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Space/time tectono-sedimentary evolution of the Umbria-Romagna-Marche Miocene Basin (Northern Apennines, Italy): a foredeep model

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Abstract The space/time evolution of the Umbria-Romagna-Marche domains of the northern Apennine Miocene foredeep is proposed. In this period, the turbidite siliciclastic sedimentation is represented mainly by the Miocene Marnoso-Arenacea Formation, which generally ends with mainly marly deposits. From the internal Apennine sectors (Umbria-Romagna domain) to the external Adriatic Margin (Marche domain) the siliciclastic succession overlies hemipelagic marly deposits (Schlier Formation). The whole depositional area can be considered as a single wide basin with depocenter or main sedimentation areas progressively migrating eastwards. This basin is characterized by some morphological highs which did not constitute real dams for the sedimentary flows (turbidity currents). Multiple feeding (arkose, litharenites, calcarenites) from different sources is related to palaeogeographical and palaeotectonic reorganization of the most internal, previously deformed, Apennine areas. The activation of the foredeep stage is marked by the beginning of the siliciclastic sedimentation (Late Burdigalian in the most internal sector). This sedimentation ends in the most external sector in the Early Messinian, pointing to a depositional cycle of about 9–10 Ma. The diachronism of the base of the siliciclastic deposition proves to be almost 5 Ma. The syn-depositional compressional deformation, which shows a marked diachronism, affected the internal area of the foredeep in the Early-Middle Serravallian, and progressively migrated up to Late Miocene, involving more and more external sectors. The deformed siliciclastic sedimentary wedge constitutes an orogenic pile incorporated in the Apennine Chain, represented by different tectonic elements superimposed by means of NE-vergent thrusts. The main stratigraphic and tectonic events of the Toscana-Romagna-Marche Apennines are presented in a general framework, resulting also in a terminological revision.

Keywords Apennine orogen · Foreland basin · Fold-and-thrust belt · Stratigraphy · Tectonics · Marnoso-Arenacea Fm

1 Introduction

The Umbria-Romagna-Marche Apennines (Fig. 1) represent a thrust-and-fold belt forming an arc bounded eastwards by the Sibillini thrust and its northward extension. The chain is typified by faulted E-vergent asymmetric anticlines affecting the Mesozoic-Tertiary sedimentary succession. These anticlines are separated by narrower, often markedly asymmetric, synclines. The Umbria-Romagna-Marche Apennines have been traditionally considered to be a thin-skinned chain (Bally et al. 1988, and references therein), but more recently a deformation involving the Hercynian basement has been pointed out (Lavecchia et al. 1994; Barchi et al. 1998; Coward et al. 1999; Mazzoli et al. 2001, 2005).

The Umbria-Romagna-Marche Apennines are characterized by a sedimentary succession deposited over a

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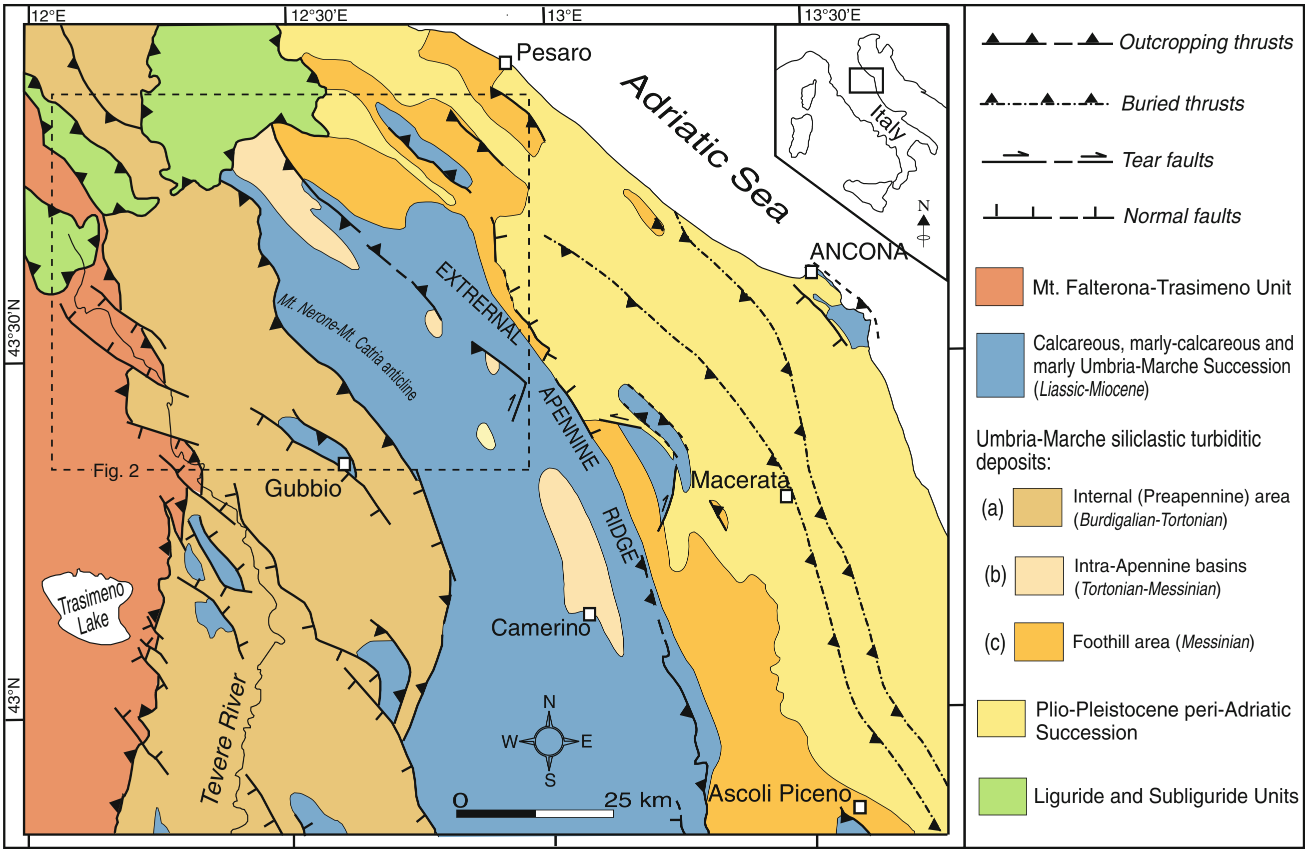

Fig. 1 Geological scheme of the Umbria-Romagna-Marche Apennines and surrounding areas, showing the area studied in detail (see Fig. 2)

Hercynian continental crust (Adriatic Microplate), representing a portion of the northern margin of the African Plate.

The Alpine geological history of the study area started about 200 Ma ago, when an old continent characterized by prevailing metamorphic rocks of the previous Hercynic orogenic cycle was affected by marked extensional tectonics. This phase caused a progressive rifting, by which the evolution in the Toscana and Umbria-Romagna-Marche domains led to the individuation and the successive formation of the passive margin, characterizing the southern part of the Tethys (Adriatic Margin) in the Early Jurassic (e.g. Mazzoli and Helman 1994; Turco et al. 2012, and references therein). This passive margin developed through a progressive transition from a continental environment to a shallow water environment (evaporitic-carbonate platform) and successively to pelagic environments. In this area the so-called Umbria-Romagna-Marche succession was deposited from the Jurassic to Miocene.

The lower portion of mainly carbonate succession, was deposited during the extensional tectonics linked to the opening and evolution of the Tethys Ocean (Channell et al. 1979). The main Jurassic tectonic phases of the study area are related to normal faulting which controlled the development of the passive margin succession. The Jurassic sedimentation is mainly continuous but shows marked lateral variations related to differences in depositional environments controlled by the extensional tectonics (horst and graben). During the Early Cretaceous the depositional area reached its largest size, as testified by the maximum lateral continuity of lithofacies, due to a generalized subsidence. Cretaceous basin carbonate sedimentation records pulses of accelerated subsidence (Marchegiani et al. 1999) that could also be related to the Late Cretaceous extensional tectonics recorded in the carbonate platform domains (e.g. Shiner et al. 2004). The carbonate sedimentation continued up to the earliest Miocene with a progressive increase of fine clastic material, resulting in the prevalence of marly lithofacies. Early Miocene sedimentation is marked by the occurrence of volcanogenic deposits representing a regional event observed in several chains of the central-western Mediterranean (e.g. Guerrera and Veneri 1989; Balogh et al. 1993; Guerrera et al. 1998; de Capoa et al. 2002; Savelli 2007).

The successive Miocene sedimentation is characterized by highly diffuse siliciclastic deposits showing evident diachronism proceeding towards the external Adriatic zones. The start of the main compressional tectonic phase is denoted by the deposition of the Marnoso-Arenacea Fm (Miocene). Subsequently, the deformation migrates progressively towards the Adriatic Foreland to culminate in the building of the chain during Messinian-Pliocene times.

The sedimentation rate in the Umbria-Romagna-Marche succession is highly variable. This variability is revealed by the comparison between the Early Jurassic-Early Miocene calcareous-marly group (medium thickness about 2,500–3,000 m), which characterizes the lower part of the succession deposited in ca.180–190 Ma, and the Miocene *p.p.* siliciclastic deposits (average thickness 3,000 m) deposited in only about 9–10 Ma (the entire diachronous clastic wedge). In fact, the siliciclastic deposition reflects a great palaeogeographical and palaeotectonic change, with the onset of sedimentary processes controlled directly by the evolution of the Apennine Chain and the migration of its foredeep system.

2 Aim

The aim of this paper is to reconstruct and redefine the space/time evolution of the northern Apennine foredeep corresponding to the Umbria-Romagna-Marche domain. In particular the paper focuses on verifying the relationships between the Umbria-Romagna sector and the Marche sector, where a "Marnoso-Arenacea Romagnola" Fm (MAR) and a "Marnoso-Arenacea Marchigiana" Fm (MAM) are recognized, respectively (cfr. Geological sheets of southern Romagna, Umbria and northern Marche; CARG Project-Ispra, Roma, www.isprambiente.gov.it).

The study has been carried out by analyzing the main transversal tectono-stratigraphic features of different recognized tectonic elements (Fig. 2). A stratigraphic redefinition of the most representative columns of these different tectonic elements, based mostly on physical stratigraphy (i.e. horizons correlation, and in particular marker beds) has been done. Some new biostratigraphical controls have been made in order to complete and more clearly define the ages cited in the literature. These data have helped to establish correlations between the stratigraphic columns from the different tectonic elements and to reconstruct the progressive sedimentary evolution of the basin towards the Adriatic Margin.

The main topics can be summarized as follows:

(1) To define, within the evolutionary framework of the Umbria-Romagna-Marche Apennines, the stratigraphic-structural relationships between the successions constituting the MAR and the MAM, which have been traditionally related to two adjacent palaeogeographical areas, i.e. the

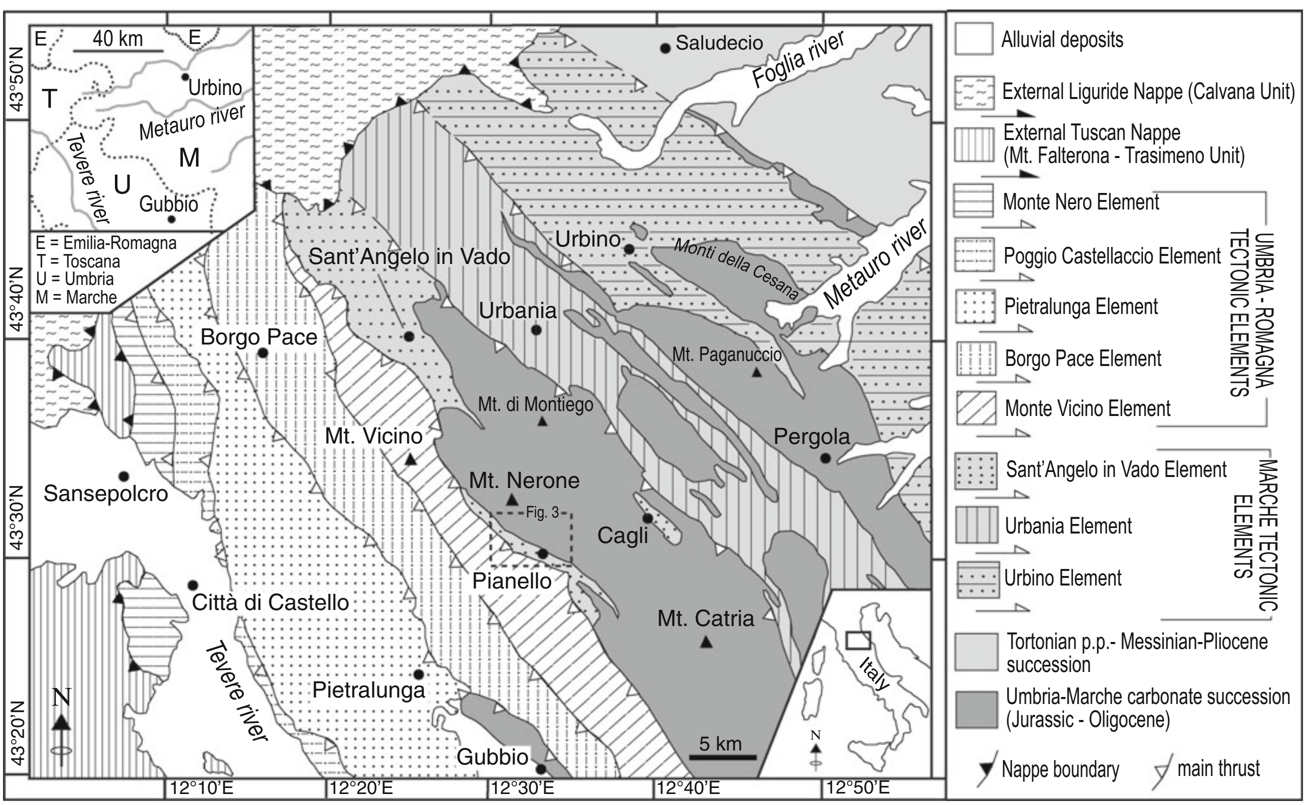

Fig. 2 Tectonic sketch of the study area in the Umbria-Romagna-Marche Apennines (after Delle Rose et al. 1990, 1991; de Feyter 1991; Capuano 2009; and original data) showing the recognized tectonic elements and the location of the Pianello key area (Fig. 3)

Umbria-Romagna Basin and the Marche Basin (Ricci Lucchi 1986; De Feyter 1991; Delle Rose et al. 1990, 1991; Roveri et al. 2002, and references therein; cf. also the geological map sheets published on the website www.isprambiente.gov.it).

A geological study including the detailed mapping of a selected key area (Pianello sector) at the scale 1:10,000 has been carried out (Fig. 3). On the basis of this map, detailed cross-sections have been constructed (Fig. 4). The field analysis allowed the reconstruction of the local stratigraphic succession and the relationships between the formations recognized. Moreover, investigations have been extended also towards the northwest in the area east of Mt. Vicino (Fig. 2), near Piobbico (cfr. de Feyter et al. 1986), where the tectonic boundary between the Monte Vicino Element (Schlier and Marnoso-Arenacea Fms) and the western limb of Mt. Nerone Anticline is recognizable. This limb is represented by some formations (Scaglia Variegata, Scaglia Cinerea and Bisciaro Fms) of the Umbria-Marche Succession.

(2) To describe more clearly the evolution of the Miocene foredeep siliciclastic sedimentation by means of further stratigraphic and tectonic analyses considered in the regional context.

(3) To revise the tectono-stratigraphic relationships of the units characterizing the Apennine sector which extends between the External Toscana Basin and the External Marche Basin, as presented in Table 1. The data compiled provides useful indications for revising the terminology of the units characterizing the studied sector of the chain.

In this paper, we assume the concept that the siliciclastic deposition occurred in a single basin (subdivided into minor depositional areas) controlled by the interference between tectonics and sedimentary processes. Moreover, an overall review of the terminology is presented (cfr. Table 1).

3 Geological features of the Pianello key-area

Useful information has been gathered through a detailed analysis of the internal sector of Mt. Nerone (Pianello area, near Cagli; Fig. 1). In fact, this represents a key area for understanding the relationships between tectonic elements

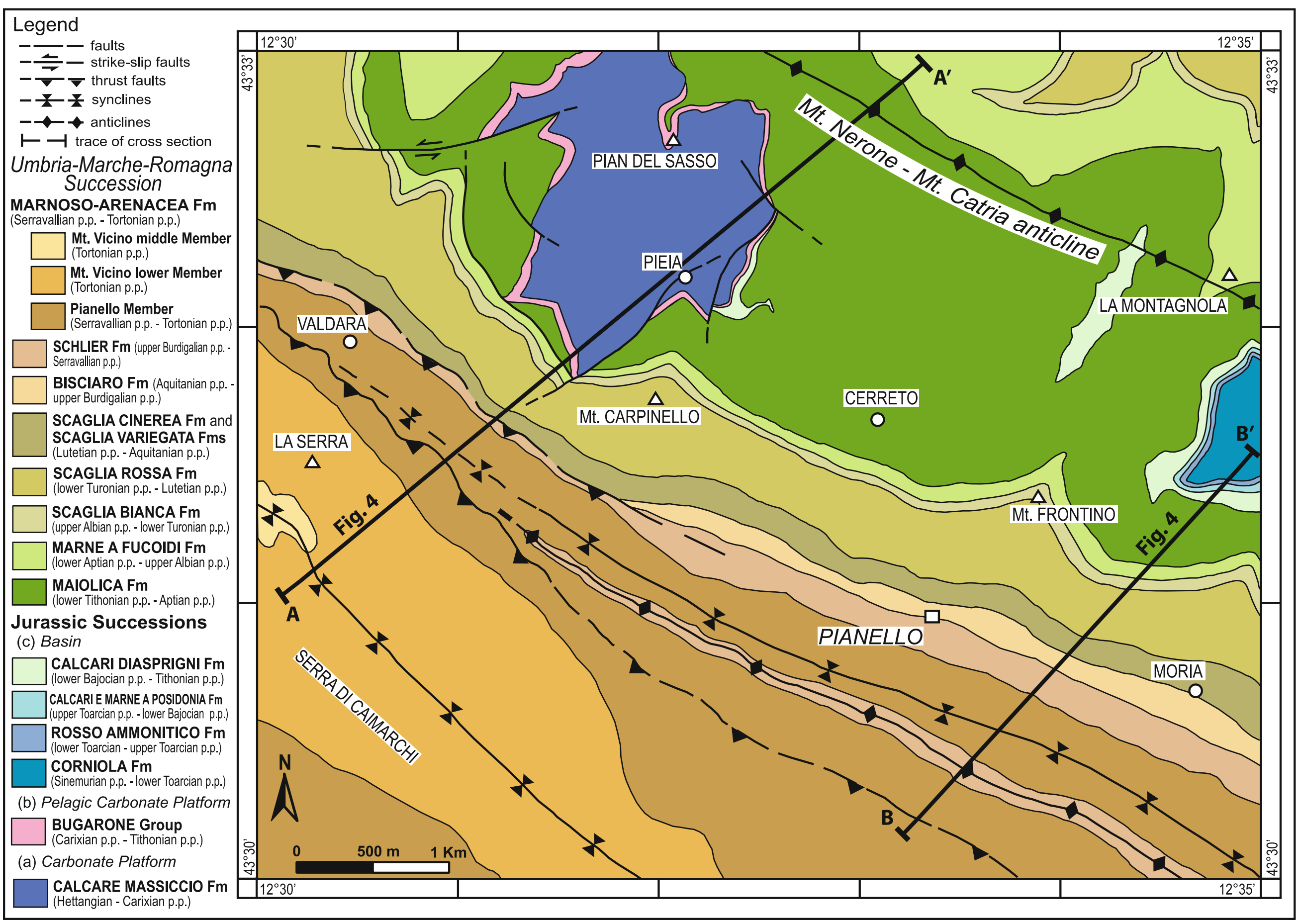

Fig. 3 Geological map of the western limb of Mt. Nerone anticline in the Pianello key area

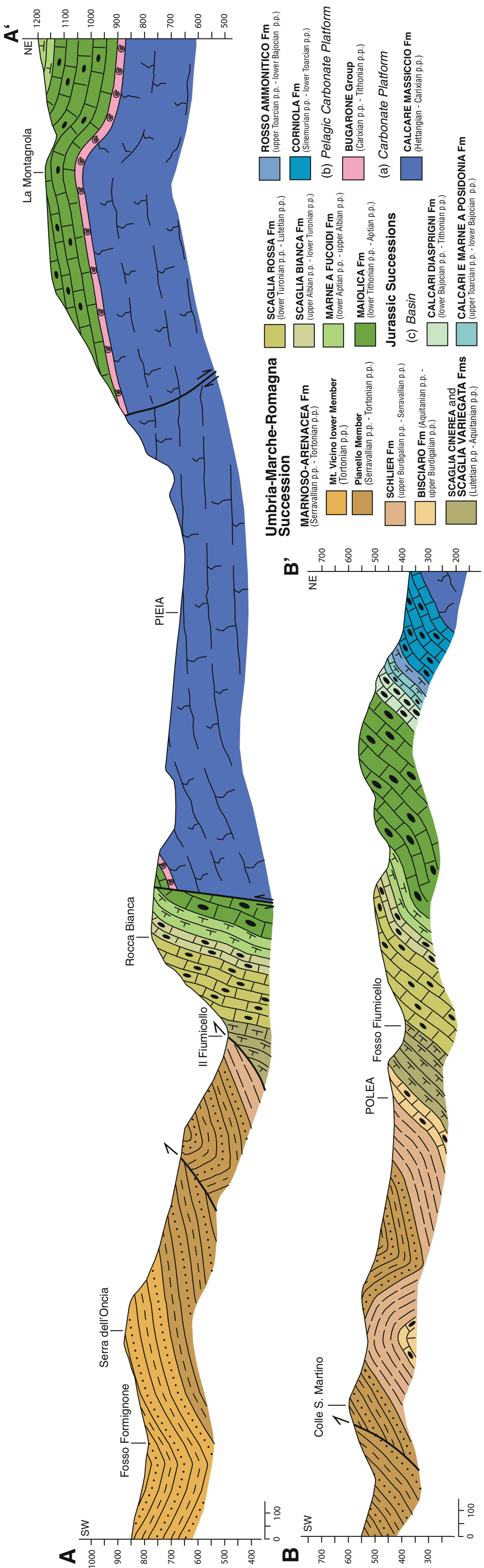

Fig. 4 Representative geological sections through the Pianello key area; location is indicated in Fig. 3

resulting from the more internal Umbria-Romagna domain (*auct.*) and the formations of the Umbria-Marche domain (*auct.*). In the Pianello area and its surroundings the thrust front of the so-called Umbria-Romagna Parautochthon (de Feyter 1991) and the adjacent Monte Vicino Element to the east are recognizable (Fig. 2). This thrust regionally marks the contact between the Umbria-Romagna tectonic elements and the more external Marche tectonic elements (Fig. 2).

In the Pianello area (Figs. 3, 4) a part of the internal limb of Mt. Nerone anticline is present. This anticline represents a main fold of the internal part of the northern Marche Apennines and creates the high relief of the northern part of the "Dorsale carbonatica Umbro-Marchigiana" (*Auct.*). The core of the anticline is characterized by Jurassic deposits affected by syn-sedimentary extentional faults. The orogenic tectonics results in compressional structures represented by thrusts and related folds. The thrust fault indicated between the Schlier and the Scaglia Variegata-Scaglia Cinerea Fms (Fig. 3) probably represents a splay of the main Monte Vicino Element thrust-front. The anticline located southwest of Pianello is probably related to the presence of a blind thrust.

Near Pianello, in the internal limb of the fold, the stratigraphic formations of the Umbria-Romagna-Marche Succession are continuous up to the "Marnoso-Arenacea-Marchigiana" Fm (MAM). In this area the "Marnoso-Arenacea Romagnola" Fm (MAR) of Monte Vicino Element overrides the MAM. In the northwest sector of the internal limb of the anticline, the Monte Vicino Element (MAR and underlying Schlier Fm) overrides directly the Umbria-Marche carbonate formations (Fig. 2). Even more to the northwest (Sant'Angelo in Vado area; Fig. 2), the Monte Vicino Element again overrides directly the Marnoso-Arenacea Fm (internal portion of the MAM) to reach the front of the external Liguride Nappe (Fig. 2).

The Pianello area is characterized by the presence of both deposits of the Umbria-Marche Succession, represented by formations ranging in age from the Jurassic to Middle Miocene and of the Umbria-Romagna Succession. The latter is represented by the Miocene *p.p.* Schlier and Marnoso-Arenacea diachronous formations (cfr. Delle Rose et al. 1994a). The Jurassic interval of the succession shows frequent marked lateral variations. Folds and faults constitute the main tectonic features of the area but their nature and importance differ mainly in relation to the units and deformation phases involved.

The outcropping succession may be subdivided as follows (Fig. 3):

(a) the Jurassic interval which includes (1) a "carbonate platform succession" (Calcare Massiccio Fm); (2) a "pelagic carbonate platform (PCP) succession" (sensu Santantonio 1993, 1994) represented by a condensed and discontinuous structural high pelagic deposition (Bugarone Group); and (3) a "basin succession": Corniola, Rosso Ammonitico, Calcari e Marne a Posidonia, Calcari Diasprigni (including Calcari a Saccocoma and Aptici Mbr) and Maiolica Fms characterized by thicker and continuous deposition;

(b) the Cretaceous *p.p.*-Middle Miocene *p.p.* marly-limestone interval (from the Marne a Fucoidi Fm to Schlier Fm);

(c) the Middle-Late Miocene *p.p.* siliciclastic interval (Marnoso-Arenacea Fm), which represents the typical foredeep deposition of the Romagna area (Ricci Lucchi 1986).

The stratigraphic relationships of the Jurassic formations allow the reconstruction of a complex palaeogeography controlled by extensional tectonics which is well documented by marked lateral lithofacies variations. These features fit well with palaeogeographical models considering the evolution of the Adriatic Margin (Schettino and Turco 2011, and references therein). The Jurassic starts with a wide regional peritidal carbonate platform (Calcare Massiccio Fm; Hettangian-Sinemurian *p.p.*). In the Late Hettangian-Sinemurian the Tethyan rifting dismembered the Calcare Massiccio platform into fault blocks, producing a complex submarine morphology characterized by small intrabasinal structural highs. Sinemurian to Tithonian deep-water pelagic and calcareous turbiditic deposits (Corniola, Rosso Ammonitico, Calcari e Marne a Posidonia, Calcari Diasprigni Fms) sedimented into basin areas. Instead, the shallow-water sedimentation extended on the structural highs up to the Early Pliensbachian (Early Carixian, see Morettini et al. 2002). Later, on these highs, a condensed sedimentation of pelagic carbonate platform deposits (PCP, sensu Santantonio 1993, 1994) developed, induced by the full drowning of remnant blocks of the productive carbonate platform. With the deposition of the Maiolica Fm (Upper Tithonic *p.p.*-Lower Cretaceous *p.p.*), almost uniform environmental conditions were established throughout the Umbria-Marche Basin (Centamore et al. 1971; Donatelli and Tramontana 2012).

From the Early Cretaceous to the Middle Miocene, the Umbria-Marche pelagic basin recorded the deposition essentially of fine-grained limestones and marls (from the upper part of the Maiolica Fm to the Schlier Fm). This succession is marked by some major regional tectono-sedimentary events and/or marker beds, which are important for correlations at intra-basinal, extra-basinal, and Mediterranean scale.

(1) The Selli Level is one of the major episodes of organic-matter deposition of the Lower Aptian, constituting a basinal marker bed at the base of the Marne a Fucoidi Fm (Coccioni et al. 1987). It represents a radiolaritic-bituminous ichtyolitic horizon recording the Lower Aptian global palaeo-oceanographic event: the so-called "Oceanic Anoxic Event 1a" (OAE1a) (Baudin et al. 1998, and references therein).

(2) The Bonarelli Level constituting a regional marker bed located at the top of the Scaglia Bianca Fm, close to the Cenomanian/Turonian boundary. This marker consists of organic-rich sediments related to the well-known "Oceanic Anoxic Event 2" (OAE2) (Turgeon and Brumsack 2006, Donatelli et al. 2010, and references therein).

(3) The K/T (Cretaceous/Tertiary) boundary is located in the middle-upper part of the Scaglia Rossa Fm (Turonian *p.p.*-Eocene *p.p.*) and corresponds to a clay bed characterized by an anomalous iridium concentrations (Alvarez 2009, and references therein). This marker bed provided the first evidence to interpret the great mass extinction occurring about 65 Ma ago, perhaps caused by a catastrophic event which, according to Alvarez et al. (1980), was due to the impact of a large asteroid against the Earth.

(4) During the Eocene, gentle tectonic activity was probably due to a distant reflection of the neo-Alpine tectonics and gravitational deposits (slumps and olistostromes) caused in the upper member of the Scaglia Rossa and Scaglia Variegata Fms.

(5) The Raffaello marker bed marks the lithostratigraphic boundary between the Scaglia Cinerea Fm (Upper Eocene *p.p.*-Aquitanian *p.p.*) and the overlying Bisciaro Fm (Aquitanian *p.p.*-Burdigalian *p.p.*). This marker is represented by the first volcaniclastic bed occurring within the Miocene succession of the Umbria-Marche Basin (Montanari et al. 1994, and references therein). The Raffaello level is constituted by a volcanogenic benthonitic bed which represents a basinal marker.

(6) The Bisciaro Fm (volcaniclastic event). This formation is characterized by the occurrence of volcanogenic materials related to Lower Miocene volcanic activity. The Bisciaro Fm can be correlated with analogous volcaniclastic deposits recognized in coeval sedimentary basins of the Mediterranean region (e.g. Guerrera and Veneri 1989; Balogh et al. 1993; Guerrera et al. 1998, 2004; Savelli 2007). The great areal diffusion and the composition (intermediate to acid) of these volcaniclastic deposits reflect the presence of a calc-alkaline magma source probably connected to a subduction zone along a continental margin located in the central-western Mediterranean (Guerrera et al. 1986, 1998, 1993, 2004, 2005; Coccioni et al. 1988; Cipollari et al. 1998; de Capoa et al. 2002, 2004).

(7) In the study area the lithostratigraphic boundary between the Bisciaro Fm and the overlying Schlier Fm is considered to correspond to a thin marker bed (i.e. the Piero della Francesca Level), which is represented by a thin volcaniclastic clayey layer attributed to the Burdigalian (about 17 Ma; Deino et al. 1997). However, in our interpretation, the Piero della Francesca Level cannot be

considered a lithostratigraphic boundary because it is discontinuous, and not easily detectable, and its basinal extension has not been demonstrated. Moreover, no real lithological changes occur below or above this level and some diluted volcanogenic materials are also recognizable in the lower part of the Schlier Fm.

(8) The Schlier sedimentation is characterized by a high lateral variability in age and facies. The Schlier Fm shows a marked reduction in volcaniclastic material and this feature is the most prominent lithostratigraphical difference with respect to the Bisciaro Fm. This formation is characterized mainly by hemipelagic lithofacies which prevail especially towards the external (Adriatic) zones where a foreland ramp occurs. In this area, contributions by gravity flows are reduced, although these are more frequent in more internal sectors (Dubbini et al. 1991). The top of the formation systematically becomes younger towards the external Adriatic area. In fact, the transition to the overlying formation is Langhian in the internal zones and reaches the Late Tortonian-Early Messinian in the external zones (Fig. 5). This diachronism reflects the progressive migration from west to east of the Apennine foredeep.

(9) The deposition of the Schlier Fm is followed by a typical siliciclastic turbiditic succession (Marnoso-Arenacea Fm) for which the first occurrence in the Umbria-Romagna-Marche areas becomes progressively younger from the internal to the external (Adriatic) zones. The siliciclastic supply indicates the onset of a foredeep stage, showing marked diachronism and very abundant sedimentation. This event is controlled in space and time by an uplift of more internal sectors during the orogenic phases of the northern Apennines, which modify and cause the migration of the depositional area/internal basin margin system. In the Pianello area the Marnoso-Arenacea Fm ends in the Middle-Tortonian when this sector was affected by the compressional tectonics which closed this portion of the basin.

The importance of the Pianello area as a key for understanding the regional synthesis consists in the possibility to investigate the relationships between the Marnoso-Arenacea Fm of the most external Umbria-Romagna Basin (*Auct.*) and different formations of the Umbria-Marche Succession (*Auct.*). The stratigraphic boundary between the Schlier Fm and the overlying Marnoso-Arenacea FM (MAM) recognized SW of Pianello, is the same which characterizes the boundary between these two formations in the Mt. Vicino Element (well observable toward the northwest, near Mt. Vicino), testifying to the lateral continuity of siliciclastic deposition predating the deformation. The similar age of the Marnoso-Arenacea Fm in the hanging wall and in the footwall of the Mt. Vicino Element thrust shows that the foredeep siliciclastic deposition extends to both the Marche and Umbria-Romagna domains as also demonstrated on a larger scale by stratigraphic correlations and detected ages (Fig. 5).

4 Structural and stratigraphic framework of the Miocene Apennine foredeep

The Miocene siliciclastic deposition of the Northern Apennines foredeep is represented mainly by the Marnoso-Arenacea Fm and it is well-known in the literature, e.g. Ricci Lucchi and Pialli 1973; Ricci Lucchi and Valmori 1980; Gandolfi et al. 1983; Ricci Lucchi and Ori 1985; Chiocchini et al. 1986; Ricci Lucchi 1984, 1986; Delle Rose et al. 1990, 1991; Van Wamel and Zwart 1990; Capozzi et al. 1991; de Feyter 1991; Carlini et al. 1995; di Biase and Mutti 2002; Roveri et al. 2002; Capuano 2009.

In this chapter, based on these studies and our own research, a model for this foredeep basin is proposed (Sect. 4.1), followed by a preliminary revision of the biostratigraphical data (Sect. 4.2).

4.1 The Marnoso-Arenacea Basin

The Marnoso-Arenacea depositional area is considered to have been a basin at least 400 km long in a NW–SE direction and 60 km wide, where more than 3,000 m of sediments were deposited during the Middle to Late Miocene *p.p.* These sediments crop out mainly along the Emilia Romagna, Toscana, and Umbria Apennines. Therefore, the Marnoso-Arenacea Fm represents one of the most important detrital wedges in the compressive Apennine foredeep evolution.

Recently, the Marnoso-Arenacea Fm has been subdivided into the Marnoso-Arenacea Romagnola Fm and the Marnoso-Arenacea Marchigiana Fm (Capuano 2009, and references therein) corresponding to the deposition in the Umbria-Romagna and in the Internal Marche areas, respectively. The Marnoso-Arenacea Romagnola (MAR, Upper Langhian-Lower Tortonian) and the marly members marking the end of its sedimentation are recognizable within five tectonic elements, these being from west to east: Monte Nero, Poggio Castellaccio, Pietralunga, Borgo Pace and Monte Vicino (e.g. de Feyter 1991; Delle Rose et al. 1990, 1991, 1994a, b). These elements (Fig. 2), which result from different sectors of the depositional area, are detached along a sole fault located in the Schlier Fm. They are stacked to form a geometric pile in which the Monte Nero Element is the highest element and the Monte Vicino Element is the lowest one, representing the most external element of the Romagna Basin of de Feyter (1991). These elements have been considered by this latter author to form the so-called Umbro-Romagnan Internal and External Parautochthon.

The Marnoso-Arenacea Marchigiana (MAM) (Upper Serravallian p.p.-Lower Messinian *p.p.*) of the Internal Marche Basin (*Auct.*) shows a progressively reducing thickness towards the east and, in the more external portion

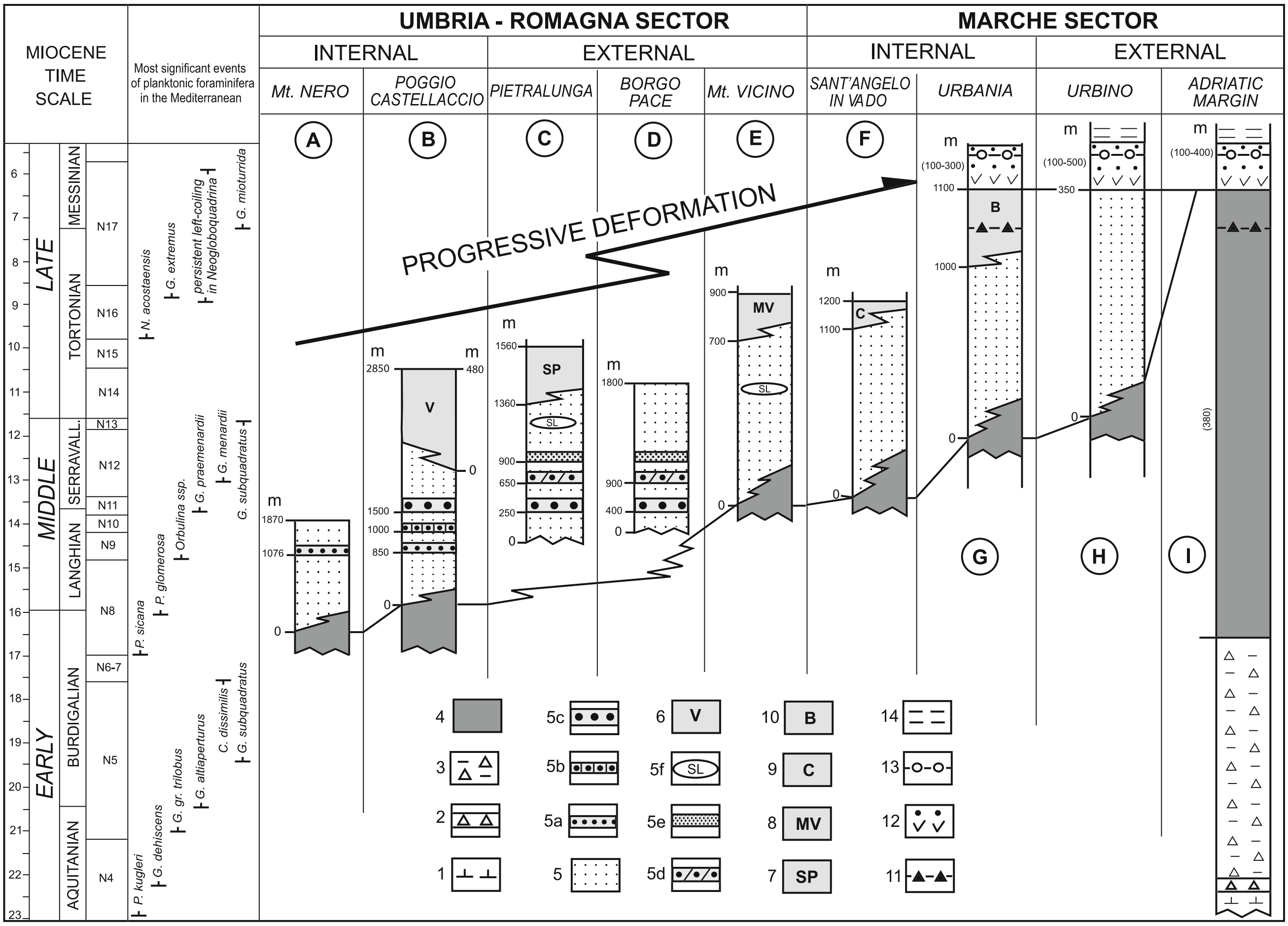

Fig. 5 Stratigraphy of the Marnoso-Arenacea Fm in the Umbria-Romagna-Marche Basin showing (1) the lateral evolution of the different elements; (2) the diachronic boundaries; (3) marker beds and correlations; (4) the marked diachronism of deposits above the Schlier Fm; (5) the absence of the Marnoso-Arenacea Fm in the more external areas (Adriatic Margin).Representative stratigraphic sections and considered tectonic slices: *A* Campigna-Stregorata (Monte Nero Element); *B* Bocca Trabaria-Alpicella, Scalacci (Poggio Castellaccio Element); *C* Montelabreve-Monte Viale (Pietralunga Element); *D* Borgo Pace Element; *E* Pieve dei Graticci (Monte Vicino Element); *F* Sant'Angelo in Vado Element; *G* Urbania Element; *H* Urbino Element; *I* Northern Marche coastal area. Compiled from: Delle Rose et al. 1990, 1991, 1994a, b; de Feyter 1991; Dubbini et al. 1991; Montanari et al. 1991; Carlini et al. 1995; Capuano and D'Antonio 1992; Capuano 2009; and original unpublished data. Key: *1 upper* portion of the Scaglia Cinerea Fm; *2* Raffaello marker bed; *3* Bisciaro Fm; *4* Schlier Fm; *5* Marnoso-Arenacea Fm: *5a* Fiume marker bed; *5b* Poggio della Rocca marker bed; *5c* Contessa marker bed; *5d* Guinza marker bed; *5e* Monte Viale marker bed; *5f* main mega-slump horizon; *6* Verghereto Mbr.; *7* Marne di San Paolo Mbr.; *8* Marne di Monte Vicino Mbr.; *9* Marne di Campo Mbr.; *10* Marne di Belvedere Mbr; *11* Rossini marker bed; *12* Messinian Evaporitic and post-Evaporitic succession; *13* Messinian volcaniclastic marker bed; *14* Pliocene deposits

of the External Marche Basin (*Auct.*), is replaced by the Schlier Fm. The Schlier Fm shows an eastward rejuvenation, with the Burdigalian *p.p.*-Langhian in the Monte Nero Unit (Romagna Basin), Burdigalian *p.p.*-Tortonian *p.p.* in the Sant'Angelo in Vado-Urbania Elements (Internal Marche Basin), and Burdigalian *p.p.*-Lower Messinian *p.p.* being on the Adriatic Margin (e.g. Delle Rose et al. 1994; Capuano 2009).

According to de Feyter (1991), the Monte Vicino Element overrides the Serravallian *p.p.*-Tortonian *p.p.* succession of the MAM of the Sant'Angelo in Vado Element (see later) which ends with the Marne di Campo Member (Lower Tortonian *p.p.*). This latter element represents a less deformed marly unit showing gentle folds and some thrust faults with a small displacement. This tectonic contact bounding eastward the Monte Vicino Element, on the western side of Mt. Nerone and Mt. Catria (Fig. 2) leads the siliciclastic succession and its basal Schlier Fm to directly override the Eocene-Lower Miocene formations of the Umbria-Marche Succession (de Feyter et al. 1986, 1991).

In our interpretation, the subdivision of the Marnoso-Arenacea Fm in MAR and MAM as related to two different depositional areas (Capuano 2009) represents only a schematization resulting from mainly tectonic considerations (cfr. de Feyter 1991). Really, this distinction seems to be inconsistent because no main geological and/or structural features support the separation into different basins, and the whole siliciclastic wedge is affected by a progressive deformation which causes a marked parautochthony. Moreover, on the basis of most recent data, it is now verified that the substantial lithologic homogeneity, even if some mineralogic-petrographic differences are recognizable, does not allow an objective identification of two distinct and well-defined individual depositional basins.

4.2 Biostratigraphic data

The bio and chronostratigraphic analysis consists of a preliminary revision of recent data from literature based on a new study with two main aims: (1) to complete the chronostratigraphic attribution of formations characterizing the foredeep evolution and to date stratigraphic intervals not yet well defined; (2) to check the age of formations which are not consistent with the general geological and stratigraphical framework, especially taking into account the well-defined correlations (e.g. Contessa marker bed) resulting from lithostratigraphic data.

To carry out a temporal control of the sedimentation, the methodological approach consisted of studying the planktonic foraminifer assemblages resulting from samples collected in the stratigraphic interval ranging from the top of the Scaglia Cinerea Fm to the upper part of the Marnoso-Arenacea Fm. All data are summarized in Fig. 5.

The biostratigraphic and chronostratigraphic monitoring is based on the geologic time scale by Gradstein and Ogg 2004; (Lourens et al. 2004, for the Neogene Period), the standard zonal scheme of the planktonic foraminifera by Blow (1969), and the most significant events in the Mediterranean realm (e.g. Serrano 1979; Iaccarino 1985; Hilgen et al. 2000; Sierro et al. 2001; Sprovieri et al. 2002).

In the Marche basin, the pre-Schlier formations considered have been studied in the Piobbico area (Sant'Angelo in Vado Element) and are represented by the Scaglia Cinerea and Bisciaro Fms. The upper part of the Scaglia Cinerea Fm contains planktonic foraminifer assemblages with *Globigerina venezuelana* Hedberg, *Globigerina selli* (Borsetti), *Globigerina praebulloides* Blow, *Globigerinoides primordius* Blow and Banner, *Globigerinella obesa* (Bolli), *Neogloboquadrina nana* (Bolli), *Neogloboquadrina continuosa* (Blow), *Neogloboquadrina siakensis* (LeRoy), *Paragloborotalia kugleri* (Bolli), *Globigerinita juvenilis* (Bolli), *Globigerinita naparimaensis* Brönnimann, *Globorotaloides suteri* Bolli, and *Catapsydrax dissimilis* (Cushman and Bermúdez), characterizing the Zone N4 by Blow (1969) of the Lower Aquitanian. In the Raffaello marker bed at the boundary Scaglia Cinerea Fm/Bisciaro Fm, the microfauna is poorly preserved, but the persistence of *P. kugleri* suggests a similar age. Above, in the lower beds of the Bisciaro Fm, the presence of *Globoquadrina dehiscens* (Chapman, Parr and Collins) is noted and upwards the first specimens belonging to the group of *Globigerinoides trilobus* (Reuss) with primitive morphologies (cf. *Globigerinoides quadrilobatus* (d'Orbigny) and *Globigerinoides inmaturus* Le Roy) are detected, pointing to a Upper Aquitanian in age. About 10 m above the base of the formation the sediments contain *Globigerinoides altiaperturus* Bolli in association with typical forms of *G. trilobus*, thus suggesting the passage to the Burdigalian sedimentation. The uppermost sampled beds, which do not, however, represent the top of the Bisciaro Fm, yield assemblages with *G. trilobus, G. altiaperturus, Globigerinoides subquadratus* Brönnimann, *Fohsella peripheroronda* (Blow and Banner) and *Globoquadrina baroemoenensis* (LeRoy). However, *G. suteri, C. dissimilis,* and the large globigerinids of the *G. venezuelana* group are not present. These significant absences seem to indicate that its deposition occurred during the Upper Burdigalian (Zone N6–N7).

As indicated above (Delle Rose et al. 1990), the Schlier Fm in the Monte Nero and Poggio-Castellaccio Elements contain microfauna composed predominantly of planktonic forams. An update of data showed the presence of abundant *Globigerinoides* gr. *trilobus* with frequent *Globigerinoides bisphaericus* Todd. The poor preservation does not ensure the presence of specimens with two dorsal apertures at the base of the last chamber, and thus are assigned to *Praeorbulina sicana* (De Stefani). However, no specimens assignable to *Praeorbulina glomerosa* (Blow) have been found. The frequent appearance of *G. baroemoenensis* and *Globoquadrina langhiana* Cita and Gelati, in association with rarer specimens of *G. altiaperturus*, *Globoturborotalita woodi (Jenkins), G. obesa, N. siakensis,* and *Globorotalia praescitula* Blow is also noteworthy. These assemblages point out still a Upper Burdigalian age (zone N6–N7 or lower part of the zone N8).

In the Borgo Pace Element, the assemblages are barely significant; only the presence of rare *G. trilobus* is highlighted, and thus, in agreement to Principi et al. (2011), it is not possible to define a more detailed age within the Burdigalian-Langhian.

In the most internal areas of the Umbria-Romagna sector, the stratigraphic contact Schlier/Marnoso-Arenacea Fms occurs near the Burdigalian-Langhian boundary (Delle Rose et al. 1990, and references therein). In the Poggio-Castellaccio Element, we noted that the first levels belonging to the Marnoso-Arenacea Fm show the presence of *P. glomerosa* (zone N8). In the Monte Nero Element, the contact Schlier/Marnoso-Arenacea Fms seems to occur even just before this last species (Principi et al. 2011; Plesi 2010).

In the Monte Vicino Element (external Umbria-Romagna sector) the deposition of the Schlier Fm persists at least up to the Lower Serravallian and the upper beds of this formation yield assemblages with *Globorotalia praemenardii* Cushman and Stainforth, *O. universa, N. siakensis, G. trilobus, G. baroemoenensis* among others (Zone N11).

In the Marche sector, the Schlier sedimentation persists longer during the Serravallian times. In the internal area (Sant'Angelo in Vado Element), the top of the Schlier Fm is Middle Serravallian, based on assemblages composed by *G. praemenardii, Globorotalia menardii* (Parker, Jones and Brady), *G. subquadratus*, and *Globoturborotalita drury* Akers, among others (N12). In more external areas (Urbania and Urbino Elements), the Schlier Fm is maintained up to the Upper Serravallian-lowest Tortonian. Data from the Urbania area (Urbania Element) show that the uppermost beds of this formation yield *G. menardii* in association with *N. siakensis, Globigerinoides obliquus* Bolli y *Globigerina decoraperta* Takayanagi and Saito; in addition, occasionally *Globigerina nepenthes* Todd appears, and also the absence of *G. subquadratus* is noteworthy. These features are characteristic of the N13–N14 zones. In the most external Adriatic margin the Schlier Fm reaches the Lower Messinian (Cipollari et al. 1998, and references therein).

On the basis of the data presented above, a progressive and marked rejuvenation of the top of the Schlier Fm from the internal to external element is clearly defined.

Also the time span of the Marnoso-Arenacea Fm varies in the different sectors. In the most internal element of the Umbria-Romagna sector (Monte Nero), the Marnoso-Arenacea sedimentation ends before the deposition of the Contessa marker bed, attributed to the Lower Serravallian (Van Wamel and Zwart 1990). In contrast, the Marnoso-Arenacea deposits of the adjacent Poggio Castellaccio Element reaches the Serravallian, and the onset of the deposition of the Verghereto Marls Mbr, locally representing the ending member of the Marnoso-Arenacea Fm, occurred in the Middle Serravallian (Van Wamel and Zwart 1990; Delle Rose et al. 1990, and references therein). In the most external Borgo Pace Element, the Marnoso-Arenacea deposits reach the Upper Serravallian-lowest Tortonian (zones N13–N14), bearing assemblages similar to those mentioned above for the top of the Schlier Fm in the Sant'Angelo in Vado Element. In the Monte Vicino Element, the uppermost beds of the Marnoso-Arenacea Fm yield *Neogloboquadrina acostaensis* (Blow) with both dextral and sinistral coiling, thus characterizing Zone N16 of the Lower Tortonian in age.

Similarly, also in the Marche sector, a rejuvenation of the top of the Marnoso-Arenacea Fm occurs from internal to external areas. In the Sant'Angelo in Vado Element, the Campo Marls Mbr closes the Marnoso-Arenacea sedimentation during the Lower Tortonian (Zone N16), based on the presence of *N. acostaensis, G. obliquus, G. menardii,* and *Globorotalia merotumida* Blow and Banner, in the transition levels. According to Capuano (2009), the Belvedere Marls Mbr (Upper Tortonian-Lower Messinian) ends the Marnoso-Arenacea Fm in the Urbania Element. Within this member a volcaniclastic marked bed marks the Tortonian/Messinian boundary (Cipollari et al. 1998). Above this marker bed the persistence of the Belvedere Marls Mbr deposits up to the Messinian is supported by the presence of the *Globorotalia miotumida* Kennett plexus (including *Globorotalia mediterranea* Catalano and Sprovieri). Finally, in the most external areas of the Marche sector (Adriatic margin), the entire sedimentation of the Middle and Late Miocene before the Messinian Salinity Crisis deposits is characterized by the Schlier Fm, which entirely replaces the Marnoso-Arenacea Fm.

5 Discussion

5.1 Space–time evolution of the siliciclastic sedimentation

The Marnoso-Arenacea Fm is the most widespread formation in the Romagna-Marche sedimentary area, which during the Miocene represented a wide basin in front of the rising Apennine Chain (Ricci Lucchi 1986), characterized by a high rate of syn-tectonic sedimentation. In fact, this formation represents a mega-siliciclastic turbiditic wedge consisting of an upwardly thickening progradational sequence, sedimented in a foredeep and at present structurally subdivided into several thrust sheets (tectonic elements). The lithostratigraphic analysis of the Marnoso-Arenacea Fm, summarized in Fig. 5, indicates: (a) the space/time evolution of the main sedimentary successions constituting the tectonic elements and migrating from the Umbria-Romagna sector to the Adriatic Margin (Marche sector); (b) the presence of main marker beds (e.g., Fiume, Poggio della Rocca, Contessa, Guinza, Monte Viale marker beds in the Marnoso-Arenacea Fm) allowing correlations in the different tectonic elements; (c) the diachronous boundary between Schlier Fm and Marnoso-Arenacea Fm; (d) the diachronous base of the mainly marly members (Marne di Verghereto, Marne di San Paolo, Marne di Monte Vicino, Marne di Campo, and Marne di Belvedere Members; Delle Rose et al. 1990, 1991; de Feyter 1991; Capuano 2009, and references therein) closing the sedimentation of the Marnoso-Arenacea Fm. Up to now, these marly deposits have not been recognized in the Monte Nero, Borgo Pace and Urbino Elements. As regards the Monte Nero Element, this absence is probably due to the occurrence of an early deformation while in the other elements the presence of this is still to be defined; (e) the progressive thinning and disappearance of the Marnoso-Arenacea Fm towards the external areas (Adriatic Margin). The characteristic diachronism of the base of the Marnoso-Arenacea wedge can be calculated at about 5 Ma (Fig. 5, Table 1) from the more internal sector of the Romagna sector (Monte Nero Element) to the external Marche sector (Urbino Element). This diachronism is related to the progressive migration of the tectonic deformation towards the external areas.

The clastic supply constituting the Marnoso-Arenacea wedge comes from directions which vary in time and space, as indicated by the presence of diversified petrofacies and palaeocurrent directions. In fact, two main longitudinal provenances are indicated by palaeocurrents, the main ones being towards the SE and another towards the NW, together with other transversal less abundant palaeocurrents. Different petrofacies have been distinguished and they have been related to different source areas identified in the Alpine chain, the Apennine forming chain and the Latium-Abruzzi Carbonate Platform (e.g. Ricci Lucchi and Valmori 1980; Ricci Lucchi 1981; Gandolfi et al. 1983; Valloni and Zuffa 1984; Ricci Lucchi and Ori 1985; Chiocchini et al. 1986; Delle Rose et al. 1990; Delle Rose et al. 1991; Capozzi et al. 1991; Zuffa 1991; di Biase and Mutti 2002; Roveri et al. 2002; Amy and Talling 2006; Talling et al. 2007). The nature of clasts indicates that the source area was represented by an orogen characterized by units similar to Penninic and Austro-alpine Nappes of the Alps. Moreover, the textural features of sandstones suggest rapid erosion and sedimentation processes not involving significant rounding, sorting, or clast alteration, thus indicating the proximity of erosional areas. Hence, it does not seem possible to consider the far Alps as the source area of the Marnoso-Arenacea Fm. During much of the Miocene, Penninic, and Austroalpine-type Units resulting from the deformation of a microplate (Mesomediterranean Microplate; Guerrera et al. 2004, 2005; de Capoa et al. 2003, and references therein) probably cropped out close to the Marnoso-Arenacea Basin, in a more internal position, and constituted the geometrically highest units of the Apennine palaeochain. On the other hand, many other clastic formations of the Northern Apennines and in particular coeval foredeep deposits recognizable in surrounding areas have also been considered as derived from a different source area (Di Staso et al. 2009).

5.2 Tectonic evolution and timing of the deformation

The tectonic control during the Marnoso-Arenacea sedimentation has been debated by several authors (de Jager 1979; Ricci Lucchi and Ori 1985; Ricci Lucchi 1975, 1981, 1986; Martelli et al. 1994; De Donatis and Mazzoli 1994; Roveri et al. 2002; Mutti et al. 2002, 2003), but all consider the Marnoso-Arenacea Basin a very complex foredeep (sensu Ricci Lucchi 1986), which was separated into several sub-basins or structural elements by the syn-sedimentary propagation of the main thrust fronts (Van Wamel and Zwart 1990; De Donatis and Mazzoli 1994; Martelli et al. 1994; Lucente 2004). In reality, the siliciclastic foredeep sedimentation is affected by a syn-depositional Miocene progressive deformation which led to the development of different tectonic elements (Fig. 5) superimposed by means of thrust faults. However, a subdivision of the foredeep into several sub-basins is not supported by our data. In fact, the lateral continuity and correlation of different marker beds recognized in different tectonic elements (as considered in Delle Rose et al. 1990, 1991) testify that the different tectonic elements do not correspond to single sub-basins; each element does not result from the deformation of a single sub-basin. According to our reconstruction the syn-sedimentary diachronous tectonics did not lead to the formation of numerous sub-basins but rather caused the development of some main wide depositional areas. Also the diversification of the sedimentary supplies can be related to the palaeotopographic complexity determined by the progressive eastwardly migrating tectonic deformation and controlling the depositional processes and sediment distribution. In conclusion, we consider the following four main depositional sub-basins:

(1) the Monte Nero sub-basin, which does not comprise the well-known Contessa marker bed (Ricci Lucchi and Pialli 1973; lowest Serravallian in age after Van Wamel and Zwart 1990) deformed before the more external tectonic elements;

(2) an intermediate sub-basin from which the Poggio Castellaccio, Pietralunga and Borgo Pace tectonic elements originated; characterized by the Contessa marker bed, together with other marker beds (Fig. 5), deformed after the uppermost marly deposition (up to Lower Tortonian);

(3) the Monte Vicino-Sant'Angelo in Vado sub-basin, which does not show the Contessa marker bed or a Messinian sedimentary cover, and deformed after the uppermost marly deposition (up to Middle Tortonian);

(4) the Urbania-Urbino sub-basin, which does not show the Contessa marker bed and characterized by an unconformable Messinian sedimentary cover indicating a more recent deformation (Early Messinian).

For the evolution of the considered foredeep sector, it is particularly significant to take into account the interference between thrusts and folds developed in the foredeep succession of the Marnoso-Arenacea and those involving the carbonate substratum. During foredeep development at convergent plate margins, normal faults are often associated with flexure of the foreland lithosphere as pointed out by some authors also on the Marnoso-Arenacea Fm (cfr. Tavarnelli and Peacock 2002; Tinterri and Muzzi Magalhaes 2011).

In foredeeps, turbiditic sedimentation occurs on top of previously or synchronously stretched substratum. Thus, the Marnoso-Arenacea Fm may be deposited above the stretched Umbria-Marche carbonate substratum. Normal faults parallel to basin strike develop in response to lithospheric bending (e.g. Tankard 1986; Sinclair 1997). Foredeep-forebulge evolutionary models have been proposed in last 20 years (e.g. Suppe and Medwedeff 1990; Sinclair and Allen 1992; Crampton and Allen 1995; DeCelles and Giles 1996; Castle 2001). Normal faults in foredeep and forebulge settings show both foreland-ward and hinterland-ward dips (e.g. Maillard et al. 1992; Scisciani et al. 2001; Tavarnelli and Peacock 2002; Bolis et al. 2003; Tinterri and Muzzi Magalhaes 2011) and form half-grabens, grabens and horsts controlling the distribution and accumulation of foredeep deposits (e.g. Casnedi 1988; Tinterri and Muzzi Magalhaes 2011). This type of normal faulting therefore may have controlled the initial development of the sub-basins of the Marnoso-Arenacea Fm. Foredeep extensional structures, particularly faults parallel to basin strike and associated basin depocentres and structural highs, are well known to play a key role in subsequent tectonic processes associated with thrust propagation into the foredeep (e.g. Butler 1989; Scisciani et al. 2001; Tavarnelli and Peacock 2002; Bolis et al. 2003). Hence, we consider the possibility that the depozone evolution and differentiation was controlled at least in part by normal faulting, rather than exclusively by thrusting and related folding. The significant structural elevation of the Mt. Nerone ridge with respect to the Marnoso-Arenacea Basin (cf. cross-section A–A′, in Fig. 4) could be related to forebulge normal faulting activity, similarly to what occurs for the younger (Laga) foredeep located to the east and southeast of this area (e.g. Schettino and Turco 2011; Tozer et al. 2006, and references therein) where structural elevation and coeval depocentre development to the west occur.

The recognized tectonic elements are the result of a compressional tectonic evolution partially reactivating some former normal faults and controlling the development of the foredeep and the successive thrust-top basin stage.

The five tectonic elements recognized in the Romagna sector (Fig. 5), already studied by some authors (e.g. de Feyter 1991; Delle Rose et al. 1990, 1991) consist of broad NE-facing asymmetric synclines separated by listric thrust faults showing strong longitudinal continuity. They constitute the previously described deformed Romagna sector which overrides NE-wards by means of a main thrust carrying the most external element (i.e. the Monte Vicino Element) above the more external Marche sector. Towards the south, this main fault leads the MAR and the underlying basal Schlier (Monte Vicino Element) to override directly above different carbonate pre-Miocene formations of the Umbria-Marche Succession (e.g. in the western side of the Mt. Nerone Anticline) (Fig. 2). Along the western margin of the internal Umbria-Marche calcareous ridge, this tectonic boundary is marked by a penetrative deformation zone characterized by low-angle reverse shear planes with associated lithons and antithetic planes, which pass downwards to drag folds affecting the Scaglia Variegata to Schlier interval (Menichetti and Pialli 1986). In the area of Pianello the Monte Vicino Element overrides the siliciclastic deposits which here have been considered as belonging to the MAM (Sant'Angelo in Vado Element; Fig. 2), which stratigraphically lies above the older formations of the Umbria-Marche Succession.

The more external areas are affected by a compressional deformation leading to the development of three main thrust faults bounding three tectonic elements which from southwest to northeast are: (1) the Sant'Angelo in Vado Element, (2) the Urbania Element, and (3) the Urbino Element (Figs 2, 5). The first two elements constitute the Sant'Angelo in Vado Element of Capuano (2009) while the third element, already considered by the same author, has been extended in the present paper towards the northeast to reach a thrust externally delimiting this element.

As mentioned above, the thrust front bounding the M. Vicino Element on the eastern side marks the tectonic contact between the Umbria-Romagna and the Marche sectors (Fig. 2) and extends northwest of the Mt. Nerone anticline, up to the Val Marecchia Nappe (external Ligurids). Where the thrust front cuts the internal side of the Umbria-Marche Chain (i.e. the formations of the Umbria-Marche Succession), the superimposition of younger deposits above older deposits locally occurs by means of an out-of-sequence thrusting (de Feyter 1991). The propagation along down-section trajectories with respect to the foot-wall stratigraphy leads to pile-up slides of materials of the internal limb of the Mt. Nerone Anticline to form an imbricate stack lying above the same limb (i.e. the Monteforno structure; cfr. de Feyter et al. 1986). The peculiar trajectory should indicate that the Mt. Nerone Anticline was already incipiently formed while the thrusting occurred. However, for this tectonic contact, a different interpretation has been proposed by Menichetti and Pialli (1986), who consider the contact as being due to the emergence up-section of a thrust affecting the buried Mesozoic formations or perhaps alternatively related to a normal fault displacement along an older thrust fault.

From our reconstructions (Fig. 5), the siliciclastic deposition starts during the latest Burdigalian (about 16.5 Ma) in the most internal sectors (Monte Nero

Table 1 Synthesis of stratigraphic relationships in the Toscana and Umbria-Romagna-Marche Apennines, compiled from: Principi et al. 2011; Delle Rose et al. 1990, 1991, 1994a, b; Dubbini et al. 1991; Capuano 2009; de Feyter 1991; and original unpublished data)

<table>
<tr><th rowspan="3">MAIN ROCK SUITE</th><th rowspan="2">EXTERNAL TOSCANA BASIN</th><th colspan="5">UMBRIA-ROMAGNA BASIN</th><th colspan="4">MARCHE BASIN</th><th rowspan="3">MAIN REGIONAL EVENTS</th></tr>
<tr><th colspan="2">INTERNAL Elements</th><th colspan="3">EXTERNAL Elements</th><th colspan="2">INTERNAL Elements</th><th colspan="2">EXTERNAL</th></tr>
<tr><th>Falterona Unit</th><th>Monte Nero</th><th>Poggio Castellaccio</th><th>Pietralunga</th><th>Borgo Pace</th><th>Monte Vicino</th><th>Sant'Angelo in Vado</th><th>Urbania</th><th>Urbino Element</th><th>Adriatic Margin</th></tr>
<tr><td>pelites and subordinate arenites</td><td colspan="3" rowspan="2">deformed and emerged</td><td colspan="5">emerged</td><td colspan="2">Cella Marls - Argille Azzurre Fms (Plio-Quaternary p.p.)</td><td>Pliocene foredeep and Thrust-top Stages (compression)</td></tr>
<tr><td>black shales, evaporites, siliciclastic and marly deposits</td><td colspan="4">deformed and probably emerged</td><td colspan="3">Evaporitic and post-evaporitic Messinian successions (Messinian salinity crisis)</td><td>Forebulge extensional deformation and successive compression</td></tr>
<tr><td>mainly marly deposits</td><td>Vicchio Marls Fm (Burdigalian - Serraval. p.p.)</td><td>?</td><td>Verghereto Marls Mbr (MAR) (Serrav. p.p.- Torton. p.p.)</td><td colspan="3">?</td><td>Campo Marls Mbr (MAM) (Early Tortonian)</td><td>Belvedere Marls Mbr (MAM) (Late Torton.- Early Mess.)</td><td></td><td rowspan="5">Pre-orogenic Schlier Fm (Late Burdigal.- Early Messinian)</td><td rowspan="3">Miocene foredeep stage (progressive eastward migration)</td></tr>
<tr><td rowspan="2">siliciclastic deposits (flysch)</td><td>Mt. Falterona Sandstones Fm</td><td colspan="5">Marnoso-Arenacea Romagnola Fm (MAR)</td><td colspan="3">Marnoso-Arenacea Marchigiana Fm (MAM)</td></tr>
<tr><td>Late Aquitanian</td><td>Latest Burdig.- Langhian p.p.</td><td>Langhian - Serravallian p.p.</td><td>Langhian p.p.- Serravallian</td><td>Latest Langhian - Earliest Tortonian</td><td>Late Serraval. - Early Tortonian</td><td colspan="3">Latest Serravallian - Tortonian p.p.</td></tr>
<tr><td rowspan="2">clays, marly-clays, marls and calcareous deposits</td><td rowspan="2">Marne Varicolori, Villore Fm (Chattian - Aquitan. p.p.)</td><td colspan="2" rowspan="2">Schlier Fm (Late Burdigalian)</td><td colspan="2">Schlier Fm</td><td>Top Schlier Fm</td><td colspan="3">Top Schlier Fm</td><td rowspan="3">Pre-orogenic stage (prevaling subsidence)</td></tr>
<tr><td>?</td><td>Burdigal. p.p.- Langhian p.p.</td><td>Earliest Serrav.</td><td>Middle Serravallian</td><td colspan="2">Late Serravallian - Earliest Tortonian</td></tr>
<tr><td>marls, marly-clays, black shales, chert, limestones, volcanogenic materials</td><td colspan="6" rowspan="2">Mesozoic-Tertiary Succession</td><td colspan="4">Marne a Fucoidi to Bisciaro succession (Early Cretaceous p.p.- Early Miocene p.p.)</td></tr>
<tr><td>neritic and pelagic limestones</td><td colspan="4">From Calcare Massiccio Fm to Maiolica Fm (Early Jurassic - Early Cretaceous p.p.)</td><td>Rifting/drifting (extensional process, subsidence)</td></tr>
</table>

Element) and during the uppermost Serravallian-Lower Tortonian (about 11.5 Ma) in the most external zones (Sant'Angelo in Vado, Urbania, and Urbino Elements). Thus, a marked diachronism is confirmed, resulting also from ages observed in intermediate areas, estimated at about 5 Ma. During this time span, the foredeep sedimentation progressively migrated towards the external areas and was concomitantly followed by a progressive compressional deformation. In the internal areas of the foredeep the deformation started in the Early Serravallian and ended in the Tortonian-Messinian in the most external areas. Successively, the deformation migrated eastwards towards the Adriatic sector. In fact, the absence of siliciclastic deposits of the Marnoso-Arenacea Fm in the Adriatic Margin (foreland ramp) post-dates the activation in this zone of the Apennine foredeep, which starts from the Late Messinian. The tectono-stratigraphic relationships of units characterizing studied sectors are summarized in Table 1.

6 Conclusion

The high amount of siliciclastic sediments of the Marnoso-Arenacea foredeep basin, progressively migrating towards the Adriatic Foreland, was deposited under marked tectonic control. In fact, the absence in the underlying carbonate succession of siliciclastic supply, together with the high sedimentation rate, imply a palaeogeographical and palaeotectonic revolution in the Apennine margin/basin system during the Middle-Late Miocene. The emersion of the Apennine sector studied starts in the Middle-Late Miocene and becomes progressively younger towards the external areas.

The main results obtained in our research can be synthesized as follows:

(1) The whole depositional study area of the Marnoso-Arenacea Fm must be considered as a single wide domain characterized by a progressive and diachronous tectono-sedimentary development. Only a partial contemporaneity is

recognizable between deposits characterizing the main depositional sub-basins which develop through the time.

(2) The presence and correlation of different marker beds indicate the occurrence of sub-basins located above a substratum affected by a forebulge extension and progressively modified by a successive compressional tectonic deformation migrating towards the Adriatic Foreland.

(3) Successions which constitute the different tectonic elements are characterized by different sedimentary facies assemblages and record petrografically diversified source areas, as also indicated by the reconstruction of palaeocurrents in space, in time, and in different petrofacies.

(4) The multiple feeding (arkose, litharenites, calcarenites) is related to the palaeogeographical and palaeotectonic reorganization of the most internal already deformed Apennine areas.

(5) The deformed siliciclastic sedimentary wedge constitutes an orogenic pile incorporated in the external part of Northern Apennines and characterized by different tectonic elements which are superimposed by means of NE-verging reverse faults.

(6) The syn-depositional compressional deformation of the Marnoso-Arenacea Fm starts in the Middle Miocene (probably Lower-Middle Serravallian) in the internal areas (Monte Nero Element) and progressively affects the different more external elements up to the Upper Miocene (Tortonian-Lower Messinian), indicating a marked diachronism (about 5 Ma) with regard to both sedimentation and deformation.

(7) The deformation affected the most external areas when the internal structures of the Marche carbonatic chain (e.g. Monte Nerone Anticline) were already developing.

(8) The lack in some tectonic elements of the marly deposits representing the end of clastic sedimentation can be related to a rapid deformation and/or to successive erosion.

(9) The obtained results indicate that there is not a direct correspondence between the recognized tectonic elements and depositional areas. By means of the methodological approach followed, it is evident that a single depositional area (sub-basins of the foredeep) may give rise to one or more tectonic elements.

The main stratigraphic and tectonic events of the Toscana and Umbria-Romagna-Marche Apennines have been reconstructed also with the aim of re-organizing and homogenizing the terminology (Table 1).

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