

Research Article

Michele Marroni*, Maria Di Rosa, Edoardo Sanità, Rita Catanzariti, Francesca Meneghini, and Luca Pandolfi

Tectonics vs sedimentation in foredeep basins: A tale from the Oligo-Miocene Monte Falterona Formation (Northern Apennines, Italy)

<https://doi.org/10.1515/geo-2025-0772>

received December 06, 2024; accepted February 03, 2025

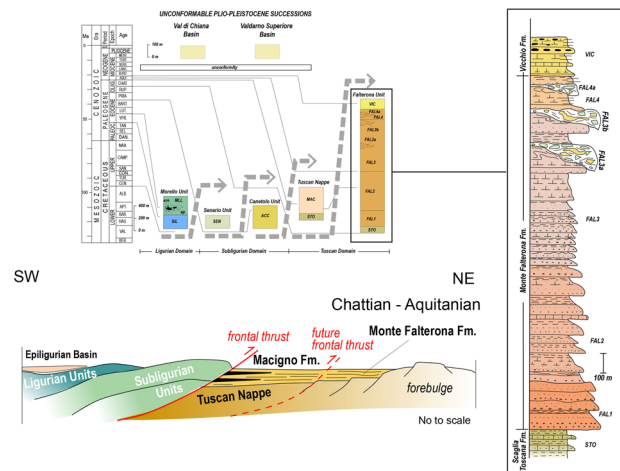
Abstract: In this article, we provide new biostratigraphic and structural data of the foredeep-derived Falterona Unit in the Arezzo area (Italy), to reconstruct the steps of evolution of the fold-and-thrust front-foredeep Apennine system. The sedimentary succession has been deposited in the N-S trending, foredeep basin bounded westward by the Apennine orogenic wedge and eastward by the Adria continental margin forebulge. The Falterona Unit mainly consists of the Monte Falterona Fm., a succession of Chattian–Late Aquitanian siliciclastic turbidites topped by the Vicchio Fm., characterized by Late Aquitanian–Early Serravallian slope deposits. The siliciclastic turbidites are interbedded with debris flows and carbonate turbidites supplied from the Apennine front and the forebulge, respectively. The foredeep basin in which the Monte Falterona Fm. deposited also includes the Macigno Fm. (Tuscan Nappe), that sedimented along the westernmost edge of the basin until its underthrusting and the subsequent migration of the fold-and-thrust system toward E. At this stage, the Monte Falterona Fm. has been transferred close to the fold-and-thrust front, triggering the sedimentation of the debris flows. In the Late Aquitanian, the Monte Falterona Fm. has been accreted to the wedge and the sedimentation of the Vicchio Fm. started.

Keywords: foredeep deposits, Monte Falterona Formation, Northern Apennines, fold-and-thrust belt evolution

* **Corresponding author: Michele Marroni**, Dipartimento di Scienze della Terra, Università di Pisa, Via Santa Maria 53, 56126, Pisa, Italy; Istituto di Geoscienze e Georisorse, IGG-CNR, Via Moruzzi 1, 56124, Pisa, Italy, e-mail: michele.marroni@unipi.it

Maria Di Rosa, Edoardo Sanità, Francesca Meneghini, Luca Pandolfi: Dipartimento di Scienze della Terra, Università di Pisa, Via Santa Maria 53, 56126, Pisa, Italy

Rita Catanzariti: Istituto di Geoscienze e Georisorse, IGG-CNR, Via Moruzzi 1, 56124, Pisa, Italy



Graphical abstract

1 Introduction

Foreland basin systems are complex depositional areas located on continental crust in front of active fold-thrust belts at the rim of the orogenic wedges [1–3]. Foreland systems include a foredeep depozone, a basin extending between the fold-and-thrust belt at the tip of the orogenic wedge, and the forebulge, a morphological high consisting of uplifted continental crust. In this basin, large volumes of sediments were accumulated on the continental crust, which is subjected to flexure due to the load of the overlying orogenic wedge. The progressive migration of the fold-and-thrust belt results in the deformation of the sediments accumulated in the foredeep basin by underthrusting and subsequently accretion to the orogenic wedge. This process produces the progressive deactivation of the foredeep basin and its consequent replacement with a younger, more external one. The foredeep basins are thus characterized by a continuous alternation of sedimentation and tectonic events, as modeled by several authors [4–8].

The Northern Apennines (Figure 1) provides well-preserved evidence of the evolution of the frontal part of an orogenic belt, with several examples of foredeep deposits related to the progressive NE migration of the front of the

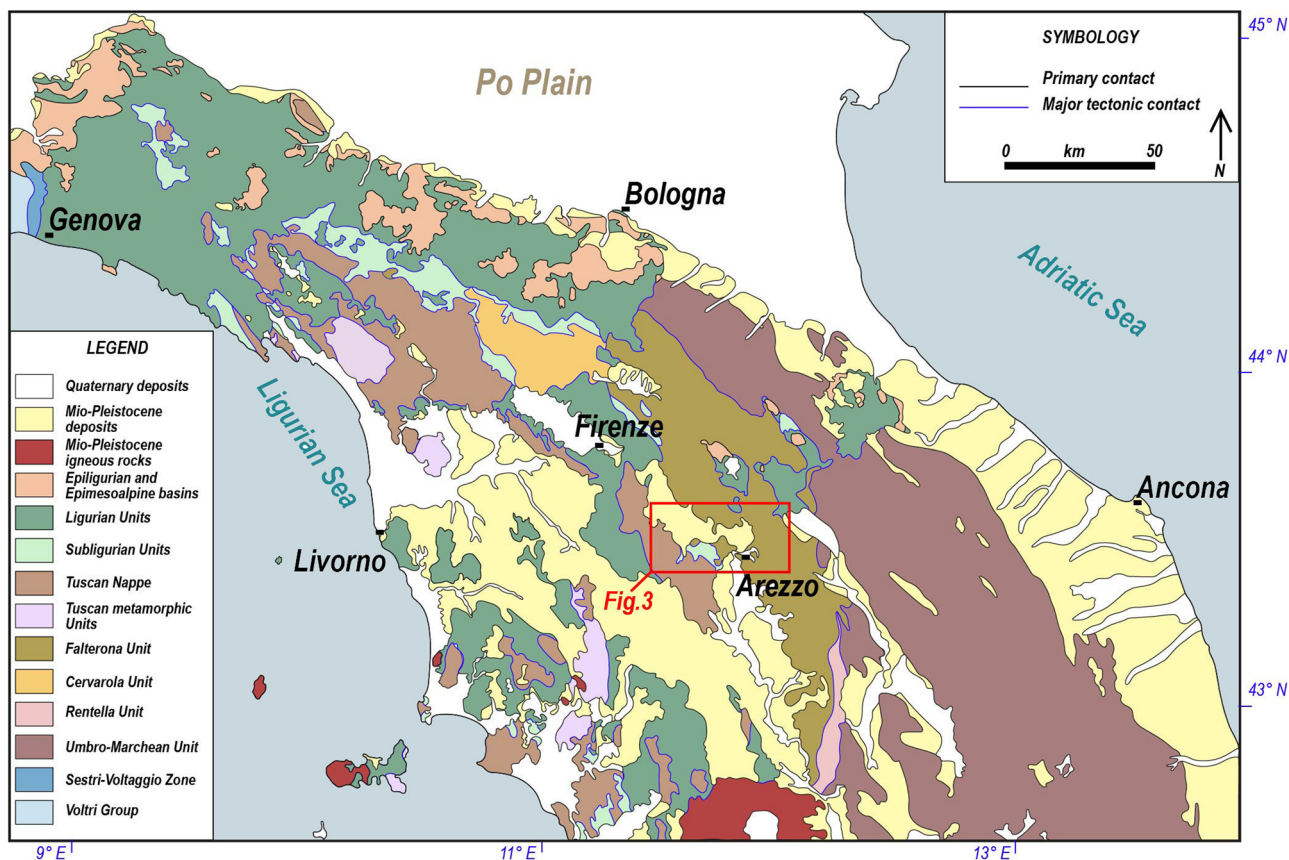


Figure 1: The tectonic units in the Northern Apennines (Italy); modified from Conti *et al.* [9]. The red box indicates the study area (Figure 3).

Apennine orogenic wedge within the continental margin of the Adria plate since the Early Oligocene [10–12]. The Late Oligocene–Early Miocene foredeep deposits are preserved in two different tectonic units, i.e., the Tuscan Nappe and Falterona Unit. These units include turbidite deposits of the same NW-SE trending foredeep basin, hereafter referred to as Macigno-Falterona foredeep. These deposits, known as Macigno Fm. in the Tuscan Nappe and Monte Falterona Fm. in the Falterona Unit, are representative of the southwestern and northeastern areas of this basin that grew and was deactivated at different times. The turbidites of the Macigno Fm. were the first to be incorporated into the orogenic wedge and the results of this event can be traced in the Monte Falterona Fm., which was only successively accreted to the Apennine orogenic wedge [13–15].

In this article, we present a complete set of geological, stratigraphic, and biostratigraphic data for the Monte Falterona Fm. in the Arezzo area. There, a well-preserved example of tectonic-controlled depositional systems within a single foredeep basin, that was deactivated in different stages, is exposed. The collected data are used to propose the tectonic evolution of the Macigno-Falterona foredeep basin at the Oligo-Miocene boundary and to discuss it in

the wider frame of the Northern Apennine geodynamic evolution.

2 The Northern Apennine collisional belt

The Northern Apennines (Figure 1) is a NW-SE to NE-SW trending collisional belt belonging to the Alpine orogenic system of the Mediterranean area [11]. The geodynamic history of the Northern Apennines was achieved in two main phases. The first phase, from Late Cretaceous to Middle Eocene, was characterized by the subduction of the lithosphere of the Ligure-Piemontese basin, a narrow oceanic domain opened in the Middle to Late Jurassic between the Europe and Adria continental margins [16]. This E-dipping subduction produced the development of an accretionary wedge whose remnants are today represented by the Internal Ligurian Units [17–19]. This subduction resulted in the continental collision when the European continental crust started to be underthrust [20–22] and triggered the progressive involvement in the orogenic wedge of the

External Ligurian Units, i.e., the fragments of the ocean-continent transition at the Adria plate margin [23,24].

The second phase started in the Late Eocene–Early Oligocene with a new W-dipping subduction of the thinned continental margin of the Adria plate [24,25]. From the Early Oligocene onward, the retreat of the subduction slab produced a progressive migration of the deformation front toward the eastern domains of the Adria plate, with the building up of a fold-and-thrust belt made of E- to NE-verging tectonic units. The built fold-and-thrust belt was facing toward the E on a foreland system that included a foredeep basin and the associated forebulge. In the Northern Apennines, the deposits of the foredeep basin generally overlap the front of the fold-and-thrust belt, so that they onlap on the tip of the orogenic wedge [26,27]. The foredeep basin hosted a thick succession of siliciclastic turbidite deposits

supplied by the Western and Central Alps collisional belt [28,29]. These deposits were progressively incorporated into the fold-and-thrust belt following the migration of the deformation front. The front of the orogenic wedge produced only small volumes of mass-gravity deposits that are now found as intercalations within the foredeep turbidites.

The migration of the deformation front was followed by an extension in the rear of the Apennine orogenic wedge [30,31]. This extension produced NW-SE trending basins whose age became progressively younger eastward.

The result of this complex structural history is the present-day tectonic setting of the Apennine orogenic wedge where the Ligurian Units, already deformed during the pre-Oligocene oceanic closure, are thrust onto the tectonic units derived from the Adria continental margin domains (i.e., the Subligurian, Tuscan, and Umbro-Marchean Units). These

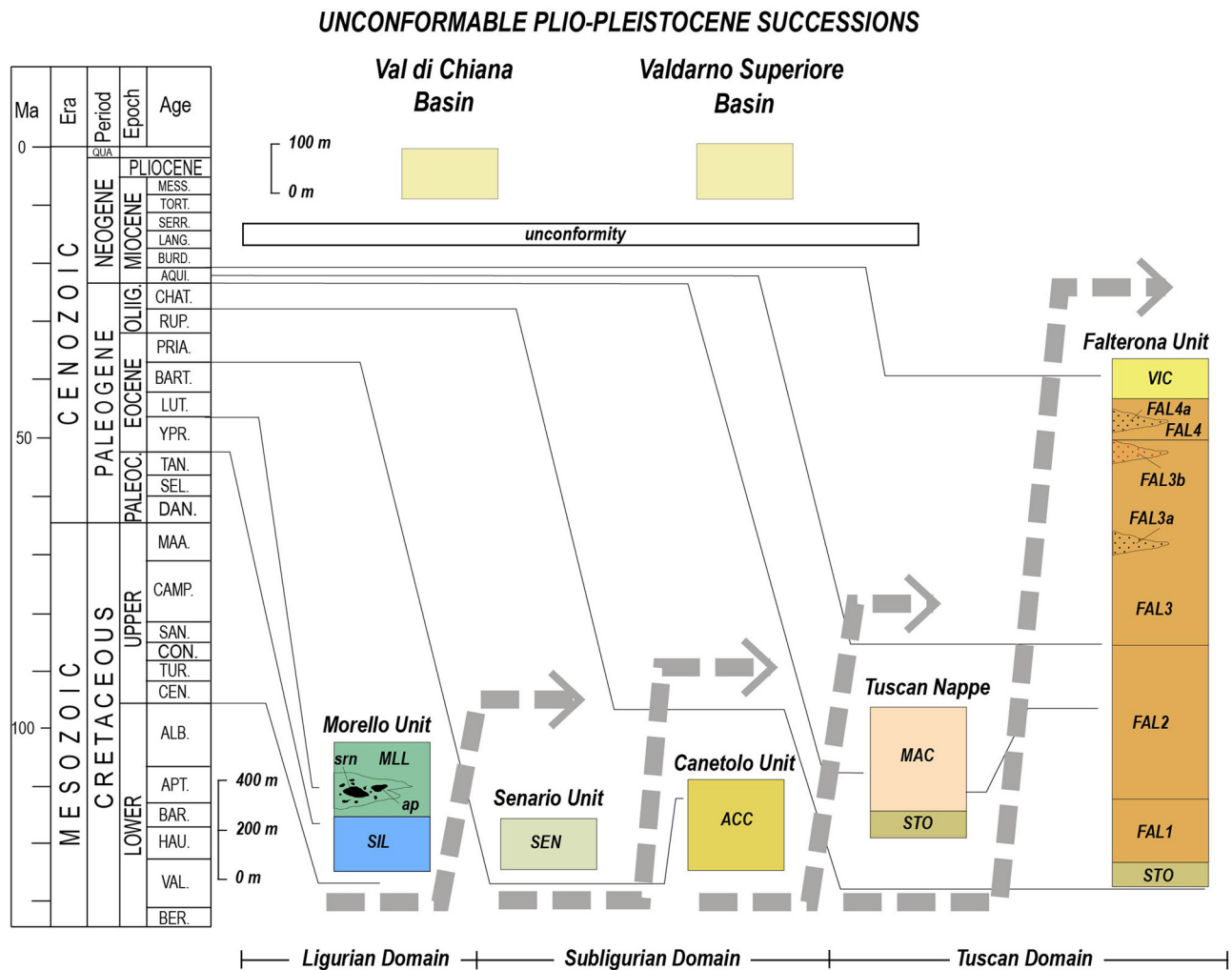


Figure 2: Stratigraphic logs of the tectonic units cropping out in the study area. ACC: Argille e Calcari Fm.; ap: Palombini Shale slide blocks; FAL1: Monte Falco member; FAL2: Camaldoli member; FAL3: Montalto member; FAL3a and FAL3b: debris flow deposits in FAL3; FAL4: Lonnano member; FAL4a: debris flow deposits in FAL4; MAC: Macigno Fm.; MLL: Monte Morello Fm.; SEN: Monte Senario Fm.; SIL: Sillano Fm.; SNE: Vico Flysch; srn: serpentinite slide blocks; STO: Scaglia Toscana Fm.; VIC: Vicchio Fm. Time scale from Gradstein et al. [32].

units were in turn deformed into an E-verging imbricated stack during the migration of the deformation front since the Early Oligocene. The stack of the tectonic units in the central and western areas of the Northern Apennines was subsequently dissected by normal faults originating during the extensional tectonics that followed the migration of the deformation front.

3 Geological setting of the Arezzo area

The study area is characterized by a pile of tectonic units stacked toward ENE (Figure 2). The lower structural levels are represented by the Falterona Unit and the Tuscan Nappe, both including Oligo-Miocene foredeep turbidites in their successions (Figure 3). The tectonic contact between these two units is represented by an NW-SE trending thrust along which the Tuscan Nappe overlies the Falterona Unit. Both these units are thrust by the Subligurian (Canetolo and Senario) Units and by Ligurian Units (Morello Unit). The tectonic stack of the study area is dissected by normal and strike-slip faults and covered by Plio-Pleistocene continental deposits filling the Valdarno Superiore and Val di Chiana extensional basins [33–35].

In the study area (Figure 3), the Tuscan Nappe only includes its uppermost deposits, i.e., the Scaglia Toscana and the Macigno Fms. W of the study area, in the Chianti region, the base of these formations includes Late Triassic to Cretaceous, mainly carbonate deposits [36,37]. The succession was detached from its substratum along the Late Triassic evaporites, today represented by a cataclastic level, known as *Calcare Cavernoso*. The Macigno Fm. is the youngest formation of the Tuscan Nappe and consists of siliciclastic turbidites ranging in age from Chattian to Early Aquitanian [12,38,39]. The Falterona Unit includes the Scaglia Toscana Fm. (Chattian), the Monte Falterona (Chattian to Aquitanian), and Vicchio Fms. (Late Aquitanian to Early Serravallian). This succession was detached from its substratum along the Scaglia Toscana Fm. [14,40,41].

The Ligurian and Subligurian Units cropping out in the study area were stemmed from the ocean-continent transition at the Adria margin and were deformed before the Miocene during their transfer to the Apennine orogenic wedge [42,43].

The Ligurian Units are represented in the area by the Morello Unit, made up of deep-sea, carbonate turbidites (i.e., Sillano and Monte Morello Fms.), ranging in age from Campanian to Middle Eocene with debris flows and slide deposits at its top [17].

The Subligurian Units crop out in the area as Canetolo and Senario Units. The Canetolo Unit is represented here by Middle Eocene carbonate turbidites [44]. The Senario Unit is made up of siliciclastic turbidites of the Late Eocene–Early Oligocene age, which include fragments of Early Oligocene andesites, that can be correlated with the Aveto Unit of the Emilian Apennines [45–47].

4 Stratigraphic features and deformation history of the Macigno Formation

Several stratigraphic and structural contributions were devoted to the Tuscan Nappe in both Northern and Southern Tuscany [9]. Overall, all the authors interpreted the succession of the Tuscan Nappe as representative of the Late Triassic–Early Miocene sedimentation on the Adria continental margins during the rifting and spreading events and the subsequent evolution from closure to the continental collision. In this frame, the Macigno Fm. is regarded as a foredeep deposits sedimented in front of the Apennine thrust-and-fold belt [10].

A detailed stratigraphic analysis of the Macigno Fm. in Southern Tuscany has been provided by Ferrini and Pandeli [48] and by Cornamusini [39,49]. According to Cornamusini [49], in the study area, the Macigno Fm. represents a deep-sea fan deposit characterized by a high-efficiency transport system. The sedimentological evidence and the arenite petrography indicate that the Macigno Fm. deposits were supplied by source areas located in the Western and Central Alps [50–53], that in the Late Oligocene–Early Miocene were subjected to exhumation and resulting high erosion rate. In the medium and upper part of the Macigno Fm., debris flow-bearing carbonate clasts derived from the Subligurian Units are interpreted as derived from the deformation front of the Apennine fold-and-thrust belt, which represented a second source of clastic material interfering with the siliciclastic turbidites. In the Emilian Apennines, Botti *et al.* [54] mapped the Macigno Fm. and described three different members. The age of the transition between the Scaglia and the Macigno Fm. is Chattian in age (MNP 25a). The first member is characterized by amalgamated thick beds of sandstones of Chattian age (MNP 25a-b). The second member is Aquitanian p.p. in age (MNN1) and consists of a thinning-fining upward sequence of thick to medium beds of sandstones alternating with thin to medium beds of siltstones and shales. The third member includes thin beds of siltstones and fine-grained sandstones of Early Aquitanian age (Zone MNN1). According to Catanzariti *et al.* [12], the age of the top of the Macigno Fm.

does not exceed the Early Aquitanian corresponding to MNN1c Subzone.

The deformation history of the Tuscan Nappe has been mainly reconstructed in the Apuan Alps area by several authors [55–58]. All the contributions [59–61] point to a poly-phase evolution made by two deformation events. The first one, generally referred to as the D1 phase, originated in the Early Miocene by contractional tectonics leading to the detachment of the Tuscan Nappe and its deformation by thrusting and folding. This phase is mainly characterized by E-verging, isoclinal folds that are associated with a slaty cleavage developed under very low-grade metamorphic conditions at a depth of about 7 km [62–64].

During this phase, the eastern front of the Tuscan Nappe was deformed by a km-scale, E-verging overturned fold recognized from the Emilian Apennines to Southern Tuscany. This fold is well exposed in the eastern rim of the study area (Figure 3). This structure is regarded as related to the late stage of the D1 phase and interpreted as a fold-propagation fold connected with the main thrust at the base of the Tuscan Nappe [60].

The second set of deformations, generally referred to as the D2 phase, was achieved during the Middle Miocene. This phase consists of folds with sub-horizontal axial planes with associated crenulation cleavage. The folds are associated with low-angle normal faults marked by

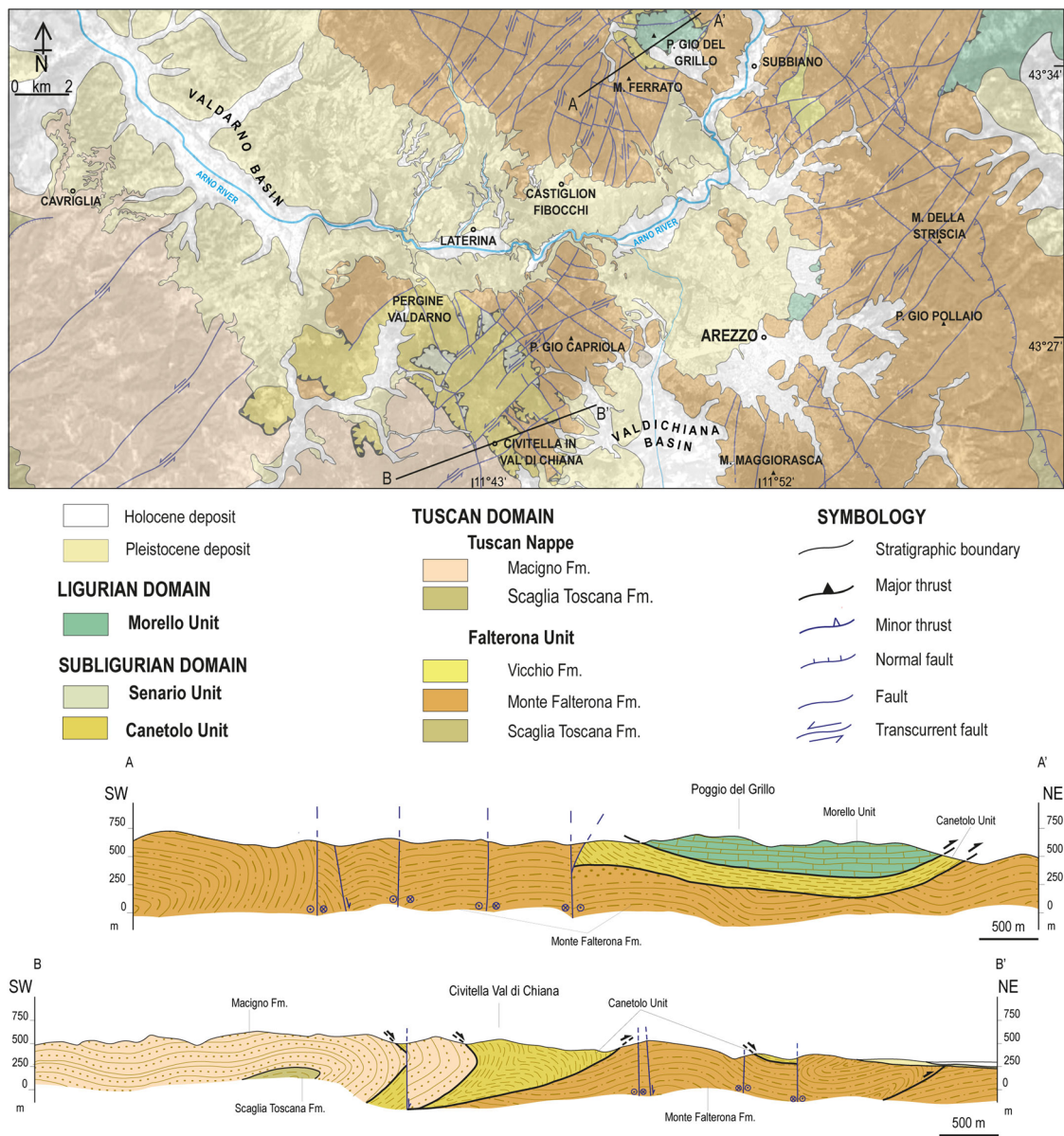


Figure 3: Tectonic sketch map of the study area and related cross-sections.

cataclastic shear zones. This phase developed during the main exhumation stage of Tuscan Nappe driven by continuous underplating of material at the base of the Apennine orogenic wedge and coeval extensional tectonics at a shallow structural level [53].

Although the ages of the deformation phases are poorly constrained for the Tuscan Nappe, the involvement in the deformation of its youngest deposits, i.e., the Macigno Fm., indicates that this unit began to be deformed from the Late Aquitanian age.

5 Methods

Field activities including stratigraphic and structural analysis were performed to reconstruct in detail the sedimentary succession of the Falterona Unit, and its deformation history. The main linear and planar structural features were systematically collected where cross-cutting relationships between different generations of structures were observed. All the measures were plotted in stereographic projections. During fieldwork, sampling for microstructural investigation and for the study of the calcareous nannofossil assemblages were performed. For the latter, a total of 144 samples were collected from several sections of the Falterona Unit (see Supplementary materials) and then prepared as smear slides following standard techniques [65]. Observation of smear slides was conducted under a polarized light microscope at 1,250 \times . For the time interval investigated, the regional biostratigraphic scheme proposed by Fornaciari and Rio [66] was adopted. The MNP-MNN biozonation is correlated with the more recent CNO-CNM biozonation reported in Raffi *et al.* [67,68] and the NP biozonation of Martini [53], together with the chronostratigraphic scale. Because of the reworking that affects some of the assemblages, which can misrepresent the amounts of long-range species (i.e., *Coccolithus pelagicus*, *Cyclicargolithus floridanus*, *Dictyococcites* spp.), and the markers that characterize the interval of time investigated, data were collected applying only one routine quantitative method. Therefore, only the marker species of the genus *Sphenolithus* (*Sphenolithus ciperensis*, *Sphenolithus delphix*, *Sphenolithus disbelemnus*, *Sphenolithus belemnus*) were counted within a prefixed number of 50–100 taxonomically related forms.

6 The Falterona Unit

6.1 Lithostratigraphy

In the study area, the Falterona Unit consists of a Chattian to Burdigalian succession up to 1,800 m thick, which

includes the Scaglia Toscana, Monte Falterona, and Vicchio Fms. (Figure 4). In the literature, the last two formations were subdivided into members. In the study area, the Scaglia Toscana Fm. represents the detachment level and crops out exclusively eastward. The top of the exposed succession is represented by the lower member of the Vicchio Fm., although recognized only in several scattered outcrops. The Monte Falterona Fm. is the most prominently exposed formation in the mapped area.

6.1.1 Scaglia Toscana Formation

The Scaglia Toscana Fm. is represented by the uppermost Monte Filoncio member. The samples collected in this study were all barren, whereas the ages reported in the literature range from Rupelian p.p. to Chattian p.p. (MNP22-MNP25b) [69]. This member, up to 150 m thick, consists of medium to thick beds of varicolored shaly marls and marls with interlayered thin beds of calcarenites. These calcarenites can be classified as packstones with fragments of filament-bearing calcilutites, biomicrites, and oosparites and calpionella-bearing calcilutites. These deposits are regarded as supplied by the uplifted forebulge of the Northern Apennine belt. The stratigraphic contact with the overlying Monte Falterona Fm. is sharp.

6.1.2 Monte Falterona Formation

The Monte Falterona Fm. consists of a thick (ca. 1,700 m) deep-sea fan turbidite succession characterized by a fining and thinning upward trend (Figure 4). From the bottom to the top, four members were distinguished based on the arenite/pelite (a/p) ratio showing an upward progressive decrease.

The Monte Falco member (FAL1, Figure 4a) represents the oldest portion of the Monte Falterona Fm. It is characterized by siliciclastic turbidites settled in thick to very thick beds of coarse-grained arenites with fine-grained conglomerates at the base. The beds are generally amalgamated and groove and flute casts as well as rip-up clasts are often observed at their base. The thickness of this member is about 250 m.

The Monte Falco member shows a gradual transition to the Camaldoli member (FAL2, Figure 4b). This member, up to 600 m thick, consists of siliciclastic turbidites represented by medium to thick beds of arenites in alternation with thin beds of siltstones and shales. The arenites are medium to coarse grained with well-graded beds and are characterized by flute clasts and rip-up clasts at their base. Medium to thick layer

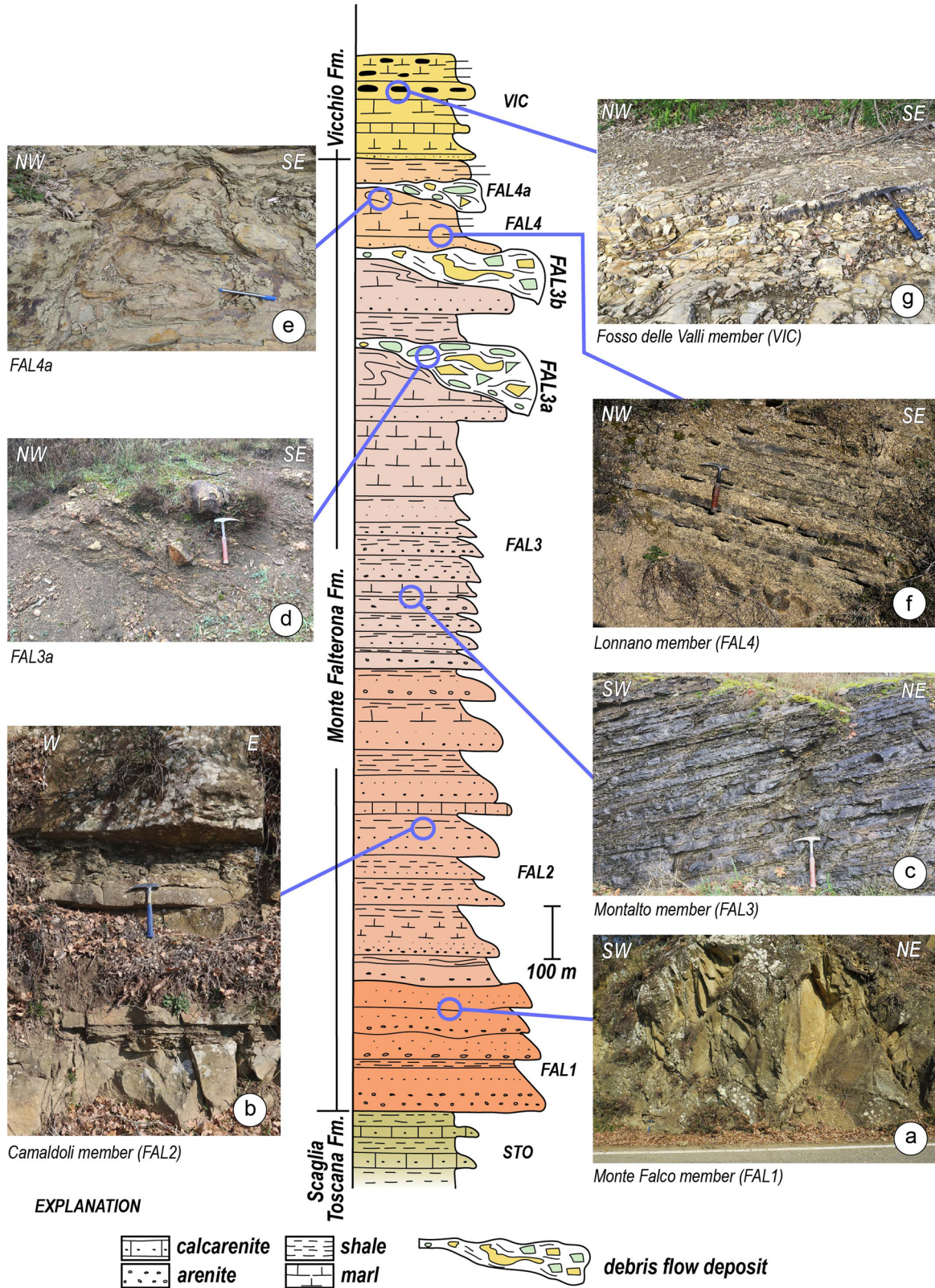


Figure 4: Lithostratigraphic log of the Falterona Unit reconstructed on the basis of the field observations and the field pictures of the rock types cropping out in the study area. For the labelled field pictures see the text.

marls, calcareous marls, and calcarenites can be observed on some outcrops of Camaldoli members.

This member gradually passes to the Montalto member (FAL3, Figure 4c) 800 m thick characterized by siliciclastic turbidites of medium to thin layered beds of fine-to medium-grained arenites topped by siltstones and shales. Flute and groove casts as well as rip-up clasts are present at the base of the thicker turbidite sequences. At its top, this member includes carbonate turbidites made of megabeds of marls that lack sedimentary structure. Within this member, two lenticular-shaped levels of debris flow (olistostromes) were mapped as FAL3a and FAL3b. These latter are made of angular to subangular clasts of carbonate, ranging in size from 0.5 cm to 15 m, set in a shaly matrix (Figure 4d). In the FAL3a deposits, the calcilutite and calcarenite clasts are Ypresian in age whereas those of the FAL3b contain a Lutetian-Bartonian foraminifera assemblage characterized by *Nummulites* sp. Overall, the clasts can be referred to as successions of the Ligurian and Subligurian Units. Slide blocks with diameters of 10–20 m composed of marly limestones, marlstones, and calcarenites are also observed within the debris flow deposits. All around these deposits, the siliciclastic turbidites are characterized by gravity-driven intraformational processes such as slumps (Figure 4e).

At the top of the Monte Falterona Fm., the Lonnano member (FAL4, Figure 4f) crops out. This member, up to 150 m thick, consists of siliciclastic thin-layered turbidites of thin layers of fine-grained arenites and thin to medium beds of siltstones, marlstones, and shales. This member includes debris flow deposits (FAL4a) similar to those in the Montalto member.

Overall, the Monte Falterona Fm. can be interpreted as formed in a depositional environment from lobe (FAL1) to fringe lobe (FAL2, 3, and 4).

6.1.3 Vicchio Formation

In the study area, the lowermost part of the Vicchio Fm., corresponding to the Fosso delle Valli member [70], crops out. This member, about 150 m thick, is made up of marlstones, silty-marlstones, and calcilutites with rare thin layers of fine-grained siltstones (Figure 4g). The characteristic of this member is the occurrence of thin layers of volcano-derived black cherty levels within the marlstones. Slumps, intraformational breccias, and debris flow deposits are also reported [70]. This formation lies, with a sharp but conformable contact, at the top of the Lonnano member of the underlying Monte Falterona Fm., without evidence of an angular unconformity, as also detected in the neighboring areas [70–72]. For

this formation, an underfilled slope depositional environment has been proposed [13,69,70].

6.2 Nannofossils dating

Calcareous nannofossil data on the Monte Filoncio member of the Scaglia Toscana Fm. outcropping in the area are taken from the literature [73,74]. For the basal part of this member, the studies reported nannofossil assemblage indicative of the Rupelian MNP22 Zone (Early Oligocene), because of the occurrence of *Dictyococcites bisectus*, *Dictyococcites scrippsae*, *Ericsonia obruta*, *Reticulofenestra hillae*, *Reticulofenestra umbilicus*, and *Sphenolithus predistentus*. The top of the member, where the reported calcareous nannofossil assemblages are characterized by the absence of *D. bisectus* and the presence of *Cyclicargolithus abisectus* <10 µm, can be assigned to the Chattian–Aquitainian transition.

The Monte Falterona Fm. is dated from Chattian to Aquitainian. Calcareous nannofossil assemblages found in samples from different successions (Figure 5) have allowed the recognition of zones and subzones from MNP25a to MNN1d p.p. Zone MNP25a was recognized in the lower part of the formation (FAL1) based on the occurrence of *S. ciperoensis* in assemblage with *C. pelagicus*, *C. abisectus*, *C. floridanus*, *D. bisectus*, *D. scrippsae*, and *Sphenolithus moriformis*. However, Cibin *et al.* [75] reported an age of FAL1 up to MNP25b Zone.

The Zone MNN1 can be attributed to FAL2, based on assemblages containing *C. pelagicus*, *C. abisectus*, *C. floridanus*, *Dictyococcites* sp. (small and medium-sized specimens <8 µm), *Discoaster deflandrei*, *Sphenolithus bipedis*, *Sphenolithus conicus*, *Sphenolithus dissimilis*, and *S. moriformis*. In literature, the FAL2 was reported ranging from Zone MNP25b to Subzone MNN1d [75].

The occurrence of *S. disbelemnus* in assemblage with *C. pelagicus*, *C. abisectus*, *C. floridanus*, *Dictyococcites* sp. (small- and medium-sized specimens <8 µm), *D. deflandrei*, *Helicosphaera carteri*, *Helicosphaera euphratis*, *S. conicus*, *S. dissimilis*, and *S. moriformis* constraints the FAL3 and FAL4 members to the Subzone MNN1d.

The Vicchio Fm. is Late Aquitainian–Early Serravallian in age. Calcareous nannofossil assemblages from Fosso delle Valli member contain *C. pelagicus*, *C. floridanus*, *Dictyococcites* sp. (small- and medium-sized specimens <8 µm), *Discoaster* sp., *H. carteri*, *Reticulofenestra* sp. (small-sized specimens <5 µm), *S. conicus*, *S. dissimilis*, and *S. moriformis*, which characterize Zone MNN1. The low occurrence of *S. belemnus* (1%) in a few of the assemblages observed also suggests the upper part of Zone MNN2b.

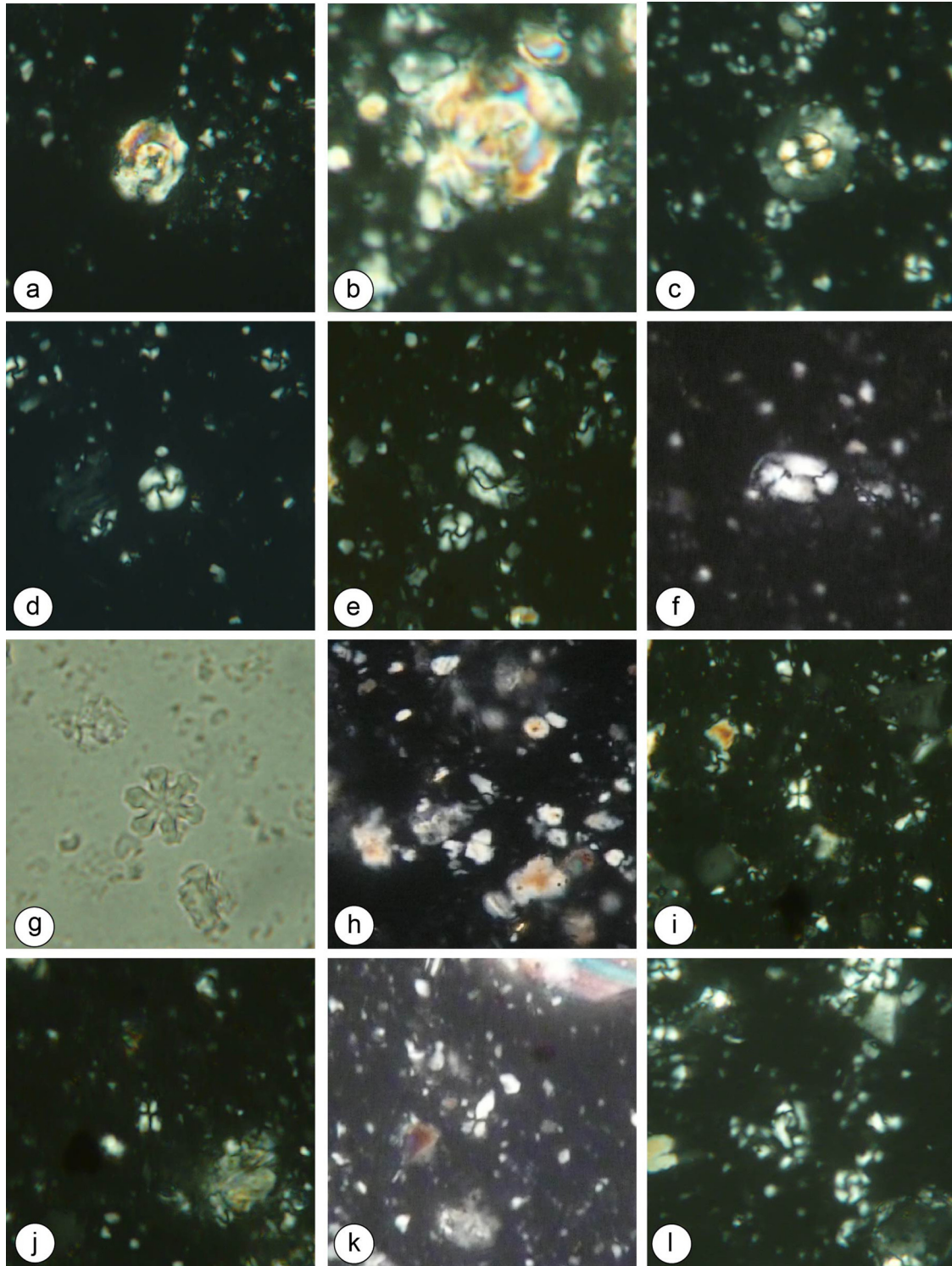


Figure 5: Microphotographs of selected calcareous nannofossil taxa recognized in the studied samples. Light Microscope photographs are in cross-polarized light (XPL) and parallel light (PL). (a) *C. abisectus*, XPL; (b) *D. bisectus*, XPL; (c) *C. pelagicus*, XPL; (d) *C. floridanus*, XPL; (e) *H. euphratis*, XPL; (f) *H. carteri*, XPL; (g) *D. deflandrei*, PL; (h) *S. ciperoensis*, XPL; (i) *S. dissimilis*, XPL; (j) *S. disbelemnus*, XPL; (k) *S. belemnus*, XPL; (l) *Reticulofenestra* sp., XPL.

The turbidites close to the debris flow deposits show a reworked nannofossil assemblage. The first reworked assemblage consists of *Chiasmolithus gigas*, *Chiasmolithus solitus*, *C. pelagicus*, *C. floridanus*, *Discoaster barbadiensis*, *Discoaster kuepperi*, *Pseudotriquetrorabdulus inversus*, *Reticulofenestra dictyoda*, *Sphenolithus cuniculus*, *Sphenolithus furcatolithoides*, *S. moriformis*, *Sphenolithus orphanknollensis*, *Sphenolithus radians*, *Sphenolithus richteri*, and *Zyghrablitus bijugatus*. The occurrence of *S. cuniculus* and *C. gigas* indicates a Lutetian age (Zone CNE11). A second reworked assemblage consisting of *C. pelagicus*, *C. floridanus*, *D. bisectus*, *D. scrippsae*, *Sphenolithus*

distentus, and *S. moriformis* suggests a Rupelian–Chattian age (Zone CNO4).

6.3 Deformation history

The deformation history of the Falterona Unit is coherent with its involvement in the Northern Apennine fold-and-thrust belt. In fact, deformation mainly consists of top-to-E/NE thrust and associated fault-propagation folds producing

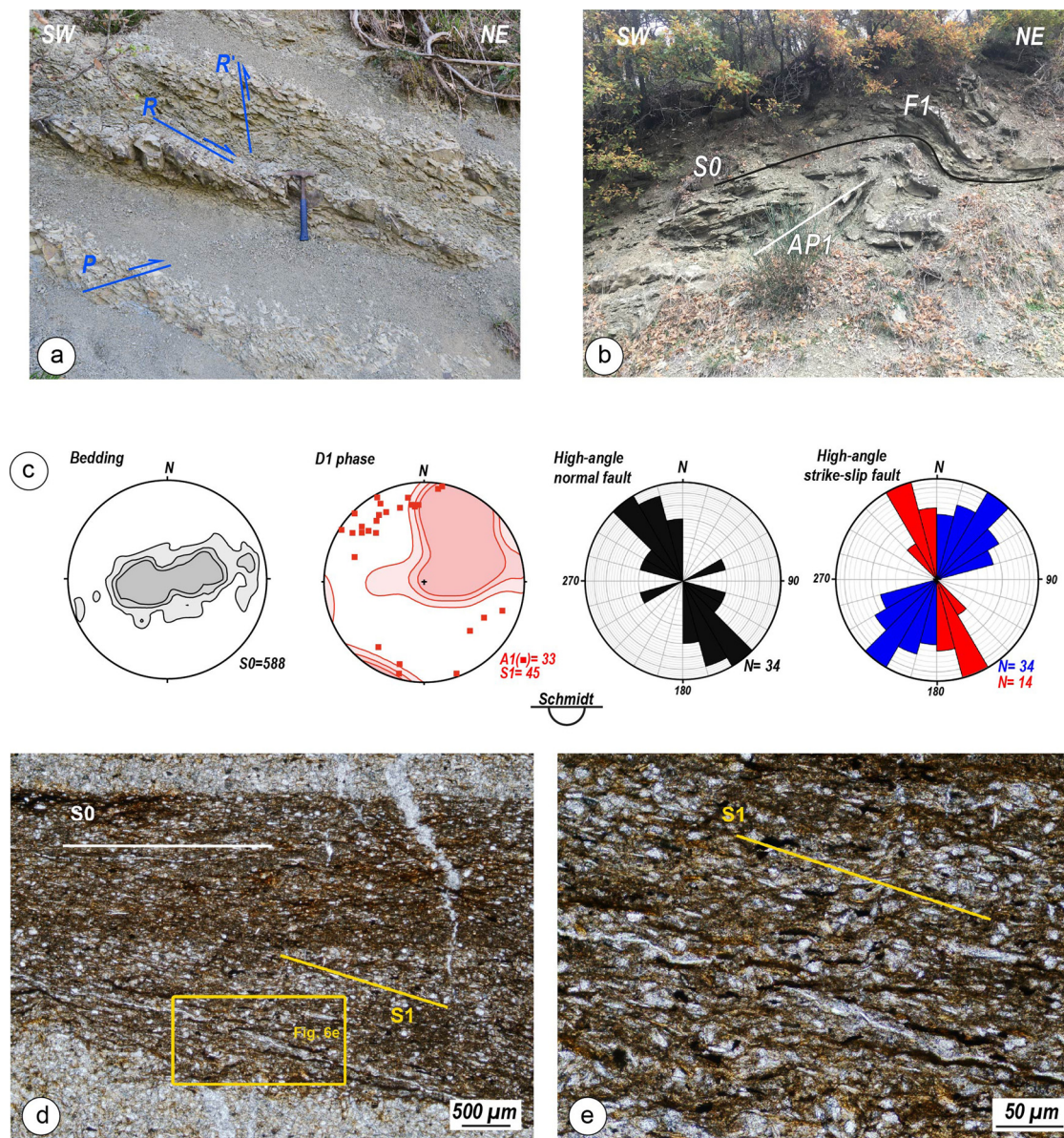


Figure 6: The structural setting in the Falterona Unit. (a) Cataclastic shear zone in the Vicchio Fm. The Riedel system suggesting a top-to-E/NE sense of shear; (b) tight F1 fold in the Camaldoli member (FAL2); (c) stereographic projections of bedding, axial planes, and fold axis (Schmidt net, lower hemisphere) and rose diagrams of the normal and strike-slip faults; (d) microphotographs showing the S1 foliation in the Montalto member (FAL3), parallel-polarized light; and (e) microphotographs showing the passive rotation of detrital phyllosilicates in the Montalto member (FAL3), parallel-polarized light.

an imbricate fan of deformed thrust sheets (Figure 3). These thrusts are characterized by a ramp and flat geometry with smooth trajectory. At the mesoscale, the thrusts are represented by m-thick cataclastic shear zones which, in the finer-grained rocks, are associated with well-developed Riedel systems coherent with a top-to-E/NE sense of shear (Figure 6a). The folds associated with the thrusts are represented by F1 tight to open folds (Figure 6b) with rare, overturned limbs. These folds are well developed in the sequence with high competence contrast. The fold axis and the axial plane show directions ranging between NW-SE to N-S (Figure 6c). The axial planes show both medium- to low-angle dipping, everywhere toward SW-W even if some back-thrusts with E-SE dipping axial planes have been recognized in the field. In the fine-grained rocks (siliciclastic pelites and/or marls), the foliation associated with the folds occurs parallel to the axial plane as a disjunctive cleavage (Figure 6d). At the microscale, the S1 foliation is represented by spaced dissolution surfaces (Figure 6e), acquired by pressure-solution processes, and passive rotation of detrital phyllosilicates without evidence of metamorphic recrystallization. This evidence is supported by the illite crystallinity data that indicate for the Falterona Unit a deformation under temperature conditions pertaining to upper diagenesis [76]. The age of this deformation history is post-Early Serravallian according to the dating of the top of the Vicchio Fm [72].

Subsequently, the pile of thrust sheets of the Falterona Unit was dissected by high-angle fault systems which cut

all the previously described structures. The fault activity is thought to have developed starting from the Pliocene, playing a key role in the nowadays morphological configuration of the Plio-Pleistocene sedimentary basin (i.e., Valdarno and Val di Chiana basins, see Figure 3) [77–83]. The oldest fault system is represented by normal faults characterized by a main trend showing an NW-SE strike and a minor trend with a WSW-ENE direction (Figure 6c). Along the fault planes associated with this system, calcite slickenfibers can be observed indicating down-dip kinematics. The younger system instead consists of strike-slip transcurrent faults whose spatial distribution reflects a well-developed Riedel structure. The main faults show an NE-SW trend with which NNE-SSW and ENE-WSW trending synthetic faults are associated (Figure 6c). Such fault system is characterized by sub-horizontal striae and calcite-rich slicken fibers indicating overall sinistral kinematics which can be well-appreciated also at the map scale. An NW-SE trending fault showing a dextral strike-slip kinematics was detected thus representing an antithetic system (Figure 6c).

7 Discussion

7.1 Comparison between the Macigno and Monte Falterona Formations

The Monte Falterona and Macigno Fms. are characterized by thinning- and fining-upward successions of siliciclastic

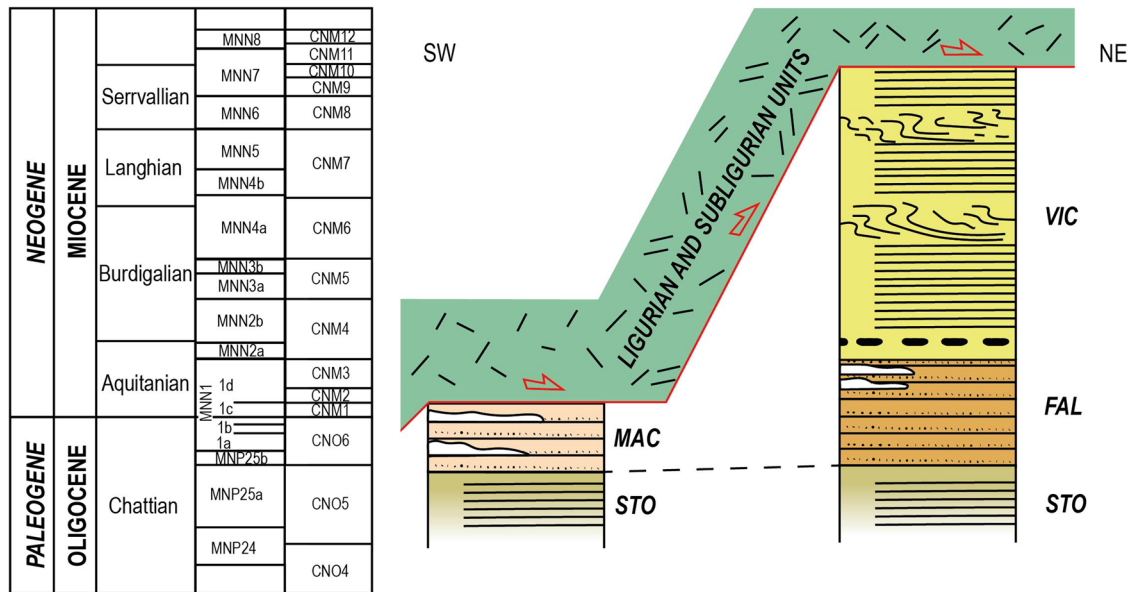


Figure 7: Schematic representation depicting the stratigraphy and the tectonic relations between the Tuscan Nappe, the Falterona Unit, and the Ligurian and Subligurian Units observed in the study area. FAL: Monte Falterona Fm.; MAC: Macigno Fm.; STO: Scaglia Toscana Fm.; VIC: Vicchio Fm. Time scale from Gradstein et al. [32].

turbidites interpreted as deposited in the same foredeep basin during the Chattian–Aquitainian. These turbidite successions are largely coeval sedimented in deep-sea fan lobes to fringe depositional environments [14,39]. However, their sedimentary evolution shows some relevant differences. The first is the age of the transition with the Scaglia Toscana Fm. (Figure 7). The transition to Macigno Fm. occurred within the MNNP25a Subzone [54], and the transition to the Monte Falterona Fm. has been assigned to the MNNP25b Subzone [69].

Another relevant difference is the age of the top of the turbidites (Figure 7) that in the Macigno Fm. has been assigned to the MNN1c Subzone, whereas the Monte Falterona Fm. has provided MNN1d Subzone [12]. It is important to outline that the entire turbidite succession of the Macigno Fm., which spans from MNN25a to MNN1c Subzones, is coeval with the first two members (FAL1 and FAL2) of the Monte Falterona Fm., whereas FAL3 and FAL4 were assigned to the MNN1d Subzone.

In addition, the Monte Falterona Fm. shows a sharp stratigraphic passage to Vicchio Fm., whose uppermost portion is Early Serravallian in age. The interpretation of this formation is still a matter of debate, even if the characterizing features are coherent with sedimentation along an underfilled slope, immediately after the detachment of the turbidites deposits of the Monte Falterona Fm. and its accretion at the front of the fold-and-thrust belt [70,72]. The Vicchio Fm. represents “draping muds” sediments characterized by slumps, intraformational breccias, and debris flow deposits indicative of intense morphotectonic instability [84–86]. The occurrence of seep-carbonates and calcarenite supplied by the carbonate shelf [86] also confirms this picture.

A further difference between Macigno and Monte Falterona Fms. is represented by the debris flow deposits supplied by the fold-and-thrust belt (Figure 7). In the Macigno Fm., these deposits [49,87,88] occur in the medium and upper parts of the succession, and their age can be regarded as Early Aquitainian. In contrast, the debris flow deposits recognized in the Monte Falterona Fm. occur only in the turbidites of the youngest members FAL3 (i.e., FAL3a and b) and FAL4 (i.e., FAL4a), that bear nannofossils assemblages suggesting a Late Aquitainian age. The carbonate turbidites supplied from the forebulge seem to be instead continuous throughout the entire sedimentation of both Macigno and Monte Falterona Fm. deposits.

These characteristics indicate for the Monte Falterona Fm. a systematic delay in the events recognized in the Macigno Fm., despite belonging to the same foredeep basin. The inception of the siliciclastic turbidite sedimentation, the emplacement of the debris flow deposits supplied

by the front of the fold-and-thrust belt, and the deactivation of the foredeep sedimentation seem to occur first in the Macigno Fm. and later in the Monte Falterona Fm.

The tectonic events that followed the turbidite sedimentation represent a further, relevant difference between the Macigno and Monte Falterona Fms. Structural analysis performed on the Falterona Unit allowed us to reconstruct a deformation history typical of the shallower crustal levels. Also, micro- to meso-scale structural features documented in the Falterona Unit, i.e., the NE-verging thrusts and the related fault propagation folds, and the missing metamorphic crystallization clearly suggest that its tectonic history developed by frontal accretion to the Apennine fold-and-thrust belt. Such structural evolution, which was reconstructed also in surrounding areas by several authors [38,89,90], resulted from the progressive eastward migration of the wedge-foredeep system. In contrast, the topmost turbidite deposits of the Tuscan Nappe (Macigno Fm.) show a different deformation history, even if sedimented in the same foredeep basin. In fact, the Tuscan Nappe was involved in a polyphase structural evolution developed under pressure and temperature anchizone conditions [91] which is regarded as reflecting underthrusting, underplating, and subsequently exhumation at shallow structural levels at the base of the Apennine orogenic wedge [59,60,76,92]. Overall, our findings outline that the Falterona Unit and the Tuscan Nappe, even if derived from the same foredeep basin, recorded a different tectono-sedimentary evolution which will be described in the next section.

It is important to outline that the Falterona Fm. has been correlated with the Modino and Cervarola Fms. from Tuscan-Emilian Apennine, both including a thick succession of siliciclastic turbidites of Early Miocene age. However, the Modino Fm. is regarded as sedimented in a wedge-top basin [93,94], i.e., a completely different geodynamic setting from the Falterona Fm. The Cervarola Fm. is instead characterized by Chattian (NP25 Zone) to Burdigalian (MNN3b Zone) turbidite succession interpreted as sedimented in a foredeep basin [12]. According to these authors, these ages indicate that the Cervarola and Falterona Fms. belonged to two separate turbidite systems, characterized by similar facies associations but with different ages of foredeep deactivation.

7.2 Reconstruction for the Macigno-Falterona foredeep

The collected data were used to propose a reconstruction of the tectono-sedimentary history of the Macigno-Falterona

foredeep basin (Figure 8). As previously stated, all the collected data indicate that Macigno and Monte Falterona Fms., even if largely coeval and belonging to the same basin, show relevant stratigraphic differences, mainly consisting in the ages of the top of the turbidite, the stratigraphic position of the debris flow deposits, the age of the topmost deposits and the contrasting deformation history.

The reconstruction of the tectono-sedimentary history started in the Chattian (Figure 8a) when the turbidites from Macigno and Monte Falterona Fms. were deposited in the same foredeep basin, as suggested by the large overlap of

their ages and their sedimentation over the same substrate, i.e., the Scaglia Toscana Fm. The sedimented turbidites were supplied from the N by the Alpine belt and channeled within the Apennine foredeep. The latter was bounded westward by the Apennine thrust-and-fold belt and eastward by the forebulge, where the carbonate sediments of the Adria continental margin were uplifted. At this time, the Apennine thrust-and-fold belt was made up of Ligurian and Subligurian Units, mainly represented by Jurassic ophiolites and Cretaceous to Oligocene sedimentary successions. The boundary between this belt and the

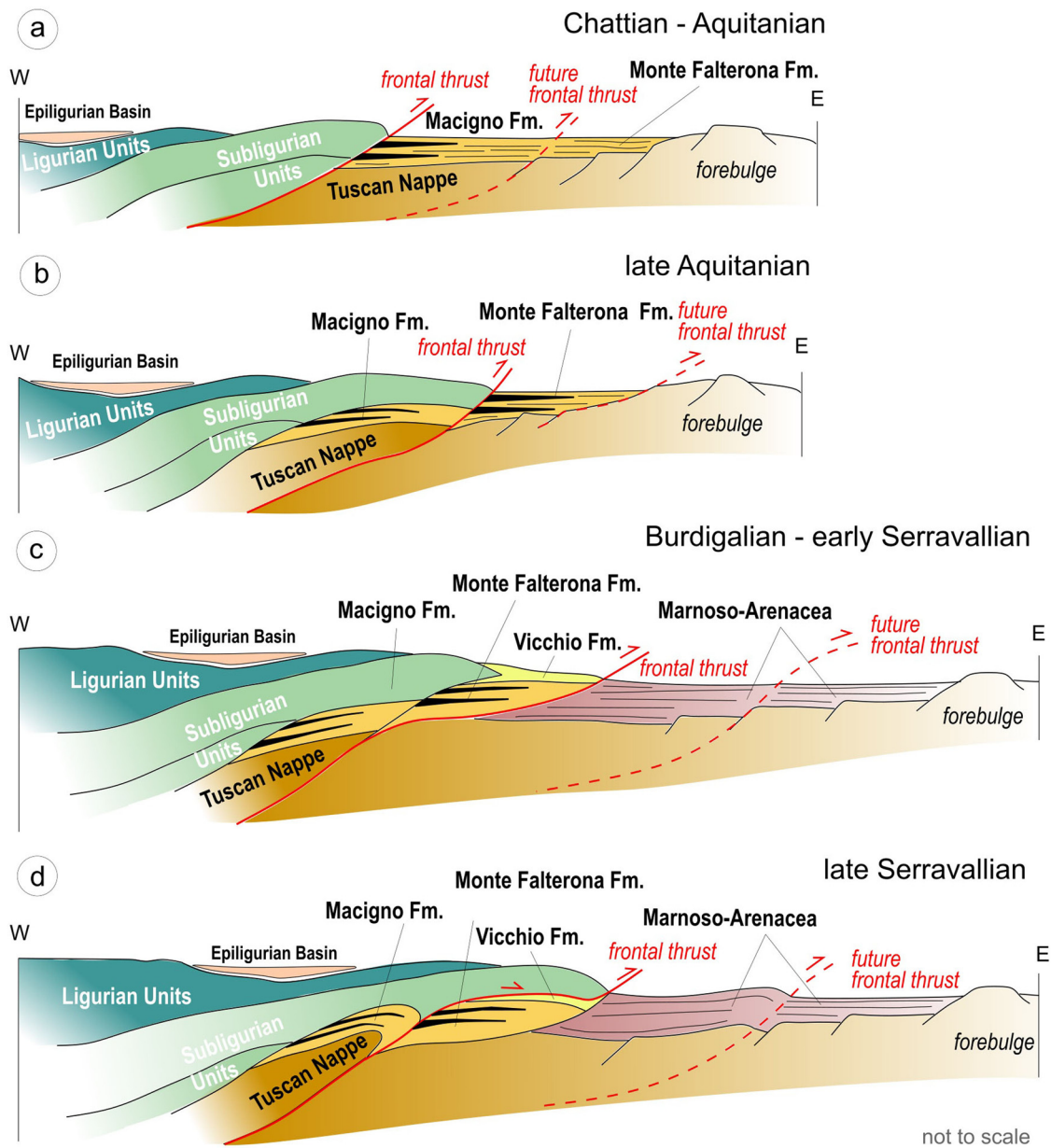


Figure 8: 2D tectonic sketch showing the evolution of the Northern Apennine foredeep in four steps: (a) Chattian–Early Aquitanian and (b) Late Aquitanian; (c) Burdigalian–Early Serravallian and (d) Late Serravallian.

Macigno-Falterona foredeep basin is represented by an active, E-verging frontal thrust. In this frame, it is important to outline that the age of the base is slightly different in the Tuscan Nappe and Falterona Unit, i.e., MNN25a and MNN25b Subzones, respectively. This evidence suggests that during the Chattian a progressive overlap of the turbidites from the Macigno-Falterona foredeep depozone toward the forebulge occurred. The turbidite sedimentation in the foredeep extended from Chattian to Early Aquitanian (MNN1c Subzone). During this time span, debris flow deposits only occurred in the Macigno Fm., whereas they are lacking in the oldest members of the Monte Falterona Fm. (FAL1 and FAL2). This occurrence implies that at this time the area where the turbidite from Tuscan Nappe sedimented was close to the front of the thrust-and-fold belt. This front was affected by active tectonics and consequently able to provide the debris flow deposits recognized in the Macigno Fm.

The main change in the Macigno-Falterona foredeep occurred in the MNN1d Subzone of Late Aquitanian (Figure 8b) when the sedimentation of the Macigno Fm. stopped and the succession of the entire Tuscan Nappe underthrust below the orogenic wedge, while the sedimentation of the turbidites of the Monte Falterona Fm. was still active. This finding can be explained by the eastward migration of the frontal thrust that moved not at the eastern border of the Macigno-Falterona foredeep basin but inside it. The frontal thrust thus cut the same foredeep basin in two different sectors that subsequently followed different evolutions. The westernmost area of the foredeep, corresponding to Macigno Fm., was subjected to underthrusting below the orogenic wedge, while the easternmost one, corresponding to the Monte Falterona Fm., remained undeformed and able to receive further turbidite deposits (Figure 8b). As a consequence, the area of sedimentation of the Monte Falterona Fm. was translated close to the front of the thrust-and-fold belt, hosting the sedimentation in the Late Aquitanian of the debris flow deposits recognized in the FAL3 and FAL4 members.

This frame is further modified in the Late Aquitanian when the sedimentation of the Vicchio Fm. started. According to Pizziolo and Ricci Lucchi [70] and Di Giulio *et al.* [40], the sharp contact between the Monte Falterona and Vicchio Fms. corresponds to a sudden bathymetric change. This change is probably the result of the frontal accretion of the Falterona Unit, that occurred when the Scaglia Toscana and Monte Falterona Fms. succession was detached at its base by a thrust, incorporated at the front of the orogenic wedge, and subsequently covered by the slope deposits of the Vicchio Fm. This event was followed by the development of a new foredeep basin, located

eastward inside the Adria continental margin, and represented by the Marnoso-Arenacea Fm. [95]. From this moment, the turbidite sedimentation in the Macigno-Falterona foredeep basin was completely deactivated. The frontal accretion of the Falterona Unit did not produce any pervasive deformation but only an uplift of its succession. This uplift was associated with a sudden break of the siliciclastic turbidites sedimentation, which became confined in the new foredeep basin.

During the sedimentation of Vicchio Fm., which lasted until the Early Serravallian (Figure 8c), the Tuscan Nappe was under deformation at a depth of about 7 km at the base of the Apennine orogenic wedge. Finally, further migration of the Apennine fold-and-thrust belt occurred in the Langhian, recorded by the D1 phase deformation of the Falterona Unit that was achieved during its thrusting by the Tuscan Nappe and the overlying Ligurian Units (Figure 8d). In the Tuscan Nappe, this event corresponds to the late stage of the D1 phase. Probably at the end of the Miocene, the entire pile of tectonic units experienced a further exhumation thus achieving the present-day structural setting.

8 Conclusions

The collected data on the Falterona Unit were used to propose a new reconstruction of the tectonic evolution of the Late Oligocene–Early Miocene Apennine foredeep. Our reconstruction indicates that until the Early Miocene (MNN1c Subzone) the siliciclastic turbidites of the Macigno and Monte Falterona Fms. belonged to the same foredeep basin. In the Late Aquitanian, the Macigno Fm. was underthrust at depth below the orogenic wedge while the sedimentation of the Monte Falterona Fm. continued up to the Late Aquitanian (MNN1d Subzone). Subsequently, also the Monte Falterona Fm. was accreted at the front of the Apennine fold-and-thrust belt and then underthrusts at the base of the orogenic wedge, but at a shallower level than that reached by the Macigno Fm.

This model indicates that the deactivation mode of the Apennine foredeep occurred by the eastward, progressive shifting of the frontal thrust that migrated within the foredeep basin itself and not at its boundary. This type of tectonic evolution seems to be repeated during the entire evolution of the Apennine belt and should be taken into account when deciphering the tectonics of the foredeep of this belt elsewhere.

Acknowledgments: We thank the reviewers and the editor for the efforts given during the submission process.

Domenico Berti is also thanked for the constructive arguments and the overall supervision.

Funding information: This research has been supported by the funds of the CARG – Project – Geological Map of Italy 1: 50,000.

Author contributions: All the authors contributed to the fieldwork. FM and MDR did the geological mapping of the area. FM, MDR, and ES collected structural data. MDR collected samples and RC studied them in the laboratory. LP and MM validated the data and reconstructed the conceptual model. MM prepared the manuscript with the contributions from all co-authors. The authors applied the SDC approach for the sequence of authors.

Conflict of interest: Authors state no conflict of interest.

References

- [1] Price RA. Large-scale gravitational flow of supracrustal rocks. South Can Rock Gravity Tecton. In: Gravity and tectonics. New York: John Wiley; 1973. p. 491–502.
- [2] Dickinson WR. Tectonics and Sedimentation. SEPM Soc Sediment Geol. 1974;22:1–27. doi: 10.2110/pec.74.22.
- [3] De Celles PG. Foreland basin systems revisited: Variations in response to tectonic settings. Tecton Sediment Basins: Recent Adv. 2012;1:405–26.
- [4] Beaumont C. Foreland basins. Geophys J R Astron Soc. 1981;65(65):291–329.
- [5] Flemings PB, Jordan TE. Stratigraphic modeling of foreland basins: interpreting thrust deformation and lithosphere rheology. Geology. 1990;18:430–4.
- [6] Sinclair HD, Coakley BJ, Allen PA, Watts AB. Simulation of Foreland Basin Stratigraphy using a diffusion model of mountain belt uplift and erosion: an example from the central Alps, Switzerland. Tectonics. 1991;10:599–620. doi: 10.1029/90TC02507.
- [7] Miall AD. Retroarc foreland and related basins. In: Busby CJ, Ingersoll RV, editors. Tectonics of sedimentary basins. Oxford: Blackwell Science; 1995. p. 393–424.
- [8] Simpson GDH. Modelling interactions between fold-thrust belt deformation, foreland flexure and surface mass transport. Basin Res. 2006;18(2):125–43.
- [9] Conti P, Cornamusini G, Carmignani L. An outline of the geology of the Northern Apennines (Italy), with geological map at 1: 250,000 scale. It J Geosci. 2020;139(2):149–94.
- [10] Ricci Lucchi F. The Oligocene to Recent foreland basins of the northern Apennines. Foreland Basins. 1986;8:103–39.
- [11] Elter P, Grasso M, Parotto M, Vezzani L. Structural setting of the Maghrebian thrust belt. Episodes. 2004;26:205–11.
- [12] Catanzariti R, Feroni AC, Ottria G, Levi N. The contribution of calcareous nanofossil biostratigraphy in solving geological problems: the example of the Oligocene-Miocene foredeep of the Northern Apennines (Italy). In: Demchuck TD, Gary AC, editors. Geologic Problem solving with microfossils: A volume in honor of Garry D. Jones. Vol. 93, Tulsa: SEPM Spec. Publ.; 2009. p. 309–22.
- [13] Plesi G, Luchetti L, Boscherini A, Botti F, Brozzetti F, Bucefalo Palliani R, et al. The Tuscan successions of the high Tiber Valley (Foglio 289-Città di Castello): biostratigraphic, petrographic and structural features, regional correlations. Boll Soc Geol Ital. 2002;121:425–36.
- [14] Barsella M, Boscherini A, Botti F, Meneghini F, Motti A, Palandri L, et al. Oligocene-Miocene foredeep deposits in the Lake Trasimeno area (Central Italy): insights into the evolution of the Northern Apennines. Ital J Geosci. 2009;128:341–52.
- [15] Brozzetti F, Cirillo D, Luchetti L. Timing of Contractional Tectonics in the Miocene Foreland Basin System of the Umbria Pre-Apennines (Italy): An Updated Overview. Geosciences. 2021;11(2):97.
- [16] Le Breton E, Brune S, Ustaszewski K, Zahirovic S, Seton M, Müller RD. Kinematics and extent of the Piemont–Liguria Basin—implications for subduction processes in the Alps. Solid Earth. 2021;12(4):885–913.
- [17] Bortolotti V, Principi G, Treves B. Ophiolites, Ligurides and the tectonic evolution from spreading to convergence of a Mesozoic Western Tethys segment. In Anatomy of an orogen: The Apennines and adjacent Mediterranean basins. Dordrecht: Springer Netherlands; 2001. p. 151–64.
- [18] Festa A, Meneghini F, Balestro G, Pandolfi L, Tartarotti P, Dilek Y, et al. Comparative analysis of the sedimentary cover units of the Jurassic Western Tethys ophiolites in the Northern Apennines and Western Alps (Italy): Processes of the formation of mass-transport and chaotic deposits during seafloor spreading and subduction zone tectonics. J Geol. 2021;129(5):533–61.
- [19] Sanità E, Di Rosa M, Marroni M, Meneghini F, Pandolfi L. Insights into the Subduction of the Ligure-Piemontese Oceanic Basin: New Constraints from the Metamorphism in the Internal Ligurian Units (Northern Apennines, Italy). Minerals. 2024;14(1):64.
- [20] Di Rosa M, Frassi C, Malasoma M, Marroni M, Meneghini F, Pandolfi L. Syn-exhumation coupling of the oceanic and continental units along the western edge of the Alpine Corsica: a review. Ofioliti. 2020;45(2):71–102.
- [21] Sanità E, Di Rosa M, Lardeaux JM, Marroni M, Pandolfi L. Metamorphic peak estimates of the Marguareis Unit (Briançonnais Domain): New constrains for the tectonic evolution of the south-western Alps. Terra Nova. 2022;34(4):305–13.
- [22] Frassi C, Di Rosa M, Farina F, Marroni M, Pandolfi L. Anatomy of a deformed upper crust fragment from Western Alpine Corsica (France): insights into continental subduction processes. Int Geol Rev. 2023;65(1):40–60. doi: 10.1080/00206814.2022.2031315.
- [23] Marroni M, Molli G, Montanini A, Tribuzio R. The association of continental crust rocks with ophiolites in the Northern Apennines (Italy): implications for the continent-ocean transition in the Western Tethys. Tectonop. 1998;292(1–2):43–66.
- [24] Marroni M, Meneghini F, Pandolfi L. A revised subduction inception model to explain the Late Cretaceous, double vergent orogen in the precollisional western Tethys: Evidence from the Northern Apennines. Tectonics. 2017;36:2227–49.
- [25] Molli G, Crispini L, Malusà M, Mosca P, Piana F, Federico L. Geology of the Western Alps-Northern Apennine junction area: a regional review. Eds Marco Beltrando, Angelo Peccerillo, Massimo Mattei, Sandro Conticelli, Carlo Doglioni J Virtual Explorer. 2010;36(3):1–49.
- [26] Mutti E, Tinterri R, Benevelli G, Di Biase D, Cavanna G. Deltaic, mixed and turbidite sedimentation of ancient foreland basins. Mar Pet Geol. 2003;20:733–55.

- [27] Turrini C, Lacombe O, Roure F. Present-day 3D structural model of the Po Valley basin, Northern Italy. *Mar Pet Geol.* 2014;56:266–89.
- [28] Garzanti E, Malusà MG. The Oligocene Alps: Domal unroofing and drainage development during early orogenic growth. *Earth Planet Sci Lett.* 2008;268(3–4):487–500.
- [29] Rosenberg CL, Schneider S, Scharf A, Bertrand A, Hammerschmidt K, Rabaute A, et al. Relating collisional kinematics to exhumation processes in the Eastern Alps. *Earth-Sci Rev.* 2018;176:311–44.
- [30] Faccenna C, Piromallo C, Crespo-Blanc A, Jolivet L, Rossetti F. Lateral slab deformation and the origin of the western Mediterranean arcs. *Tectonics.* 2004;23(1):1–21.
- [31] Barchi MR. The Neogene-Quaternary evolution of the Northern Apennines: crustal structure, style of deformation and seismicity. *J Virtual Explor.* 2010;36:1–24. doi: 10.3809/jvirtex.2009.00220.
- [32] Gradstein FM, Ogg JG, Schmitz MD, Ogg GM. The geologic time scale 2020. Elsevier; 2020.
- [33] Martini IP, Sagri M. Tectono-sedimentary characteristics of Late Miocene-Quaternary extensional basins of the Northern Apennines, Italy. *Earth-Sci Rev.* 1993;34:197–233.
- [34] Pascucci V, Merlini S, Martini IP. Seismic stratigraphy of the Miocene-Pleistocene sedimentary basins of the Northern Tyrrhenian Sea and western Tuscany (Italy). *Basin Res.* 1999;11:337–56.
- [35] Collettini C, De Paola N, Holdsworth RE, Barchi MR. The development and behaviour of low-angle normal faults during Cenozoic asymmetric extension in the Northern Apennines, Italy. *J Struct Geol.* 2006;28:333–52.
- [36] Bernoulli D, Kälin O, Patacca E. A sunken continental margin of the Mesozoic Tethys: The Northern and Central Apennines. *Symposium “Sédimentation Jurassique W Européen”: Association Sedimentologues Français Publication Spéciale. Vol. 1, 1979. p. 197–210.*
- [37] Ciarpacina G, Passeri L. Late Triassic and Early Jurassic sedimentary evolution of the Northern Apennines: An overview. *Boll Soc Geol It.* 2005;124:189–201.
- [38] Costa E, Di Giulio A, Plesi G, Villa G, Baldini C. I flysch oligo-miocenici della trasversale Toscana meridionale-Casentino: dati biostratigrafici e petrografici. *Atti Tic Sc Terra.* 1997;39:281–302.
- [39] Cornamusini G. Compositional evolution of the Macigno Fm. of southern Tuscany along a transect from the Tuscan coast to the Chianti Hills. *Boll Soc Geol It.* 2002;1(1):365–74.
- [40] Di Giulio A, Mancin N, Martelli L, Sani F. Foredeep palaeobathymetry and subsidence trends during advancing then retreating subduction: the Northern Apennine case (Oligocene-Miocene, Italy). *Basin Res.* 2013;25(3):260–84.
- [41] Carboni F, Brozzetti F, Mirabella F, Cruciani F, Porreca M, Ercoli M, et al. Geological and geophysical study of a thin-skinned tectonic wedge formed during an early collisional stage: the Trasimeno Tectonic Wedge (Northern Apennines, Italy). *Geol Mag.* 2020;157(2):213–32.
- [42] Lucente CC, Pini GA. Basin-wide mass-wasting complexes as markers of the Oligo-Miocene foredeep-accretionary wedge evolution in the northern Apennines, Italy. *Basin Res.* 2008;20(1):49–71.
- [43] Tavarnelli E, Mazzarini F, Scialoja E, Isola I. Deformation history of a foredeep basin during the incorporation of its deposits within an advancing orogenic wedge: the case of the Oligocene-Early Miocene Macigno Costiero Formation, southern Tuscany, northern Apennines, Italy. *J Struct Geol.* 2021;147:104347.
- [44] Elter P, Ghiselli F, Marroni M, Ottria G. Note illustrative del Foglio 198 “Bobbio” della Carta Geologica d’Italia in scala 1:50.000. Istituto Poligrafico Zecca dello Stato, Roma. 1997;1:1–106.
- [45] Elter P, Catanzariti R, Ghiselli F, Marroni M, Molli G, Ottria G, et al. L’Unità Aveto (Appennino settentrionale): caratteristiche litostratigrafiche, biostratigrafia, petrografia delle arenite ed assetto strutturale. *Boll Soc Geol It.* 1999;118:41–63.
- [46] Mattioli M, Lustrino M, Ronca S, Bianchini G. Alpine subduction imprint in Apennine volcanoclastic rocks. Geochemical–petrographic constraints and geodynamic implications from Early Oligocene Aveto-Petrignacola Formation (N Italy). *Lithos.* 2012;134:201–20.
- [47] Anfinson OA, Malusà MG, Ottria G, Dafov LN, Stockli DF. Tracking coarse-grained gravity flows by LASS-ICP-MS depth-profiling of detrital zircon (Aveto Formation, Adriatic foredeep, Italy). *Mar Pet Geol.* 2016;77:1163–76.
- [48] Ferrini G, Pandeli E. Le associazioni di facies torbiditiche nel Macigno dei Monti del Chianti. *Boll Soc Geol It.* 1983;102:223–40.
- [49] Cornamusini G. Evoluzione deposizionale di un settore del sistema catena-avanfossa dell’Appennino settentrionale: stratigrafia fisica e sedimentologia del Macigno della Toscana meridionale. *Boll Soc Geol It.* 2004;123:201–27.
- [50] Valloni R, Zuffa GG. Provenance changes for arenaceous formations of the northern Apennines, Italy. *Geol Soc Am Bull.* 1984;95(9):1035–9.
- [51] Dunkl I, Di Giulio A, Kuhlemann J. Combination of single-grain fission-track chronology and morphological analysis of detrital zircon crystals in provenance studies: sources of the Macigno Formation (Apennines, Italy). *J Sediment Res.* 2001;71(4):516–25.
- [52] Bruni P, Pandeli E, Nebbiai M. Petrographic analysis in regional geology interpretation: Case history of the Macigno (northern Apennines). *Geol Soc Am Spec Publ.* 2007;420:94–105.
- [54] Botti F, Daniele G, Baldacci F, Palandri S, Ribolini A, Ungari A, et al. Note illustrative della Carta Geologica d’Italia alla scala 1: 50.000 - Foglio 251 Porretta Terme. Roma: ISPRA - Servizio Geologico d’Italia; Vol. 1, 2011. p. 1–196.
- [55] Pertusati PC, Plesi G, Cerrina Feroni AG. Alcuni esempi di tettonica polifasata nella Falda Toscana. *Boll Soc Geol It.* 1977;96:587–603.
- [56] Giammarino S, Giglia G. Gli elementi strutturali della piega di La Spezia nel contesto geodinamico dell’Appennino Settentrionale. *Boll Soc Geol It.* 1990;109:683–92.
- [57] Clemenzi L, Molli G, Storti F, Muchez P, Swennen R, Torelli L. Extensional deformation structures within a convergent orogen: The Val di Lima low-angle normal fault system (Northern Apennines, Italy). *J Struct Geol.* 2014;66:205–22.
- [58] Frassi C, Ottria G, Ferdeghini A. Fault tectonics of the Tuscan Nappe in the eastern sector of the Apuan Alps (Italy). *J Maps.* 2020;16(2):745–54.
- [59] Elter FM, Sandrelli F. Inquadramento strutturale dei Monti del Chianti. *Boll Soc Geol Ital.* 1995;114:537–47.
- [60] Bonini M. Basement-controlled Neogene polyphase cover thrusting and basin development along the Chianti Mountains ridge (Northern Apennines, Italy). *Geol Mag.* 1999;136:133–52.
- [61] Brogi A, Lazzarotto A. Deformazioni sin-collisionali nella Falda Toscana a sudobest del Monte Amiata (Toscana Meridionale): il sovrascorrimento di Monte Aquilaia. *Boll Soc Geol It.* 2002;121:299–312.
- [62] Cerrina Feroni A, Plesi G, Fanelli G, Leoni L, Martinelli P. Contributo alla conoscenza dei processi metamorfici di grado molto basso

- (anchimetamorfismo) a carico della Falda Toscana nell'area di ricoprimento apuano. *Boll Soc Geol It.* 1983;102:269–80.
- [63] Carosi R, Leoni L, Montomoli M, Sartori F. Very low-grade metamorphism in the Tuscan Nappe, Northern Apennines, Italy: relationships between deformation and metamorphic indicators in the La Spezia mega-fold. *Swiss Bul Min Petr.* 2003;83(1):15–32.
- [64] Molli G, White JC, Kennedy L, Taini V. Low-temperature deformation of limestone, Isola Palmaria, northern Apennine, Italy – The role of primary textures, precursory veins and intracrystalline deformation in localization. *J Struct Geol.* 2011;33(3):255–70.
- [53] Carmignani L, Kligfield R. Crustal extension in the Northern Apennines: the transition from compression to extension in the Alpi Apuane core complex. *Tectonics.* 1990;9(6):1275–303.
- [65] Bown PR, Young JR. Techniques. In: Bown PR, editor. *Calcareous Nannofossil Biostratigraphy* (British Micropalaeontological Society Publications Series). London: Chapman and Kluwer Academic; 1998. p. 16–28.
- [66] Fornaciari E, Rio D. Latest Oligocene to early Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. *Micropal.* 1996;42:1–36.
- [67] Raffi I, Agnini C, Backman J, Catanzariti R, Pälke H. A Cenozoic calcareous nannofossil biozonation from low and middle latitudes: A synthesis. *J Nannoplankton Res.* 2016;36:121–32.
- [68] Martini E. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci A, editor. *Proceedings II Planktonic Conference, Roma; 1971.* p. 739–85.
- [69] Piali G, Plesi G, Damiani AV, Brozzetti F. Note illustrative della Carta Geologica d'Italia a scala 1: 50.000. Roma: Foglio 289 “Città di Castello”; Vol. 1, 2009.
- [70] Pizzio M, Ricci Lucchi F. Le Marne di Vicchio nel quadro evolutivo dei bacini oligomiocenici dell'Appennino Settentrionale (Zona del Casentino). *Atti II Seminario Cartografia Geologica, Bologna 1990, Regione Emilia-Romagna. Mem Descr Carta Geol Ital.* 1991;46:287–300.
- [71] De Donatis M. Considerazioni stratigrafiche e tettoniche sulla successione Falterona-Vicchio nell'alta Val Marecchia (Appennino Settentrionale). *Gior Geol.* 1993;55(2):35–49.
- [72] Delle Rose M, Guerrera F, Renzulli A, Ravasz-Baranyai L, Serrano F. Stratigrafia e petrografia delle marne di Vicchio (unità tettonica Cervarola) dell'Alta Val Tiberina (Appennino tosco-romagnolo). *Boll Soc Geol It.* 1994;113:675–708.
- [73] Plesi G. Note illustrative della Carta Geologica d'Italia a scala 1: 50.000. Roma: Foglio 299 “Umbertide”; Vol. 1, 2010.
- [74] Barchi M, Marroni M, Bizzarri R, Pandolfi L, Pazzaglia F. Note illustrative della Carta Geologica d'Italia a scala 1: 50.000. Roma: Foglio 310 “Passignano sul Trasimeno”; Vol. 1, 2010.
- [75] Cibin U, Di Giulio A, Martelli L, Catanzariti R, Poccianti S, Rosselli C, et al. Factors controlling foredeep turbidite deposition: the case of Northern Apennines (Oligocene-Miocene, Italy). *Geol Soc London, Spec Publ.* 2004;222(1):115–34.
- [76] Carmignani L, Decandia FA, Fantozzi PL, Lazzarotto A, Liotta D, Meccheri M. Tertiary extensional tectonics in Tuscany (northern Apennines, Italy). *Tectonophysics.* 1994;238(1–4):295–315.
- [77] Franceschelli M, Pandeli E, Puxeddu M, Porcu R, Fadda S. Illite crystallinity in pelitic and marly rocks from the Northern Apennines (southern Tuscany and Umbria, Italy). *Neues Jahrb Mineral Monatsh.* 1994;8:367–84.
- [78] Magi M. *Carta Geologica della Conoide di Loro Ciuffenna (Valdarno Superiore).* Firenze: S.E.L.C.A.; 1989.
- [79] Billi P, Magi M, Sagri M. Coarse-grained low-sinuosity river deposits: example from plio-pleistocene Valdarno basin, Italy. In: Ethridge FG, Lores RM, Harvey MD, editors. *Recent developments in fluvial sedimentology.* Tulsa: S.E.P.M., Spec. Publ; 1987. p. 197–203.
- [80] Billi P, Magi M, Sagri M. Pleistocene lacustrine fan delta deposits of the Valdarno basin. *Italy J Sedim Pet.* 1991;61:280–90.
- [81] Ghinassi M, Magi M, Sagri M, Singer BS. Arid climate 2.5 Ma in the Plio-Pleistocene Valdarno Basin (Northern Apennines, Italy). *Palaeogeog, Palaeoclim, Palaeoeco.* 2004;207(1–2):37–57.
- [82] Ghinassi M, Abbazzi L, Esu D, Gaudant J, Girotti O. Facies analyses, stratigraphy and paleontology (molluscs and vertebrates) in the Upper Pliocene sandy flood-basin deposits of the Upper Valdarno Basin (Northern Apennines). *Riv It Strat Paleont.* 2005;11:467–87.
- [83] Ielpi A. Orbitally-driven climate forcing in late Pliocene lacustrine siderite-rich clastic rhythms (Upper Valdarno Basin, Northern Apennines, Italy). *Palaeogeog, Palaeoclima, Palaeoeco.* 2012;331:119–35.
- [84] Fidolini F, Ghinassi M, Magi M, Papini M, Sagri M. The Plio-Pleistocene fluvio-lacustrine Upper Valdarno Basin (central Italy): stratigraphy and basin fill evolution. *It. J Geosci.* 2013;132(1):13–32.
- [85] Conti S, Argentino C, Fioroni C, Salocchi AC, Fontana D. Miocene seep-carbonates of the northern Apennines (Emilia to Umbria, Italy): an overview. *Geosciences.* 2021;11(2):53.
- [86] Lucente CC, Taviani M. Chemosynthetic communities as fingerprints of submarine sliding-linked hydrocarbon seepage, Miocene deep-sea strata of the Tuscan-Romagna Apennines, Italy. *Palaeogeogr Palaeoclimatol Palaeoecol.* 2005;227:176–90.
- [87] Fontana D, Conti S, Grillenzoni C. Evidence of climatic control on hydrocarbon seepage in the Miocene of the northern Apennines: The case study of the Vicchio Marls. *Mar Pet Geol.* 2013;48:90–9.
- [88] Castellucci P, Cornaggia F. Gli olistostromi nel Macigno dei Monti del Chianti: analisi stratigrafico strutturale. *Mem Soc Geol It.* 1980;21:171–80.
- [89] Cornamusini G, Ielpi A, Bonciani F, Callegari I, Conti P. Geological map of the Chianti Mts. (Northern Apennines, Italy). *J Maps.* 2012;8:22–32.
- [90] Barchi M, Landuzzi A, Minelli G, Piali G. Outer Northern Apennines. Anatomy of an orogen: the Apennines and Adjacent Mediterranean Basins. Dordrecht: Springer Netherlands; 2001. p. 215–53.
- [91] Brozzetti F, Boncio P, Piali GI. Early-middle Miocene evolution of the Tuscan Nappe-western Umbria foredeep system: insights from stratigraphy and structural analysis. *Boll Soc Geol It.* 2002;1:319–31.
- [92] Carosi R, Leoni L, Lezzerini M, Montomoli M, Pertusati PC. Il metamorfismo dei depositi clastici triassici affioranti nei Monti dell'Uccellina (Toscana meridionale). *Boll Soc Geol It.* 1999;118:407–24.
- [93] Marchi A, Catanzariti R, Pandolfi L. Calcareous nannofossil biostratigraphy: a tool for deciphering the stratigraphic evolution of the Mt. Modino Unit. *It J Geosci.* 2017;136(2):171–85.
- [94] Cornamusini G, Conti P, Bambini AM. The Late Oligocene to Early Miocene foredeep basin system evolution of the Northern Apennines (Emilia-Tuscany, Italy): review and new litho-and biostratigraphic data. *It J Geosci.* 2018;137(3):396–419.
- [95] Cornamusini G, Foresi LM, Massa G, Bonciani F, Callegari I, Da Prato S, et al. The Miocene successions of the Fiora Hills: considerations about the development of the minor basins of Southern Tuscany. *It J Geosci.* 2011;130(3):404–24.