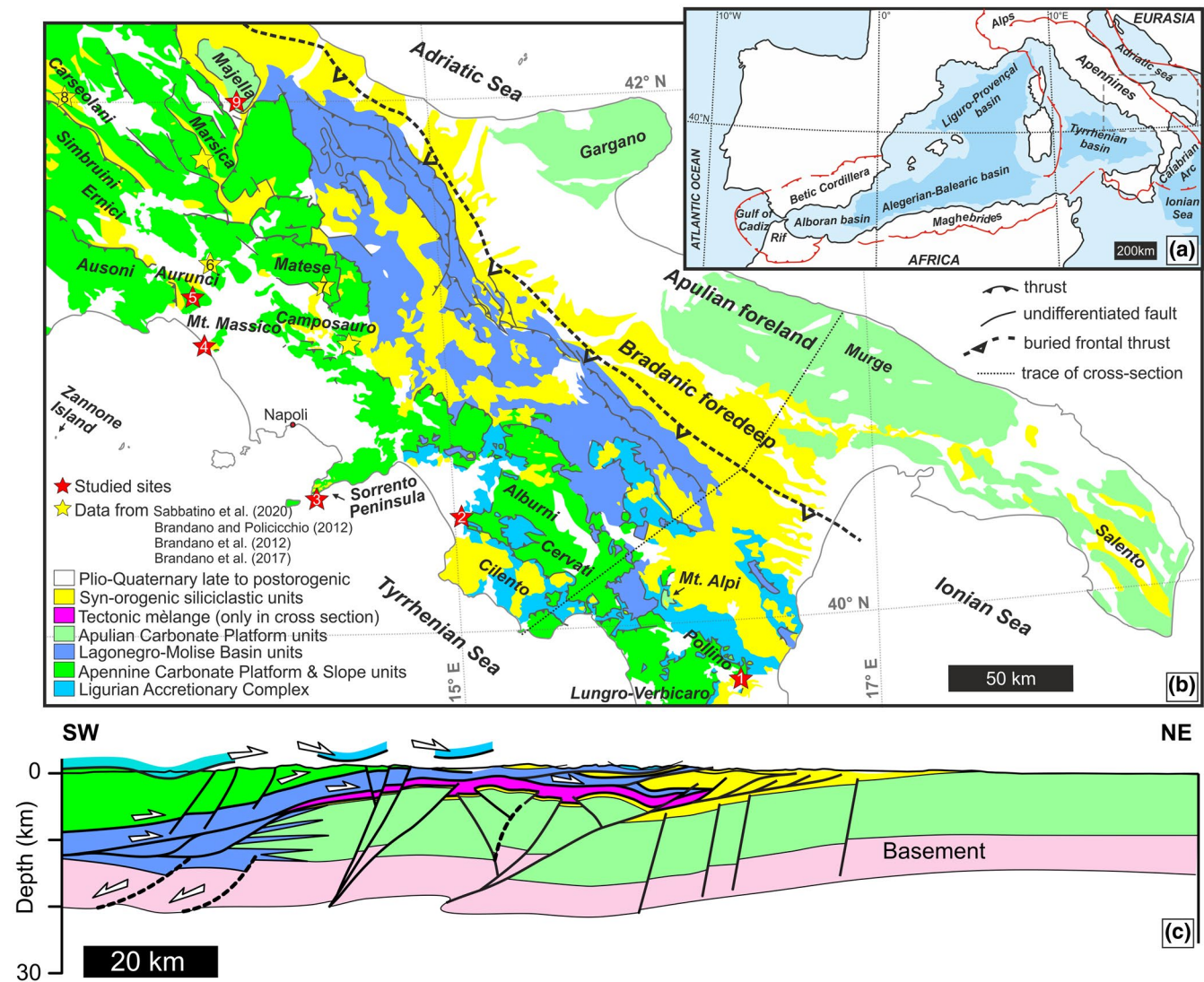
In this subduction system, information about the timing of fold-thrust belt and associated orocline development has been derived mainly by the age of syn-orogenic deposits filling the fossil foreland basins (Bigi et al., 2009; Cavinato & DeCelles, 1999; Cipollari & Cosentino, 1995; Ori et al., 1986; Vezzani et al., 2010; Vitale & Ciarcia, 2013). Indeed, the architecture and stratigraphy of foreland basins provide constraints on the evolution of the associated fold-thrust belts (e.g. Allen et al., 1986; DeCelles, 2012; DeCelles & Giles, 1996; Ori et al., 1986). Typically, foreland basin systems host four depozones: wedge-top, foredeep, forebulge and back-bulge (DeCelles & Giles, 1996). The Apennines, being a retreating collisional belt, are characterized by narrow but thick foredeep and wedge-top depozones, and very narrow forebulge and back-bulge depozones (DeCelles, 2012). In this context, the architecture and stratigraphy of the central and southern Apennines, including its fossil foreland basins, have been extensively studied in the last decades (e.g. Cosentino et al., 2010; Critelli et al., 2011; Patacca & Scandone, 2007; Vezzani et al., 2010; Vitale & Ciarcia, 2013 among others). Typically, the timing of migration and deformation of the Apennine fold-thrust belt-foreland basin system has been constrained using the ages of the hemipelagites and siliciclastic sedimentary rocks filling the foredeep and wedge-top depozones. However, those strata do not represent the first syn-orogenic depositional event on the foreland plate. In fact, the earliest stage of a foreland basin system history pre-dates the passage of the forebulge and it is recorded by the slow accumulation in the back-bulge depozone, which, in retreating collisional settings like the Apennines, may be removed by erosion during passage of the forebulge itself (e.g. DeCelles, 2012). During forebulge uplift, the lithosphere flexes upwards, causing stratigraphic condensation, erosion and development of a forebulge unconformity in shallow-water settings (Crampton & Allen, 1995). In these cases, the deposits directly overlying the unconformity constitute the first record of syn-orogenic deposition associated

## Highlights

- Sr-isotope stratigraphy is used to date the flexural wave migration in the central-southern Apennines.
- Better constraints than ages of first siliciclastics, which represent a blurred record of flexural wave migration.
- A progressive rejuvenation of the base of the foreland basin occurs towards the E/NE portions of the fold-thrust belt.
- The migration rate of the foreland system was nearly constantly 15 mm/year in the last 25 Myr interval.

with the most distal foredeep depozone, not yet reached by siliciclastic input (Figure 2).

The importance of the forebulge unconformity and the following syn-orogenic sedimentation for evaluating the dynamics of foreland basin system development has been already discussed in several orogenic belt-basin systems, such as in the Appalachians (e.g. Hiscott et al., 1986) Carpathians (e.g. Leszczyński & Nemeč, 2015), Dinarides (e.g. Babić & Zupanič, 2012), Himalayas (e.g. DeCelles et al., 1998), Northern Alps (e.g. Crampton & Allen, 1995; Sinclair, 1997), Oman-UAE (e.g. Glennie et al., 1973; Robertson, 1987), Papuan Basin (e.g. Pigram et al., 1990), Pyrénées (e.g. Vergés et al., 1998), Taiwan (e.g. Yu & Chou, 2001), Timor Trough (e.g. Veevers et al., 1978), North American Cordillera (e.g. White et al., 2002) and Zagros (e.g. Homke et al., 2009; Pirouz, Avouac, et al., 2017; Pirouz, Simpson & Chiaradia, 2015; Pirouz, Simpson, et al., 2017; Saura et al., 2015). Furthermore, the geometry of the forebulge unconformity and the progressive time-transgressive onlap of overlying sediments are of fundamental importance for understanding the history of foreland sedimentation associated with the events of the advancing orogen. In the central-southern Apennines, these deposits are typically represented by shallow-water carbonates, which have been described under different lithostratigraphic units, such as the Cerchiara, Roccadaspide, Recommono and Cusano formations, the Bryozoan and Lithothamnium Limestones and the Gravina Calcarene (Carannante et al., 1988; Civitelli & Brandano, 2005; De Blasio et al., 1981; Patacca et al., 2008; Selli, 1957; Taddei Ruggiero, 1996). To date, the early evolutionary stage in the syn-orogenic history of the central-southern Apennines has not been investigated in detail: filling this gap constitutes the main aim of this contribution. In particular, we aim at constraining precisely the age of the first carbonate sediments overlying the forebulge unconformity



**FIGURE 1** (a) Tectonic sketch map of the Western Mediterranean subduction zone; (b) schematic geological map of the central and southern Apennines showing the locations of the studied sites (modified after Vitale & Ciarcia, 2013). Numbered symbols refer to the stratigraphic logs of Figure 3). (c) Cross-section across the southern Apennines (modified after Tavani et al., 2021)

by means of Sr-isotope stratigraphy (SIS). This method is particularly suitable for high-resolution dating and correlation of Miocene marine carbonates because the reference curve for this stratigraphic interval is characterized by a very narrow statistical uncertainty and by a very high slope (i.e. rapid unidirectional change of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of the ocean through time) (McArthur, 1994). For these reasons, a resolution of up to 0.1 Ma can be potentially attained in Miocene marine deposits. Moreover, Miocene shallow-water carbonate units of the Apennines contain low-Mg calcite shells of pectinid and ostreid bivalves, which are one of the best materials for SIS (McArthur et al., 2020 and references therein).

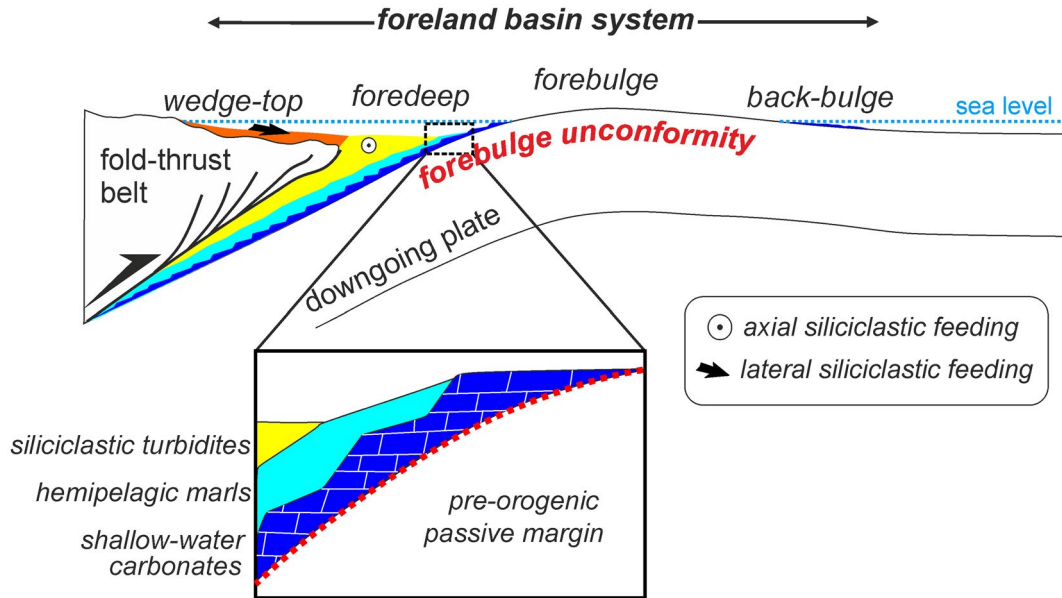
Building on the work by Sabbatino et al., 2020, who presented a first case study in the southern Apennines, we assembled a more complete data set for the base of the central-southern Apennine foreland basin – that is the first

syn-orogenic deposits associated with the most distal foredeep depozone directly overlying the forebulge unconformity – widening the area of investigation to a large transect of the orogenic fold-thrust belt, extending from inner to outer sectors (i.e. from W to E/NE; Figure 1b). Integration of these new data with previously published ages of syn-orogenic deposits allows us to better constrain the evolution of the Apennine fold-thrust belt and foreland basin.

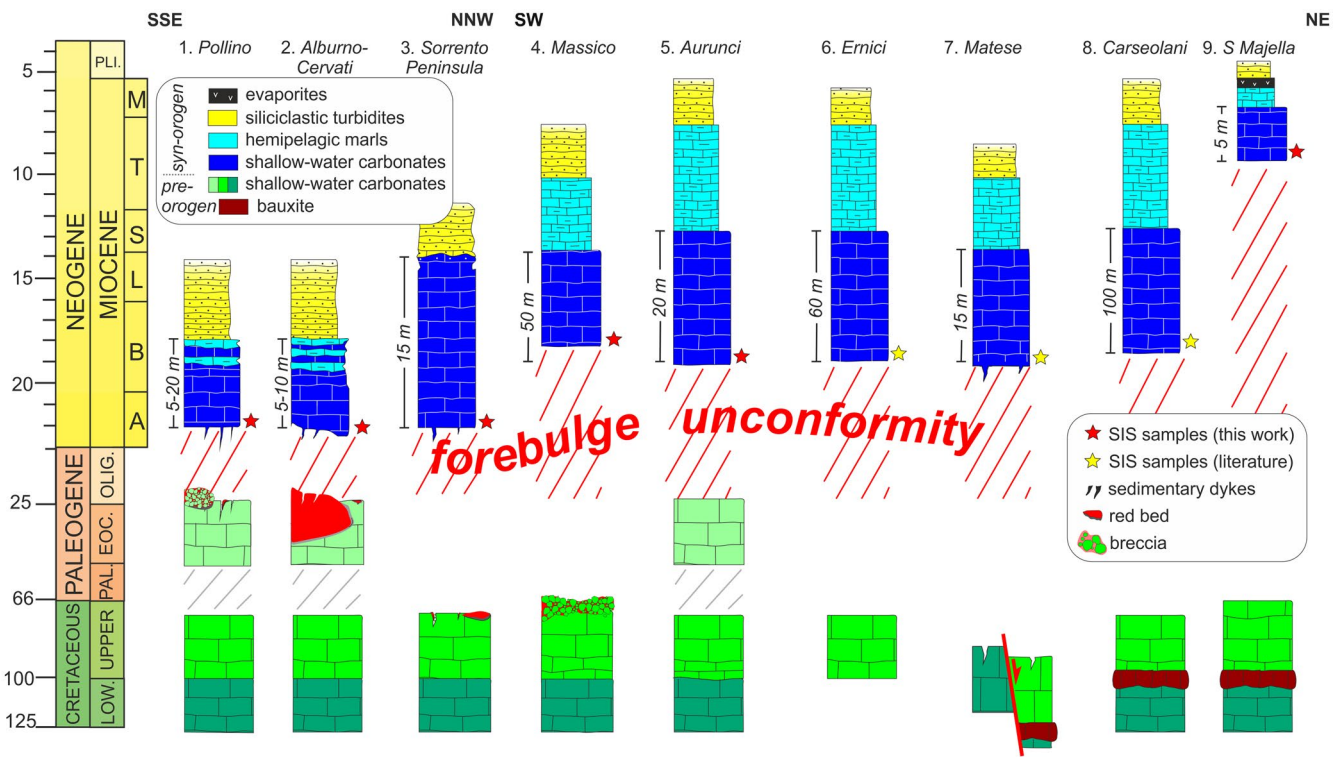
## 2 | GEOLOGICAL SETTING

The Apennines are part of the Western Mediterranean subduction zone that evolved in the framework of the Alpine-Himalayan geodynamic system (Figure 1a) (e.g. Faccenna et al., 2001; Royden & Faccenna, 2018). The orogenic system





**FIGURE 2** Schematic cross-section of a foreland basin system with the back-bulge, forebulge, foredeep and wedge-top depozones (modified after DeCelles & Giles, 1996; Sinclair, 1997; Sabbatino et al., 2020)



**FIGURE 3** Stratigraphic logs of the studied sections in the southern and central Apennines. Numbers correspond to numbered symbols on Figure 1b. Section 1 summarizes the three stratigraphic logs of Panno Bianco, Pietra Sant’ Angelo and SS92 Road; Section 3 summarizes the two logs of Reconnome and Mount San Costanzo. See the text for further details

formed by the westward subduction of Adria beneath Europe (Malinverno & Ryan, 1986) and evolved in the context of a retreating collisional system, characterized by a progressive arching of an originally nearly linear belt, following the E-ward retreat of the trench and the opening of the Tyrrhenian back-arc basin (e.g. Dewey et al., 1989; Doglioni, 1991;

Faccenna et al., 2014; Malinverno & Ryan, 1986; Mazzoli & Helman, 1994). During such convergence, several tectonic units, originally deposited in a system of carbonate platforms and intervening deep basins at the southern margin of the Alpine Tethys Ocean since the Triassic (Bosellini, 2004), were imbricated to form the Apennine fold-thrust belt.

In more detail, the Apennines can be further subdivided into two main arcs: the northern and the southern Apennines, which connect together in the central Apennines. The present-day tectonic architecture of the southern Apennines is made up of the thrust sheets of the Mesozoic Lagonegro-Molise Basin successions, sandwiched between thrust sheets composed of the overlying Apennine and underlying Apulian Mesozoic shallow-water carbonate platforms. The Apennine platform is in turn overthrust by the deep basinal units of the Ligurian accretionary complex, which was deposited on top of the Jurassic oceanic and thinned continental crust and exhumed oceanic lithosphere (e.g. Cello & Mazzoli, 1998; Mazzoli et al., 2008; Tavani et al., 2021). The western part of the Apulian carbonate platform is deformed under a thick tectonic pile and is now exposed in the Mount Alpi, in the southern Apennines and Majella Mountains in the central Apennines. The outer (eastern) sector of the Apulian carbonate platform is exposed in the foreland region of the southern Apennines to the NE, where it is locally buried underneath a Plio-Pleistocene sedimentary cover.

The foreland basin, which developed ahead of the central-southern Apennine fold-thrust belt, was progressively filled with syn-orogenic sediments, following a younging trend towards the east/north-east. The Miocene to Pleistocene syn-orogenic carbonates, object of this study, unconformably overlie the Apennine and Apulia carbonate platform pre-orogenic units. The Apennine and Apulia carbonate platform units represent allochthonous and (partly) autochthonous, respectively, paleogeographic domains witnessing a long-term record of pre-orogenic passive margin shallow-water carbonate sedimentation. Thick platform successions (up to 6,000 m; Ricchetti et al., 1988) developed from the Late Triassic to the Late Cretaceous (Bernoulli, 2001), with the only long-lasting interruption by prolonged subaerial exposure recorded in some areas by 'middle' Cretaceous karst bauxites (Mindszenty et al., 1995). Shallow-water carbonate sedimentation resumed in some sparse areas in the Paleogene and is now represented by thin and stratigraphically discontinuous deposits (Chiocchini et al., 1994; Selli, 1962) overlying unconformably Upper Cretaceous platform carbonates. In the southern Apennines, this stratigraphic interval is represented by an up to 150 m-thick sequence of lower-middle Eocene limestones, known as the Trentinara Formation (Selli, 1962), which is widely exposed in the Alburno-Cervati (Cilento Promontory) and Pollino Mountains (Figure 1). In the central Apennines analogous facies, described as '*Spirolina sp.* Limestones' (Chiocchini & Macinelli, 1977; Romano & Urgera, 1995; Vecchio et al., 2007), are much less widespread and reach a maximum thickness of about 30 m (Romano & Urgera, 1995). After this prolonged phase of passive margin sedimentation and a long-lasting Cretaceous/Eocene to Miocene hiatus, a new phase of shallow-water carbonate sedimentation

occurred starting from the early Miocene, related to the development of the Apennine fold-thrust belt.

## 2.1 | The central-southern Apennine foreland basin system

Starting from the Oligocene (and possibly as early as late Eocene; Figure 3), the foreland of the central-southern Apennines has experienced uplift and erosion, caused by isostatic loading from the growing fold-thrust belt, bending of the subducting lithosphere and by the E/NE-ward migration of the fold-thrust belt-foreland basin system (e.g. Doglioni, 1995). This tectonic stage is recorded by a regional unconformity, by extensional fracturing and faulting in the uppermost part of the lithosphere and by the onset of flexural subsidence, conforming to the models of foreland basin evolution in retreating collision systems (Bradley & Kidd, 1991; Carminati et al., 2014; Crampton & Allen, 1995; DeCelles, 2012; DeCelles & Giles, 1996; Doglioni, 1995; Turcotte & Schubert, 1982). The onset of flexural subsidence is recorded by time-transgressive deposits overlying the pre-orogenic substrate. In the absence of records of the earliest syn-orogenic back-bulge depozone, the Miocene shallow-water carbonates of the central-southern Apennines represent the base of the foreland basin mega-sequence (Sabbatino et al., 2020). The vertical stacking pattern of the Apennine foreland basin conforms to the 'Waltherian sequence' of DeCelles (2012), recording the spatial-temporal evolution and migration of syn-orogenic depozones in front of the migrating orogenic fold-thrust belt. The sequence is composed of the basal subaerial forebulge unconformity at the top of the pre-orogenic passive margin megasequence, overlain by three diachronous lithostratigraphic units, which from bottom to top are as follows: (i) a shallow-water carbonate unit, (ii) a hemipelagic marly unit and (iii) a siliciclastic turbiditic unit (Figure 2) ('underfilled trinity'; Sinclair, 1997).

The syn-orogenic shallow-water carbonate unit records the sedimentation on a carbonate ramp dominated by red algae and bryozoans, with variable amounts of benthic foraminifers. This fossil assemblage is typical of a temperate-type foramol (*sensu* Lees, 1975) or foramol/rhodalgal carbonate factory (*sensu* Carannante et al., 1988). The shallow-water carbonate ramp sedimentation was not able to keep up with accelerating flexural subsidence, and it was eventually terminated by drowning below the photic zone, as recorded by the deposition of hemipelagic marls with planktonic foraminifera (Lirer et al., 2005). The switch from hemipelagic deposits to Mio-Pliocene turbiditic siliciclastics records increasing subsidence and increased proximity to the eroding fold-thrust belt to the west (Patacca & Scandone, 2007; Sgrosso, 1998) within the frame of the abovementioned evolution of an underfilled foreland basin (Sinclair, 1997). Finally, foredeep

deposits were incorporated into the accretionary wedge and overlain by unconformable sediments deposited in wedge-top basins (e.g. Ascione et al., 2012). In the regional literature of the Apennines, different names have been used for lithostratigraphic units representing the same evolutive stage in different areas. To elucidate Apennine foreland basin evolution, we group the different formations according to the abovementioned nomenclature of Sinclair (1997). Groups of formations, biostratigraphic age and related lithostratigraphic units are listed in the Table S1.

### 3 | MATERIAL AND METHODS

SIS is a well-established tool for high-resolution dating and correlation of marine carbonates (DePaolo & Ingram, 1985; Hodell, 1991; McArthur, 1994; McArthur et al., 2020; Palmer & Elderfield, 1985). This method is based on the empirical observation that the Sr-isotope ratio of the oceanic waters has varied through geological time and on the assumption that the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio at any time is homogeneous, given the long residence time of Sr in seawater compared with the ocean mixing time (McArthur et al., 2020).

A total of 61 samples, collected from the basal levels of the transgressive syn-orogenic shallow-water carbonates of the Apennines, were used for SIS. All geochemical data, details on sample preparation, analytical procedures, precision and reproducibility of the analyses, the values of the laboratory standards, and the mean values used for the SIS age determinations are reported in the Supplementary material 2, 3 and 4 of the Supporting Information. The new Sr isotope data and SIS ages produced for this paper are listed in Table 1, along with previously published data (i.e. Brandano et al., 2012, 2017; Brandano & Policicchio, 2012; Sabbatino et al., 2020).

To correct for interlaboratory bias, the Sr isotope ratios were normalized to the value of the NIST–SRM 987 standard used by McArthur et al. (2020) for their compilation. Only the Sr isotope ratios of bivalve shell material (i.e. compact lamellar and prismatic shell layers of ostreid and pectinid bivalves, respectively), which has not been affected by diagenesis (i.e. that is considered to have retained its pristine Sr isotope value) were used for SIS. The diagenetic screening process followed the multistep procedure outlined in Frijia and Parente (2008). This procedure incorporates petrographic observation of the shell microstructure, sample by sample geochemical screening based on trace element composition of the different components (well-preserved shells, altered shells and bulk matrix), and internal consistency of the Sr isotope ratios of different well-preserved shells from the same stratigraphic level. Numerical ages were derived from the Sr isotope ratios by means of the look-up table of McArthur et al. (2020; version 6:03/20). When more than one shell was available for

the same stratigraphic level, the SIS age was derived from the mean value calculated from all the shells. Minimum and maximum ages were obtained by combining the statistical uncertainty of the samples, given by 2 standard errors (2 s.e.; McArthur, 1994) of the mean value, with the uncertainty of the reference curve (see Steuber, 2003, for an explanation of the method). When fewer than four shells per level were analysed, the precision of the mean value was considered to be not better than the average precision of single measurements, given as 2 s.e. of the mean value of the standards. The numerical ages obtained from the look-up table were translated into chronostratigraphic ages by reference to the Geological Time Scale of Gradstein et al. (2020), to which the look-up table is tied. To compare the SIS ages produced for this paper with the ones provided in previous works, we have revised all the numerical ages from the Sr isotope ratios, using the new version of the look-up table of McArthur et al. (2020; version 6:03/20).

### 4 | RESULTS

The sections that we studied for this work are located along the southern and central Apennines in the following areas (Figure 1b): 1. Pollino Massif, 2. Alburno-Cervati, 3. Sorrento Peninsula, 4. Massico, 5. Aurunci, 6. Ernici, 7. Matese, 8. Carseolani and 9. Majella Mountains. (Figure 3). The geographical coordinates of each studied section are given in Table S2; Table S3 lists the samples that were selected to calculate the mean values used for the SIS age determination. We complete a transect across the whole central-southern Apennine foreland basin by considering additionally the sections of Camposauro and Marsica Mountains. We refer to Sabbatino et al. (2020) for the details on the Matese and Camposauro sections and to Brandano and Policchio (2012), Brandano et al. (2012) and Brandano et al. (2017) for the detailed descriptions of the Ernici, Carseolani and Marsica Mountains sections.

#### 4.1 | Site 1: Pollino Massif and Cilento Promontory

The study area belonging to the Pollino Massif consists of three distinct stratigraphic sections located 2–3 km far from each other (Panno Bianco, Pietra S. Angelo and Cerchiara-SS92-road) at the southern termination of the southern Apennine chain (Figure 1b). The stratigraphy of these three sections has been summarized in the Pollino section of Figure 3. In the Pollino Massif, the shallow-water carbonates of the post-forebulge unit (i.e. the Cerchiara Formation) lie unconformably (paraconformably at the scale of the outcrop; Figure 4a) above a karstified Eocene substrate, locally

**TABLE 1** Strontium-isotope stratigraphy of the base of syn-orogenic carbonate deposits in the studied localities

Formation	Section locality	$^{87}\text{Sr}/^{86}\text{Sr}$ mean <sup>a</sup>	2 se ( $\times 10^{-6}$ )	Numerical age (Ma) <sup>b</sup>			Chronostratigraphic age <sup>c</sup>
				Min	Mean	Max	
Cerchiara Fm.	Panno Bianco (Pollino Mts)	0.708389	8	20.7	20.8	21	Upper Aquitanian
Cerchiara Fm.	Pietra S. Angelo (Pollino Mts)	0.708405	22	20.2	20.6	21	Aquitanian-Burdigalian
Cerchiara Fm.	SS92 Cerchiara (Pollino Mts)	0.708427	11	20.1	20.3	20.5	Lower Burdigalian
Roccadaspide Fm.	Trentinara (Alburno-Cervati Mts)	0.708341	9	21.4	21.6	21.8	Upper Aquitanian
Roccadaspide Fm.	Trentinara (Alburno-Cervati Mts)	0.708378	8	20.8	21	21.2	Upper Aquitanian
Recommone Calcarenes Fm.	Mt. San Costanzo (Sorrento Peninsula)	0.708335	8	21.5	21.7	21.9	Upper Aquitanian
Cusano Fm.	Mt. Rosa (Camposauro Mts)	0.708706 <sup>d</sup>	11	16.3	16.6	16.7	Upper Burdigalian
Cusano Fm.	Pietraraja (Matese Mts)	0.708511 <sup>d</sup>	10	18.9	19.1	19.3	Middle Burdigalian
Cusano Fm.	Massico Mt.	0.708577	18	17.9	18.3	18.5	Middle Burdigalian
Bryozoa and Lithothamnium Limestone Fm.	Castelforte (Aurunci Mts)	0.708504	31	18.7	19.2	19.7	Middle Burdigalian
Bryozoa and Lithothamnium Limestone Fm.	Mt Lungo (Aurunci Mts)	0.708521 <sup>d</sup>				19	Middle Burdigalian
Bryozoa and Lithothamnium Limestone Fm.	Pietrasecca (Carseolani Mts)	0.708542 <sup>d</sup>	6	18.5	18.7	18.8	Middle Burdigalian
Bryozoa and Lithothamnium Limestone Fm.	Gioia dei Marsi (Marsica Mts)	0.708678 <sup>d</sup>	15	16.7	16.9	17.1	Upper Burdigalian
Lithothamnium Limestone Fm.	Guado di Coccia (Majella Mts)	0.708926	18	7.1	8.4	9.4	Upper Tortonian

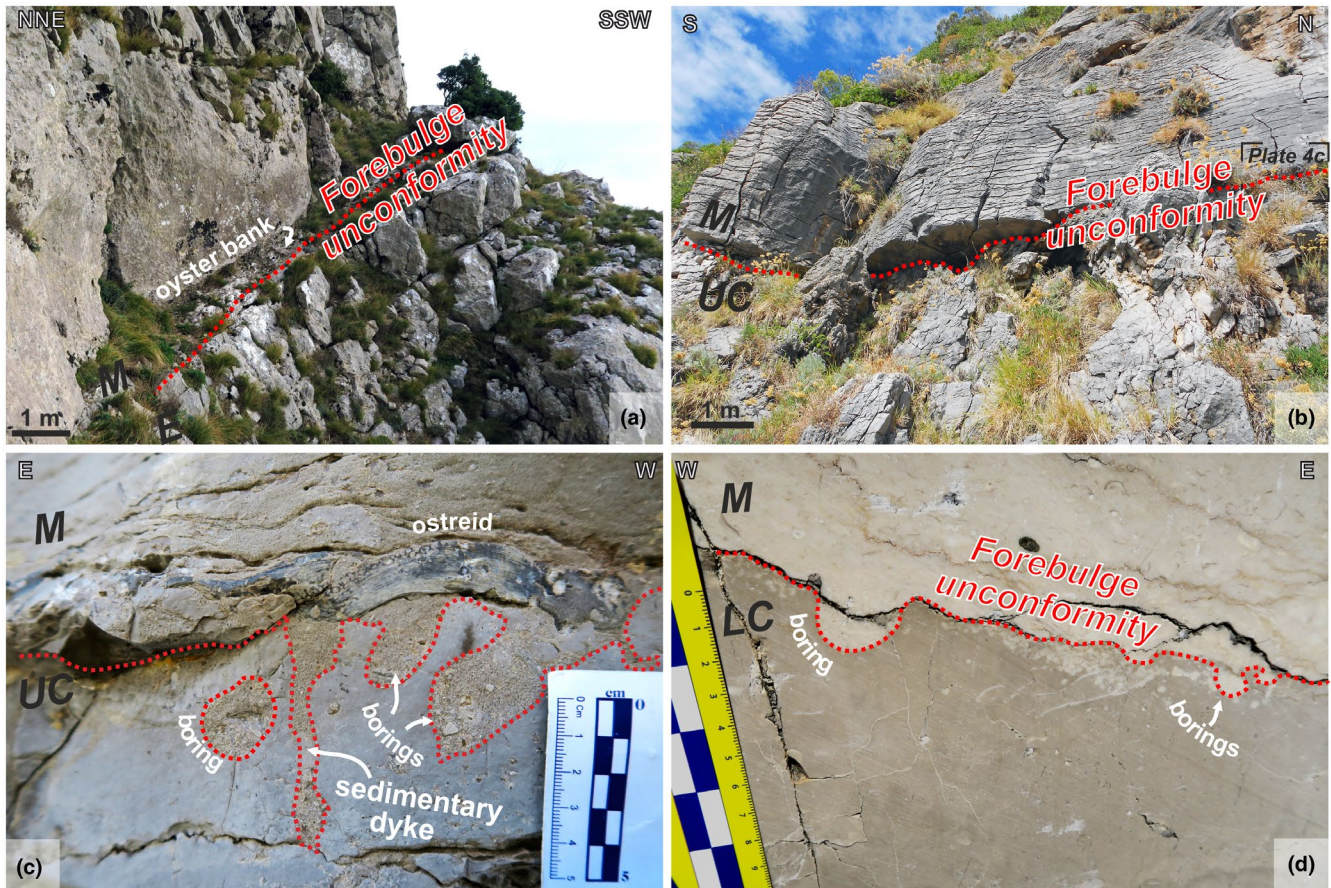
<sup>a</sup>Sr isotope ratios measured in the lab have been corrected for interlaboratory bias; see the methods section of the text for further explanations.

<sup>b</sup>The preferred numerical age has been derived from the look-up table of McArthur et al. (2020, version 6:03/20). The minimum and max age are calculated by combining the statistical uncertainty of the samples (2 SE of the mean) with the uncertainty of the reference curve (see the methods section in Frijia & Parente, 2008, for a detailed explanation of the procedure).

<sup>c</sup>The chronostratigraphy and biochronology have been derived from the numerical age using the Geological Time Scale of Gradstein et al. (2020) to which the the look-up table of McArthur et al. (2020, version 6:03/20) is calibrated.

<sup>d</sup>The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios are taken from Brandano and Pollicchio (2012), Brandano et al. (2012, 2017) and Sabbatino et al. (2020).





**FIGURE 4** Exposures of the forebulge unconformity (paraconformity at the scale of the outcrop) separating Miocene syn-orogenic deposits from the Cretaceous/Eocene pre-orogenic substrate in the central-southern Apennines. (a) Mount Panno Bianco site near Cerchiara di Calabria (Pollino Massif;  $39^{\circ}50'59''\text{N}$   $16^{\circ}22'17''\text{E}$ ): Eocene carbonate (E) covered by the Miocene shallow-water carbonate deposits (M). The sharp contact is marked by an oyster bank in life-position. (b and c) Recommona site (Sorrento Peninsula;  $40^{\circ}35'03''\text{N}$   $14^{\circ}21'54''\text{E}$ ): overview and detail of the sharp contact between the Miocene shallow-water carbonate deposits (M) and the Upper Cretaceous substrate (UC). The contact is marked by a level with ostreids in life-position and by dykes and borings filled and sealed by Miocene sediments. (d) Pietraraja site (Matese Mountains;  $41^{\circ}20'59''\text{N}$   $14^{\circ}33'09''\text{E}$ ). The Miocene shallow-water carbonate deposits (M) lie on top of Lower Cretaceous carbonates (LC). The contact is marked by a stylolite surface and borings

brecciated and with lenses of residual clays. The thickness of the shallow-water carbonate unit decreases from 20 m to less than 10 m moving from south to north/northeast. The base of the shallow-water carbonate unit is marked by an oyster bank (Figure 4a) in all the three studied sections. The facies progressively pass upwards into proximal marine to more open marine shallow-water facies (Consorti et al., 2020). Pristine shells sampled from the oyster bank were used for SIS. The mean value of the Sr isotope ratio calculated for the basal level of the shallow-water carbonate unit in the above-mentioned Panno Bianco, Pietra S. Angelo, Cerchiara SS92 road sites give the following ages: 20.8, 20.6 and 20.3 Ma (see Table 1 for the associated uncertainty bar). These numerical ages correspond to a chronostratigraphic age ranging from the upper Aquitanian to the lowermost Burdigalian. Moving towards N-NE, in the Alburno-Cervati Mountains of the Cilento promontory (Figure 1b), Miocene post-forebulge shallow-water carbonates (Rocccadaspide Formation) seal the

forebulge unconformity on top of an Eocene substrate showing evidence of subaerial exposure, including residual clays (up to 10 m of 'lateritic clays' in: Boni, 1974) (Figure 3). The base of the shallow-water carbonate unit is marked by an oyster bank, passing upwards into paralic facies evolving to more open marine calcarenites (Consorti et al., 2020). The SIS results produced for shells of the basal oyster bed sampled at this site provide a numerical age of 21.6–21 Ma, corresponding to an upper Aquitanian chronostratigraphic age. The shallow-water carbonate unit is overlain by middle Burdigalian–Langhian (18–13.5(?) Ma) calciclastic-siliciclastic deposits which are then capped by wedge-top siliciclastic deposits, latest Burdigalian – earliest Tortonian in age (17.8–8.5 Ma; see Table S1). Henceforward the ages reported with the wording '?' refer to uncertain ages, not precisely constrained by biostratigraphic markers; the GTS 2020 is used for converting from chronostratigraphic ages given in literature to numerical ages.



## 4.2 | Site 2: Sorrento Peninsula

In the Sorrento Peninsula, we have studied two outcrops: Recommone and Mount San Costanzo. These sections have been merged into the log of Figure 3 (see Table S2, for the geographic position of the sections). The post-forebulge Miocene shallow-water carbonate deposits (i.e. Recommone Calcarenites) overlie paraconformably an highly bioeroded Upper Cretaceous pre-orogenic substrate (Figure 4b,c). Evidence of subaerial exposure is here represented by paleokarstic cavities and sedimentary dykes in the Cretaceous bedrock, filled by the bioclastic Miocene calcarenite. The Miocene deposits cropping out in these sites are up to a few tens of meters thick and are representative of an open marine environment. The shallow-water carbonate unit passes gradually upwards to Serravallian (13.8(?)–11.6(?) Ma) sandstones, which are then capped by wedge-top siliciclastic deposits late Tortonian in age (8.2–7.4 Ma; see Table S1).

The shells sampled from the basal oyster level at the Mount San Costanzo site give a numerical age of 21.7 Ma (late Aquitanian) (Table 1). The material sampled at Recommone site showed important signs of diagenetic alteration and was not used for calculating a SIS age (see Table S2).

## 4.3 | Site 3: Massico, Aurunci and Ernici Mountains

At Mount Massico site, the post-forebulge shallow-water carbonate unit (i.e. Bryozoan and Lithothamnium Limestone; Table S1), crops out on top of locally brecciated Upper Cretaceous carbonates (Figure 3). It is made of about 50 meters of carbonate ramp facies, consisting mainly of bryozoan and rhodolith rudstone-floatstone with shells and fragments of bivalves, balanids, echinoid fragments and spines, benthic foraminifers, and rare planktic foraminifers. The age obtained by SIS for the basal levels of the shallow-water carbonate unit in the Massico site is 18.2 Ma, corresponding to the middle Burdigalian. In the Castelforte section (Aurunci Mountains), Miocene deposits of the post-forebulge carbonates overlie Eocene carbonates (Figure 3). The basal facies correspond to a middle ramp environment. The Sr-isotope value obtained by analysing bivalve shell fragments from basal levels of the formation provides a numerical age of 19.2 Ma, which corresponds to the middle Burdigalian. About 17 km north of Castelforte, in the Cassino plain, the Mount Lungo section (Ernici Mountains) exposes 60 m of shallow-water carbonate rocks resting on top of Upper Cretaceous limestones (Figure 3) (Brandano & Policchio, 2012; Damiani et al., 1992). The basal facies are representative of an inner ramp environment and grade upwards to middle and outer ramp facies (Brandano & Policchio, 2012). A numerical

age of 19 Ma was calculated using the Sr-isotope value given by Brandano and Policchio (2012) for the base of these deposits.

In all these sites, the ramp carbonate facies pass upwards to Serravallian-Tortonian hemipelagic deposits evolving in turn to siliciclastic turbidites (13.9–7.5 Ma; see Table S1). Uppermost Tortonian to lower Messinian (7.9–6 Ma) wedge-top siliciclastic deposits cap the foredeep sequence (see Table S1).

## 4.4 | Site 4: Matese and Camposauro Mountains

Sixty km east of Massico site, in the Matese and Camposauro Mountains sites (Figures 1b and 3), the shallow-water carbonate unit is the first syn-orogenic deposit unconformably overlying the top of the Cretaceous substrate, which ranges in age from the Early Cretaceous to the Late Cretaceous. The contact between pre-orogenic and syn-orogenic rocks is marked by a stylolitic surface, borings and sedimentary dykes filled by the syn-orogenic deposits (Figure 4d). The Miocene deposits are representative of open marine facies deposited in middle ramp environments. Recently, Sabbatino et al. (2020) reported Sr-isotope values corresponding to a SIS numerical age of 16.3 and 19.1 Ma (middle Burdigalian) for the base of the shallow-water carbonates at Camposauro and Matese sites, respectively. The authors interpret the diachrony between the base of the shallow-water carbonate unit in these two sites as related to a locally complex paleotopography, with horst and graben extensional structures inherited by previous tectonic events and subsequently active again during the forebulge stage.

In both the Matese and Camposauro Mountain areas, the shallow-water carbonate unit passes upwards to the Serravallian – lower Tortonian (13.2–10.5 Ma) hemipelagic marly unit and then to lower-middle Tortonian (10.5–8.2 Ma) siliciclastic turbiditic unit (see Table S1). The foredeep siliciclastic deposits are topped by upper Tortonian–lower Messinian (8.2–6.5 Ma) wedge-top deposits (see Table S1).

## 4.5 | Site 5: Marsica and Carseolani Mountains

In the Marsica Mountains (Figure 1b), up to 70–80 m of Miocene post-forebulge shallow-water carbonate units are exposed. The basal facies are attributed to middle ramp environments and dated as 16.9 Ma (upper Burdigalian) by Brandano et al. (2012). In the area of the Carseolani Mountains (Figures 1b and 3), at the Pietrasecca site, up to 100 m of shallow-water carbonate rocks cover paraconformably an Upper Cretaceous substrate (Brandano et al., 2017).

The post-forebulge shallow-water carbonate unit in this site comprises three main facies types that can be ascribed to an outer ramp environment (Brandano et al., 2017). The SIS numerical age calculated from the Sr-isotope value given by Brandano et al. (2017) is 18.7 Ma, corresponding to the middle Burdigalian (Table 1). In both these sites, the shallow-water carbonate unit passes upwards to Serravallian – lower Messinian hemipelagic (13.9–6.8 Ma) marly deposits and then to Tortonian – Messinian (10.7–5.5 Ma) siliciclastic turbiditic deposits. The latter are topped by upper Messinian – lower Pliocene (6–5.1 Ma) wedge-top siliciclastic deposits (see Table S1).

#### 4.6 | Site 6: South Majella Mountains

In the studied site at South Majella Mountains (Figures 1b and 3), the first syn-orogenic carbonates (i.e. Lithothamnium Limestone; Table S1) cover unconformably uppermost Cretaceous pre-orogenic carbonates. The unconformity surface is marked by nondepositional and/or erosional features, and locally, it is intensely bioeroded (Danese, 1999). In the section of Capo di Fiume, about 4 km east of Guado di Coccia, syn-orogenic shallow-water carbonates overlie paleosols that lie in turn on an Upper Cretaceous substrate. The basal facies of the shallow-water carbonate unit at the Guado di Coccia site consist of a few meters of bioclastic calcarenites, rich in red algae and corals, representative of an open marine environment, passing upwards into deposits of a coastal-transitional marine environment with an evolution from wetland to estuarine conditions at the Capo di Fiume site (Carnevale et al., 2011; Danese, 1999). The  $^{87}\text{Sr}/^{86}\text{Sr}$  mean value of pectinid and ostreid shells collected from basal levels of the syn-orogenic sequence gives a numerical age of 8.4 Ma, which corresponds to the late Tortonian (Table 1). The shallow-water carbonates pass upwards into Messinian (6.4–5.6 Ma) hemipelagic deposits and then to evaporite levels (Gessoso-Solfifera Formation; Danese, 1999). The latter are topped by lower Pliocene (5.3–3.9 Ma) siliciclastic turbiditic deposits and then by middle-upper Pliocene (3.6–2.1 Ma) wedge-top siliciclastic deposits (see Table S1).

## 5 | DISCUSSION

The discussion is organized in two subsections. In the first one, we summarize our findings in terms of age and characters of the base of the syn-orogenic sequence in different areas (Figures 5 and 6a). In the second subsection, we compare the time-transgressive age of the carbonates deposited in the distal foredeep with the age of the onset of siliciclastic sedimentation in foredeep and wedge-top depozones.

Then, all these ages are plotted in their pre-orogenic positions, to discuss mode and rate of the flexural wave migration (Figure 6b,c).

### 5.1 | Dating the base of the syn-orogenic megasequence in the southern-central Apennines

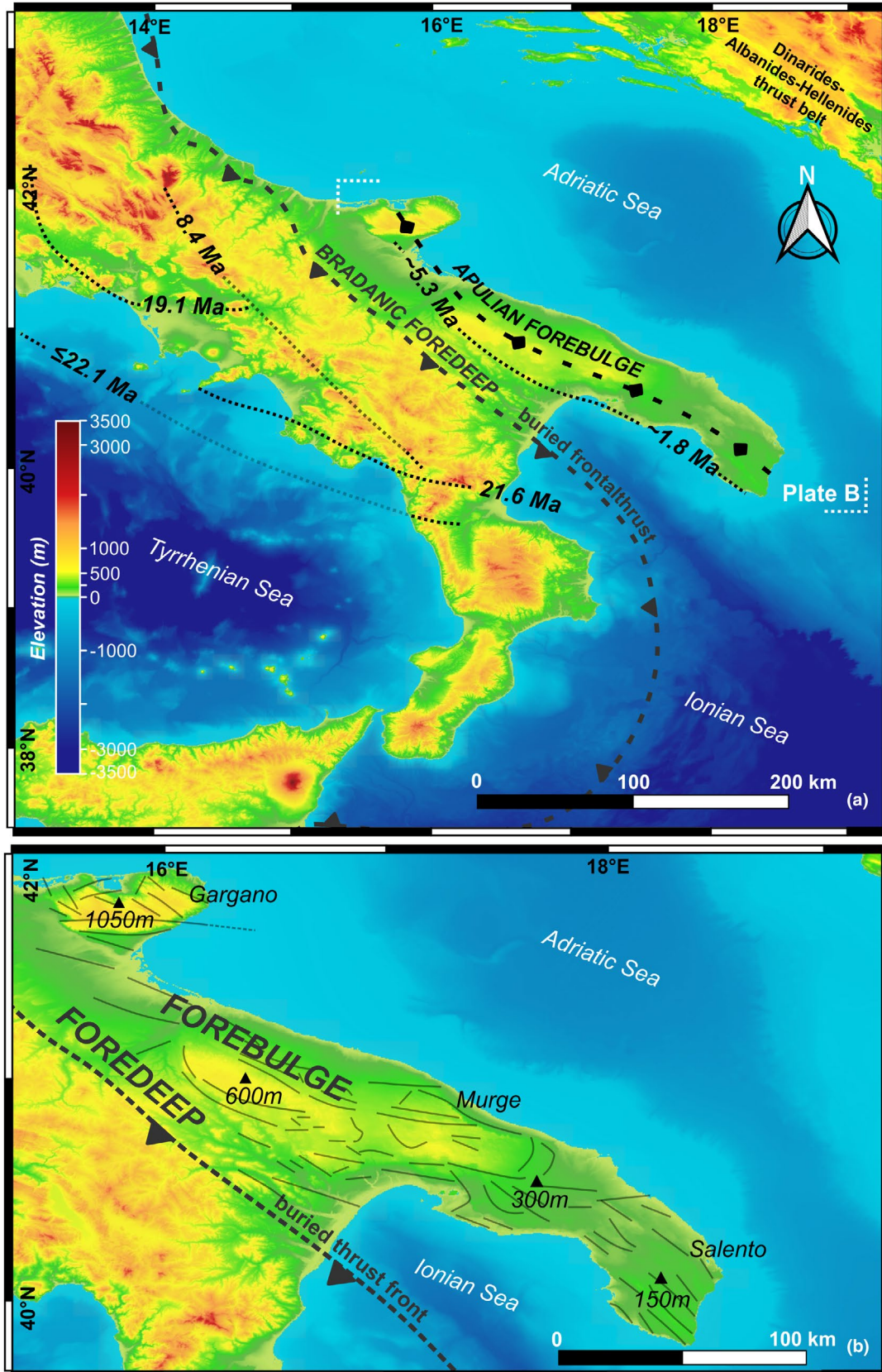
Each subsection provides a detailed discussion for individual study sites. In addition, we complete the picture of the Apennine foreland basin depozones by a brief description of the first syn-orogenic deposits in the innermost sectors of the Apennine foreland and in the external sectors of the Apulian foreland domain that are exposed at Mount Alpi and in the present-day Apulian foreland (Figures 1 and 5).

#### 5.1.1 | Lungro-Verbicaro and Zannone Island

In the Lungro-Verbicaro site (Figure 1b), middle Eocene to Aquitanian calcareous breccias, with platform-derived limestone clasts, alternating with marls and shales (i.e. the Colle Trodo Formation; Iannace et al., 2007) lie transgressively on a Maastrichtian-Paleocene paleosubstrate and grade upwards to siliciclastic deposits of Aquitanian age (i.e. Scisti del Fiume Lao Formation; D'Errico & Di Stasio, 2010; Table S1). These Aquitanian deposits are substantially coeval with the Flysch unit of the Zannone Island, located W of Mount Massico (Figure 1b), which have been recently interpreted as the oldest foredeep depozone of the central Apennines by Curzi et al. (2020). The authors constrained the age of those deposits as spanning from late Oligocene to early Aquitanian (not younger than  $22.1 \pm 0.6$  Ma) by K-Ar dating of fault gouge clay related to the end of thrusting leading the Mesozoic carbonate rocks onto the turbidites. We infer that both the deposits of the Lungro-Verbicaro area and of Zannone Island were part of the same innermost and oldest foredeep depozone (Figure 5a).

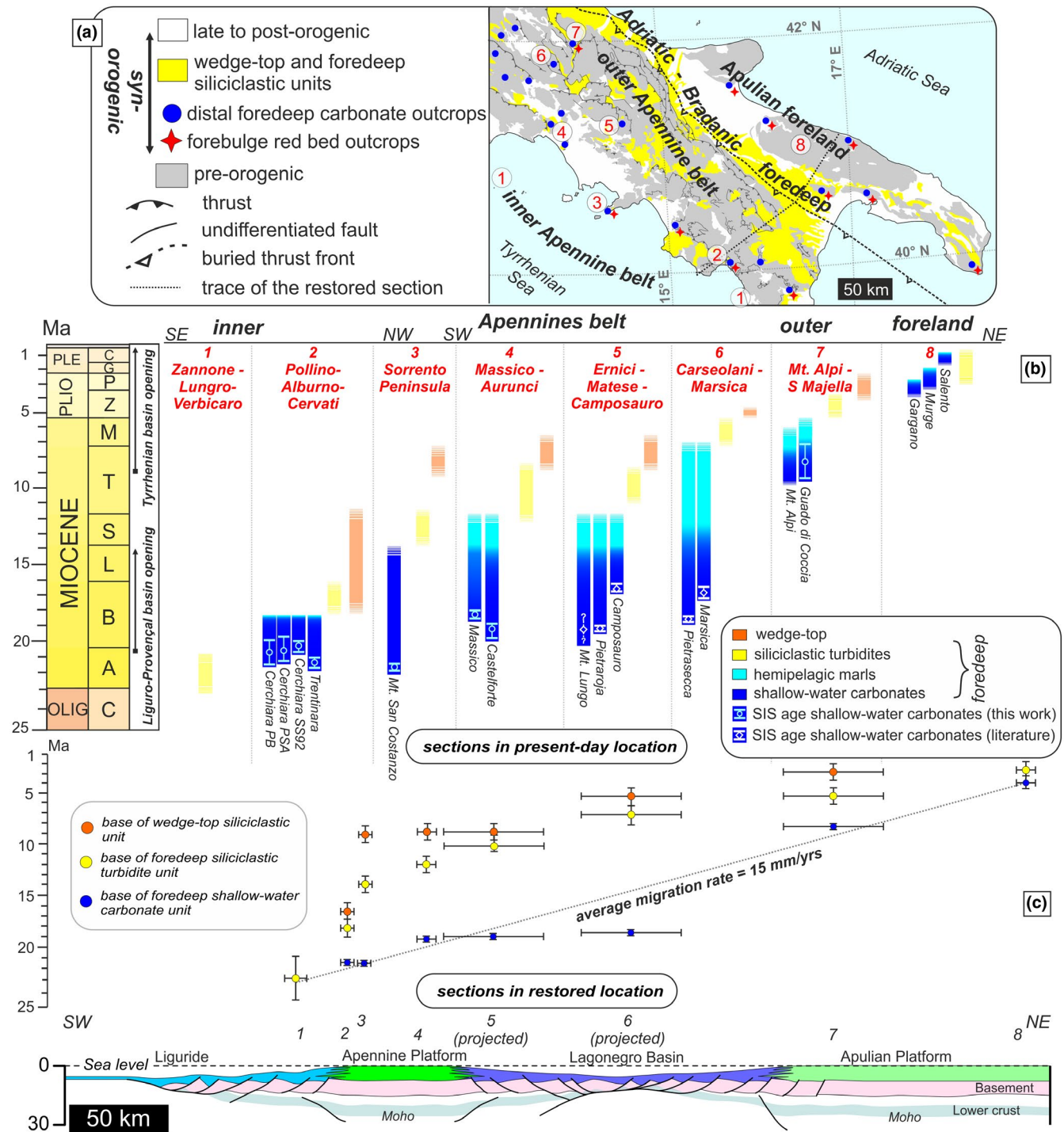
#### 5.1.2 | Pollino Massif and of the Cilento Promontory

In these areas, the forebulge stage is represented by continental red beds and breccia-conglomerate levels that overlie the pre-orogenic Eocene substrate (Figure 6a). Forebulge driven subaerial exposure is evidenced by paleokarstic cavities present within the topmost strata of the pre-orogenic rocks, along with sedimentary dykes filled and sealed by meteoric cements and continental to marine sediments belonging to the overlying deposits. The overlying carbonate rocks had been dated only by biostratigraphy (Carannante, Matarazzo,



**FIGURE 5** (a) Isochrones of the base of the foredeep depocenters. (b) Modern Apulian foreland. The mapped faults are taken from Doglioni et al. (1994) and Pieri et al. (1997). Bathymetry and land elevation outside Italy were obtained from GEBCO Bathymetric Compilation Group (2020) Grid (doi: 10/dtg3) with a spatial resolution of 15 arc seconds. Land elevation for Italy territory was downloaded from the Institute for Environmental Protection and Research of Italy (ISPRA, 2021) website (<http://www.sinanet.isprambiente.it/it/sia-ispra/download-mais/dem20/view>).





**FIGURE 6** (a) Simplified geological map of the central-southern Apennines summarizing the syn-orogenic deposits in the different sites of the fold-thrust belt and foreland. (b) Time framework for the evolution of the central-southern Apennine foreland basin. The ages of the first syn-orogenic deposits are constrained by high-resolution strontium-isotope stratigraphy (this work). The ages of the other lithostratigraphic units are constrained by biostratigraphy (taken from the literature). (c) Ages of the base of the syn-orogenic lithostratigraphic units plotted on a restored section of the pre-orogenic Adria passive margin (modified after Tavani et al., 2021).

et al., 1988; Selli, 1957). In detail, the occurrence of *Miogypsina socini* and *M. globulina*, markers of the shallow benthic zones (SBZ) 24 and 25 (Cahuzac & Poignant, 1997), provided an age ranging from the early Aquitanian to the end of the Burdigalian. The limitations of these biostratigraphic

data are twofold: (a) the SBZ zonal scheme has a resolution of 2–4 Ma for the early Miocene and (b) miogypsinids are rare in these formations and they are not present in the basal levels, so that the age of a single level with miogypsinids is generally extended to the whole section. Our SIS ages

of 20.8, 20.6, 20.3, 21.6, and 21 Ma, for the base of the shallow-water carbonate unit in different sites (i.e. Cerchiara Panno Bianco, Pietra Sant'Angelo, and SS92, and two sites at Trentinara; Table 1) (Figure 5a), are compatible with the biostratigraphic data, but they allow a much higher time resolution. The slightly variable ages of such deposits can be attributed to a complex paleotopography affecting the foreland through horst and graben structures before the onset of syn-orogenic sedimentation, as documented in other sites of the central-southern Apennines and in the present Apulian foreland (Figure 5b and Section 5.1.6) (e.g. Billi & Salvini, 2003; Doglioni et al., 1994; Sabbatino et al., 2020). Such inherited paleotopography has also influenced the depositional environment and thickness of the shallow-water carbonate units in the different studied sites.

The age of the base of the siliciclastic foredeep deposits overlying the basal carbonate unit in the Pollino Massif and Cilento Promontory (Figures 1 and 3) falls in the Burdigalian (20–17.5 Ma; Table S1).

### 5.1.3 | Sorrento Peninsula

In this area, forebulge emersion is evidenced by a sharp unconformity surface, sedimentary dykes and paleokarstic cavities on top of the Upper Cretaceous substrate, filled and sealed by very thin continental deposits and open-marine carbonates (Figures 4b,c and 6a). The post-forebulge shallow-water carbonate unit was previously attributed to the Burdigalian-Langhian, based on the occurrence of miogypsinids (De Blasio et al., 1981). Our SIS results on the basal shallow-water carbonate unit at Mount San Costanzo site constrain the age of the base of this formation at 21.7 Ma (late Aquitanian) (Figure 5a; Table 1). The age of the first siliciclastic deposits is considered not older than Serravallian (13.8–11.6(?) Ma; Table S1).

### 5.1.4 | Massico, Aurunci, Ernici, Matese, Camposauro, Marsica and Carseolani Mountains

In this large area, which extends from the northern termination of the southern Apennines to the central Apennines, the base of the syn-orogenic deposition overlying the pre-orogenic Cretaceous carbonates of the Apennine Carbonate Platform varies from 18.3, 19.2, 19, 19.1, 16.6, 18.7 and 16.9 Ma (i.e. middle to late Burdigalian) in the sites of Massico, Aurunci (Castelforte site), Ernici (Mount Lungo site), Matese (Pietraraja site), Camposauro, Carseolani (Pietrasecca site) and Marsica Mountains, respectively (Figures 1, 3 and 5a; Table 1). The basal facies are also variable from inner to outer ramp. The Miocene shallow-water carbonates evolve upwards to hemipelagic marls and then to

siliciclastic turbidites, which testify the acceleration of the flexural subsidence (Carminati et al., 2007). The age of the base of siliciclastics varies from the middle Tortonian to the Messinian (10.5–5.5 Ma; Table S1).

### 5.1.5 | South Majella and Mount Alpi

In the South Majella Mountains, the transgressive shallow-water carbonate unit covers a strongly bioeroded pre-orogenic Maastrichtian limestone substrate of the Apulian Carbonate Platform (e.g. Danese, 1999). Our SIS age for the basal levels of the syn-orogenic sequence at the Guado di Coccia site (Figures 1, 3 and 5a) is 8.4 Ma, which corresponds to the late Tortonian. An uppermost Tortonian-Messinian age was reported by Danese (1999), based on the presence of the nanofossil *Amaurolithus* sp. in the matrix of the basal bioclastic calcarenites levels. The SIS age is compatible with the biostratigraphic age if we consider the error band (7.1–9.4 Ma; Table 1). Moreover, the slight mismatch could be due to infiltration of a slightly younger matrix with nannoplankton into the biocalcarene, for instance, from the overlying marly deposits. The shallow-water carbonate unit evolves upwards to hemipelagic marls during the Messinian (6.4–5.6 Ma; Table S1). The onset of the siliciclastic sedimentation is here dated as early Pliocene (5.3–3.9 Ma; Table S1).

Mount Alpi exposes an inner sector of the Apulian platform exhumed from underneath its tectonic cover of allochthonous Lagonegrese and Liguride Units in the axial zone of the Apennine fold-thrust belt (Figure 1) (Mazzoli et al., 2006). In this site, syn-orogenic carbonate deposits overlie paraconformably pre-orogenic Lower Cretaceous carbonates (La Bruna et al., 2018; Vezzani et al., 2010). The age of the syn-orogenic deposits is constrained by the presence of *Turborotalia multiloba* and *Amaurolithus primus*, planktic and nanofossil assemblages, respectively, pointing to a latest Tortonian - early Messinian age (9–6.4 Ma; Table S1; Bonardi et al., 2016; Taddei & Siano, 1992). The shallow-water carbonate deposits evolve to hemipelagic marls, which are overlaid by siliciclastic deposits. The age of the latter, albeit not well constrained, is considered not older than late Messinian (<6.4–6(?) Ma; Table S1).

### 5.1.6 | Apulian foreland

The first syn-orogenic shallow-water carbonate rocks of the current Apulian Foreland onlap Upper Cretaceous pre-orogenic carbonates in the three isolated structural domains of Gargano, Murge and Salento (Figures 1 and 5a) (Tropeano & Sabato, 2000). In response to the foreland flexural subsidence, these domains were progressively drowned (Iannone & Pieri, 1983), and the Murge and Salento domains became

archipelagos (see figure 2 in Pomar & Tropeano, 2001). The base of the syn-orogenic carbonate unit is attributed to the middle-late Pliocene in the NW sectors of the Apulia region (i.e. Gargano; Figure 5a), due to the occurrence of *Globigerinoides obliquus extremus*, *Globigerina pachyderma*, *Globorotalia crassaformis* and *G. hirsuta aemiliana*, included within the *Globorotalia margaritae* planktic zone (Moretti et al., 2011). Moving from NW to SE, towards the Murge and Salento areas, the same formation is dated progressively younger, until Calabrian (3.7–0.8 Ma) (Figure 5a), due to the presence of *Arctica islandica*, *Hyalinea baltica* and *Globorotalia truncatulinoides* (Ricchetti & Ciaranfi, 2009). The onset of the siliciclastic deposition into the foredeep, which represents the current Adriatic-Bradanic Foredeep (Casnedi, 1988), spans from Pliocene to Holocene (5.3–0.1 Ma; Table S1).

The Apulian foreland is of particular interest since it represents the best modern analogue of the Miocene paleotopography of the Apennines foreland region, strongly affected by inherited structures and newly forming foreland faults and fractures (e.g. La Bruna et al., 2018; Sabbatino et al., 2020). The modern Apulian foreland is characterized by strong variability in altitude between different locations (0 m to 1,050 m) with a forebulge that is ca. 100 km wide and 300 m high (Figure 5b). Complex and tectonically controlled topography (Figure 5b) (e.g. Doglioni et al., 1994; Pieri et al., 1997; Billi & Salvini, 2003) has influenced the deposition of the Plio-Pleistocene foredeep depocenter as well (e.g. Pomar & Tropeano, 2001).

## 5.2 | The flexural wave migration of the Apennine forebulge-foredeep

In Figure 6, we integrate our new high-resolution data set delineating the age of the earliest foreland basin deposits with the previous knowledge of the central-southern Apennine foreland basin. Figure 6b shows the age and location of distinct lithostratigraphic units grouped using the underfilled foreland basin nomenclature of Sinclair (1997), that is, (i) basal shallow-water carbonate unit, (ii) hemipelagic marl unit, and (iii) siliciclastic turbiditic unit and (iv) wedge-top sediments. In Figure 6c, these ages are plotted on a restored section of the Adria passive margin. For the sites located far away from the section (i.e. 3 to 7), the position has been projected based on the structural position within the fold-thrust belt. This solution entails a significant but poorly constrained error for sites 3 to 7, which has been arbitrarily taken as 33% of the distance from the section. In addition to this error, the uncertainty on the age due to the poor biostratigraphic resolution (affecting the age of the base of the turbidites) has been taken into account. Despite all these issues, our reconstruction suggests that the average migration velocity of

the flexural wave, as constrained by the age of the base of the post-forebulge shallow-water carbonate unit, was almost constant in the last 25 Myr at nearly 15 mm/year. This linear regression fits the entire dataset, with the exception of point 6, which is positioned more than 200 km away from the section trace, thus representing the less constrained part of the restored section.

### 5.2.1 | Dating the forebulge emersion interval

Constraining directly the timing of forebulge migration would entail dating forebulge deposits, which is very challenging or even impossible in many cases, due to their absence. Accordingly, it is only possible to bracket the onset of the forebulge unconformity development, constrained by the youngest strata underlying the unconformity and the first Miocene shallow-water carbonates above the unconformity. This approach does not take into account the amount of erosion of the pre-orogenic substrate and introduces a great uncertainty, especially where the Miocene carbonate rocks sit directly on Cretaceous substratum. However, in several localities of the central-southern Apennines, Eocene strata are found beneath the unconformity, so it can be safely assumed that the onset of forebulge arching post-dates the Eocene. In such cases the time span of passage of the forebulge would include all of the Oligocene plus the very earliest million or two million years of the Miocene (the SIS ages indicate max Miocene ages of 21.7 Ma, suggesting an age span of ca. 10–13 Myr). The time span recorded by the forebulge unconformity can provide geodynamic information, because it records the time it took for the forebulge to pass a given location, which is related to its width and thus to the rheology of the foreland plate (Flemings & Jordan, 1990). Assuming an elastic plate thickness of 20 km and a flexural rigidity of ca.  $6 \times 10^{22}$  N m (Royden et al., 1987; Turcotte & Schubert, 2006), the Apennines produce a forebulge roughly 100–150 km wide and a few tens to a few hundred meters high. Dividing the width of the forebulge by the age span of the unconformity, provides a flexural wave velocity of ca. 7.5–15 mm/year, fitting with the results presented above.

### 5.2.2 | Onset of siliciclastic sedimentation versus flexuring

Figure 6c illustrates the poorly organized trend of the base of the siliciclastic deposits in the foredeep and wedge top depozones that have been considered indicative of the style and rate of foreland basin migration in the Apennines (e.g. Critelli et al., 2011; Patacca & Scandone, 2007; Vezzani et al., 2010; Vitale & Ciarcià, 2013). These deposits show an E-ward younging progression, similar to the age of the base



of the syn-orogenic post-forebulge shallow-water carbonate unit, but significantly deviating from its linear trend. These differences are due to the fact that siliciclastic sediments do not represent the first phase of syn-orogenic sedimentation in the foreland, but rather the first siliciclastic input to the system. The latter is not necessarily related to the flexure itself (e.g. DeCelles, 2012) and it is subject to many different controls, including sediment routing. In particular, a few to several million years of geological history of a fold-thrust belt could be missed using the first arrival of siliciclastic sediments, since the siliciclastic rocks represent neither the base of the foredeep depozone nor the onset of syn-orogenic sedimentation. In underfilled basins such as the Apennine foredeep, the arrival of siliciclastic sediments into the foredeep depozones is driven by the rates of erosion and propagation of turbidite lobes longitudinally from the Apennine front or axially from far away sources (e.g. the Alps for the northern Apennines foredeep; Ricci Lucchi, 1986), and this can occur several million years after the onset of orogeny.

### 5.2.3 | Base of the post-forebulge carbonates as a proxy for the flexural wave

The earliest onset of syn-orogenic sedimentation occurs within the back-bulge depozone and subsequently within the forebulge depozone following a “flexural wave” pattern. In retreating collisional belts like the Apennines, in the absence of a dynamic load, the forebulge and back-bulge depozones are generally poorly preserved or completely absent (DeCelles, 2012). In the central-southern Apennines, the back-bulge is, indeed, not preserved, and a few meters of forebulge depozone are recorded in only a few sectors of the Apennine fold-thrust belt (Figure 6a). Our computation of the bulge migration velocity, based on elastic parameters and on the age of forebulge unconformity (Section 5.2.1), indicates a wave velocity of 7.5 to 15 mm/year. This value is in agreement with the migration rate of the distal foredeep depozone, calculated from the age of first post-forebulge carbonates, which represents to date the most reliable constraint on the velocity of flexural wave migration.

Shallow-water carbonates of the distal foredeep have already been successfully used in many other orogenic belts to derive a detailed record of the first phases of foreland basin evolution (Bosence, 2005; Dorobek, 1995; Galewsky, 1998). In this framework, here we have shown that central-southern Apennines offer a good example of ramp profiles on the foreland margin, characterized by backstepping geometries in front of positive and underfilled accommodation zones (Figure 2) (Catuneanu et al., 2011; Sinclair, 1997). Such carbonate platform dynamics are particularly suitable to constrain the diachronous migration of an entire orogenic system, as demonstrated worldwide also

for many other orogenic systems such as the Alps (Allen et al., 1991; Sinclair, 1997), Pyrenees (Vergés et al., 1998), Taiwan (Yu & Chou, 2001), Timor Trough (Veevers et al., 1978), Papuan Basin (Galewsky et al., 1996) and Zagros (Pirouz et al., 2017).

## 6 | CONCLUSION

In this work, we have provided a new high-resolution regional SIS dataset for the base of the time-transgressive shallow-water carbonate unit at the bottom of the foreland basinal megasequence sealing the forebulge unconformity in the central-southern Apennines. Integration with previously published data on syn-orogenic sediments of the area demonstrates that, among the different lithostratigraphic units of the foreland megasequence, dating the base of post-forebulge carbonate deposition is the best tool to constrain the shape and migration rate of the foreland basin. Our newly presented dataset allowed us to constrain, with unprecedented resolution, the migration rate of the foreland system, which was nearly constantly 15 mm/year in the last 25 Myr interval.

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## CONFLICT OF INTEREST

The authors declared no conflict of interest.

## AUTHOR CONTRIBUTIONS

Conceptualization, M.S., S.T., S.V., K.O., A. Co. and M.P.; methodology, M.S. and M.P.; field investigation and data

acquisition M.S., A. Co. and L.C.; laboratory analysis M.S., I.A. and A. Ci.; writing – original draft preparation, M.S., S.T. and M.P.; writing – review and editing, M.S., S.T., S.V., K.O., A. Co., L.C., I.A., A. Ci. and M.P.; project coordinator, M.P.









## PEER REVIEW

The peer review history for this article is available at <https://publons.com/publon/10.1111/bre.12587>.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supplementary material of this article.

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### SUPPORTING INFORMATION

Additional Supporting Information may be found online in the Supporting Information section.

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