"il Casone-Monte delle Fate" olistostrome in the middle Eocene of the Eastern External Ligurian Unit (Monti della Tolfa, northern Latium, Italy): new constraints on the geodynamic evolution of the northern Apennines

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ABSTRACT

To the NE of Santa Severa (RM) some Meso-Cenozoic carbonate rocks with Tuscan affinity crop out in tectonic windows within the allochthonous *Flysch della Tolfa* (External Ligurian Unit). These carbonate rocks are mainly referable to the *Calcare Massiccio*, *calcari selciferi*, and *scaglia toscana*. Field work for the geological survey of the CARG Project 364-Bracciano, carried out in the area between "Monte delle Fate" and "Bagni" (Pian della Carlotta, Cerveteri, RM), provided new insights into the relationships among these Meso-Cenozoic carbonate rocks and the *flysch della Tolfa*. In the "il Casone" and "Monte delle Fate" areas, the stratigraphical and geometrical evidence observed in the field point to a stratally disrupted chaotic complex, consisting of exotic blocks with respect to the matrix (extrabasinal blocks with Tuscan affinity) embedded within a highly tectonized argillaceous matrix. We define it as a sedimentary mélange that we call "il Casone-Monte delle Fate" olistostrome. The calcareous nannofossil assemblages from the argillaceous matrix of this olistostrome point to a Bartonian age (middle Eocene). This chronostratigraphical result suggests the presence of a significant middle Eocene submarine mass wasting process emplacing a sedimentary mélange in the depositional setting of the External Ligurian sedimentary basin. The reactivation of pre-existing extensional faults at the ocean-continent transition between the Adria passive margin and the Ligurian Domain is the suggested triggering mechanism for explaining the middle Eocene "il Casone-Monte delle Fate" olistostrome. The comparison with a nearly coeval olistostrome at the base of the Epiligurian succession (*brecce argillose di Baiso*) gives us new insights on the deformation of the External Ligurian Domain.

KEY-WORDS: olistostrome, External Ligurian Domain, Tolfa Unit, middle Eocene, calcareous nannofossils.

INTRODUCTION

The allochthonous Ligurian Units define the highest nappe of the tectonic stack in the innermost portion of both northern (e.g., Conti et al., 2020) and central Apennines (e.g., Cosentino et al., 2002) (Fig. 1). The Ligurian Units cropping out in southern Tuscany and northern Latium pertains to the External Ligurian Domain (e.g., Marroni et al., 2001, 2017; Conti et al., 2020). In particular, these allochthonous units are correlatable with the Eastern External Ligurian Domain (e.g., Marroni et al., 2001, 2017; Conti et al., 2020), which includes the Santa Fiora Unit and the Tolfa Unit.

The Santa Fiora and Tolfa units tectonically overlie the Meso-Cenozoic succession of the Tuscan nappe (e.g., Conti et al., 2020 and references therein), and, in the surrounding of Rome, the Umbria-Marche succession (Funiciello & Parotto, 1978). In the Tragliata area, NW of Rome (Fig. 1), two deep boreholes Roma 1 [2901 m total depth (t.d.)] and Roma 2 (2480 m t.d.) intersect the Tolfa Unit for 1600 m and 1000 m, respectively (ENEL, 1987). At -1390 m, the Roma 2 borehole crosses the tectonic boundary between the Tolfa Unit and the underlying Meso-Cenozoic Umbro-Sabina succession.

In the central Apennines, to SE of Rome (Carpineto Romano area), the Tolfa Unit tectonically covers the Meso-Cenozoic succession of the Latium-Abruzzi carbonate platform (Mts. Lepini succession, Cosentino et al., 2002, 2010) (Fig. 1). The Tolfa Unit cropping out in the surrounding of Carpineto Romano represents the southernmost outcrop of the Ligurian Unit of the Apennines.

The External Ligurian Domain became part of the Apennine orogenic-wedge starting from the middle Eocene (e.g., Elter, 1975; Marroni et al., 2001, 2015, 2017; Conti et al., 2020; Festa et al., 2020). Subsequently, it was tectonically transported towards NE, overthrusting the different Meso-Cenozoic palaeogeographic domains developed onto the continental crust of the Adria plate. During the orogenic transport of the Ligurian Units, several Epiligurian basins developed onto the allochthonous mobile belt (Fig. 1). In the most of the northern Apennine sectors where the Eastern External Ligurian Units (*sensu* Marroni et al., 2001) crop out, the base of the Epiligurian Unit is commonly characterized by a mid (?)-upper Lutetian-lower Bartonian olistostrome, known as the "*brecce argillose di Baiso*" (e.g., Bettelli et al., 1987; Bettelli and Panini, 1989; Festa et al., 2020).

In northern Latium, the Ligurian Units are represented by the Tolfa Unit. This is made of two formations: the "*Pietraforte*" fm (Turonian-Santonian) and the *Flysch della Tolfa* [Upper Cretaceous (Campanian)-Eocene] (ISPRA – Servizio Geologico d'Italia, 2020). According to different authors (Fazzini et al., 1972; de Rita et al., 1989), NE of Santa Severa (RM), in the *il Casone* and *Monte delle Fate* areas, some Meso-Cenozoic carbonate rocks, with Tuscan affinity, crop out in tectonic windows of the overlying *Flysch della Tolfa* (External Ligurian Unit) (Fig. 2). These carbonate rocks have been mainly referred to the *Calcare Massiccio*, *calcari selciferi*, and *scaglia toscana*. A different interpretation of the relationship of these carbonate rocks with the overlying succession *(Flysch della Tolfa*) was previously suggested by Bertini et al. (1971). These authors indicated that the *Calcare Massiccio* and the *calcari selciferi* cropping out in *Bagni*, *il Casone*, and *Monte delle Fate* are the substratum of the *Flysch della Tolfa*, which transgressively overlies the Meso-Cenozoic formations with Tuscan affinity.

Recently, field work for the geological survey of the CARG Project 364-Bracciano, carried out in the area between *Monte delle Fate* and *Bagni* (Pian della Carlotta, Cerveteri, RM), has provided

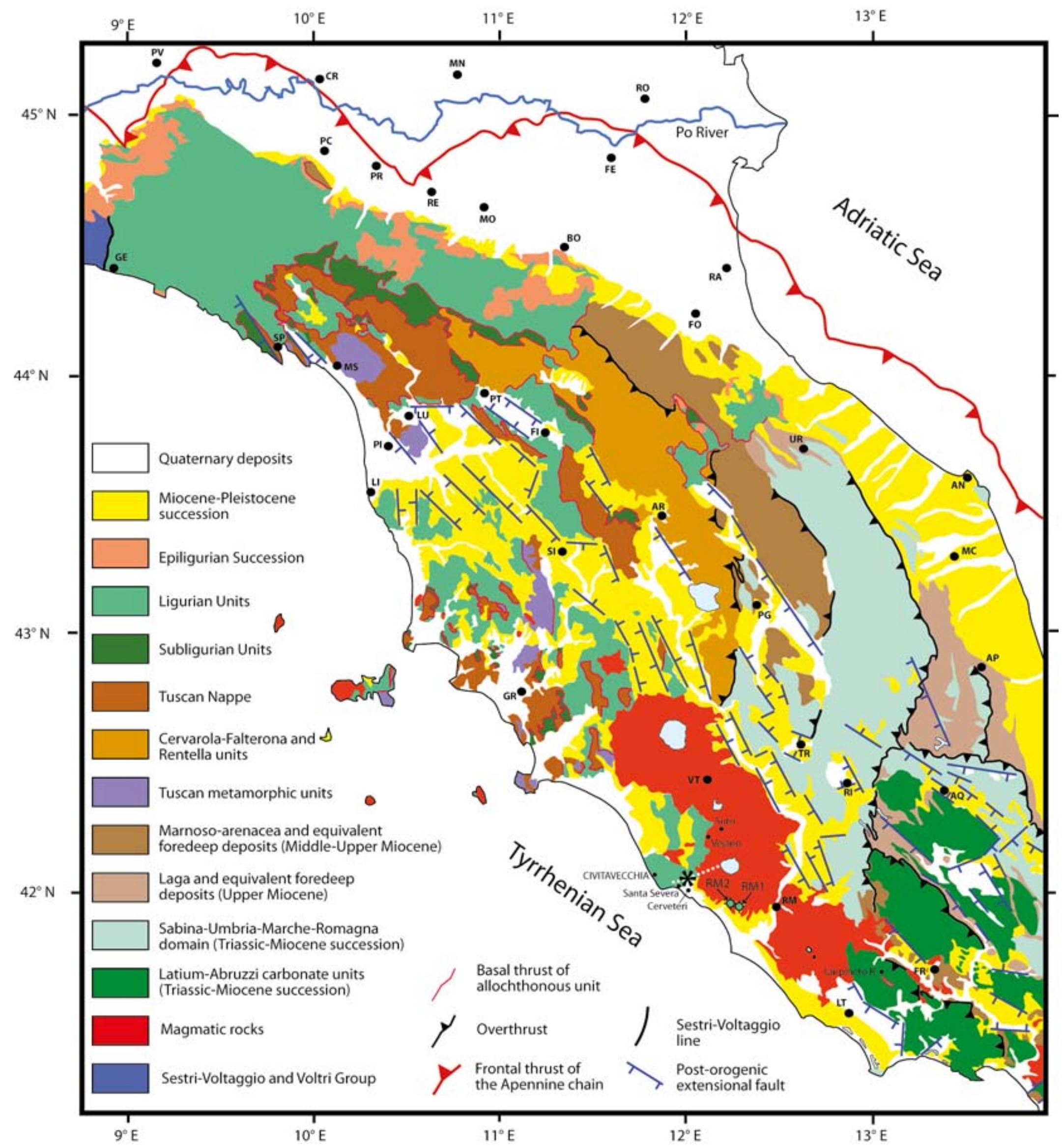

Fig. 1 - Structural model of the northern and central Apennines. The asterisk shows the position of the "il Casone-Monte delle Fate" area, at the southern margin of the Monti della Tolfa. The white dashed line shows the trace of the geological cross section in Fig. 3. RM1 and RM2 are the locations of Roma 1 and Roma 2 deep boreholes, which drilled the allochthonous Ligurian Unit (Tolfa Unit). Data from Conti et al. (2020), northern Apennines, and Cosentino et al. (2002, 2010), central Apennines. AN-Ancona; AP-Ascoli Piceno; AQ-L'Aquila; AR-Arezzo; BO-Bologna; CR-Cremona; FE-Ferrara; FI-Firenze; FO-Forlì; FR-Frosinone; GE-Genova; GR-Grosseto; LI-Livorno; LT-Latina; LU-Lucca; MC-Macerata; MN-Mantova; MO-Modena; MS-Massa; PC-Piacenza; PG-Perugia; PR-Parma; PT-Pistoia; PV-Pavia; RA-Ravenna; RE-Reggio Emilia; RI-Rieti; RM-Roma; RO-Rovigo; SI-Siena; SP-La Spezia; TR-Terni; UR- Urbino; VT-Viterbo.

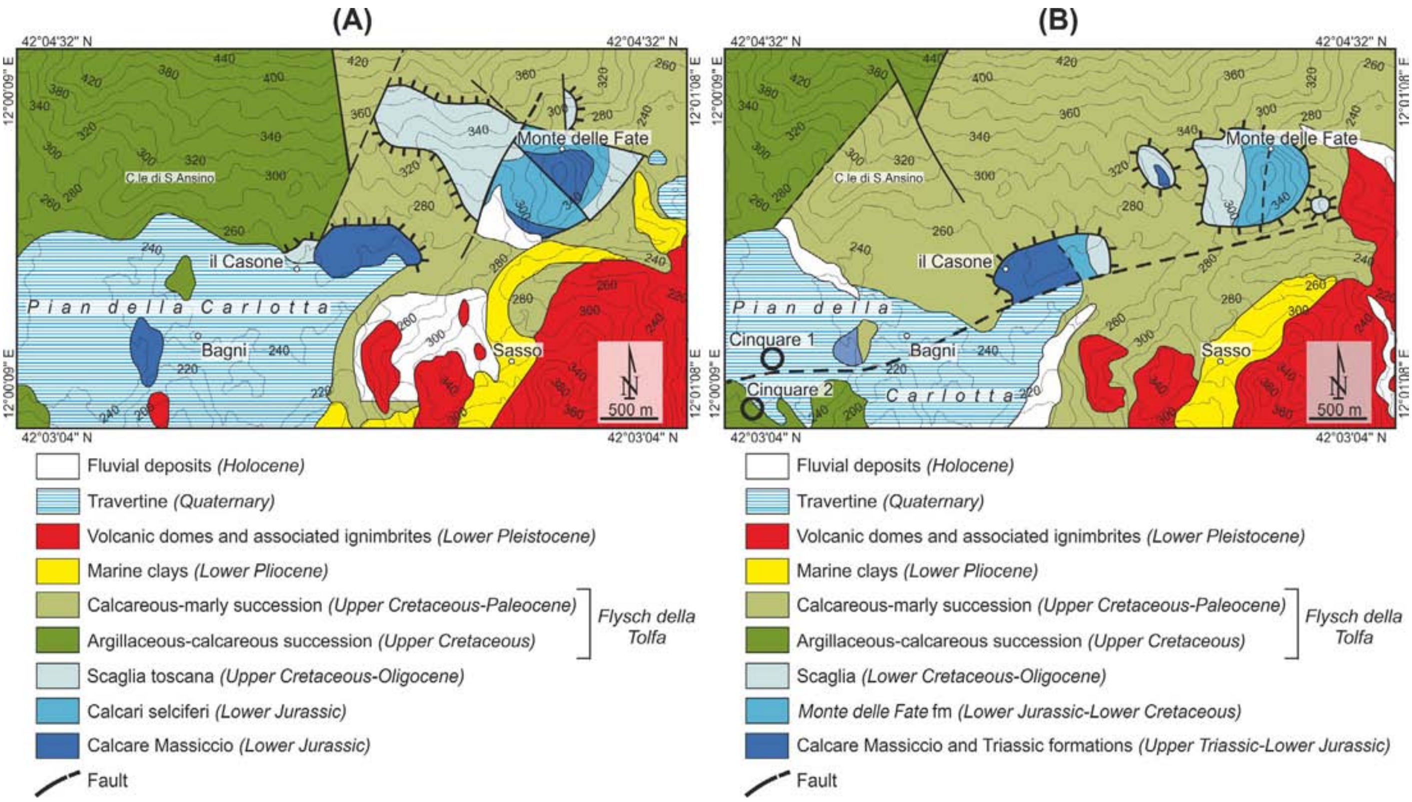

Fig. 2 - Geological map of "*il Casone-Monte delle Fate*" area according to (A) Fazzini et al. (1972) and (B) de Rita et al. (1989). Both geological maps represent "il Casone" and "Monte delle Fate" areas as tectonic windows.

new insights into the relationships among the Meso-Cenozoic carbonate rocks with Tuscan affinity and the *flysch della Tolfa*.

In this paper, the results obtained from geological mapping, microfacies analysis, and calcareous nannofossil biostratigraphy are presented and discussed. Our results bring into question the consensus in the literature on the *"il Casone"* and *"Monte delle Fate"* tectonic windows, and suggest a new tectono-stratigraphic setting for this portion of the northern Apennines. In addition, these results provide new insights into the tectono-sedimentary evolution of the External Ligurian Domain of the northern Apennines.

GEOLOGICAL SETTING AND PREVIOUS STUDIES

The *"Pian della Carlotta"* area (Cerveteri, RM), including *Bagni*, *il Casone*, and *Monte delle Fate*, was previously mapped by different authors (Servizio Geologico d'Italia, 1971; Bertini et al., 1971; Fazzini et al., 1972; de Rita et al., 1989). Bertini et al. (1971) recognized some calcareous lithofacies that they correlated to the *"Calcare Massiccio"* (Lower Jurassic) and *"Calcari con selce"* (Middle-Upper Jurassic) cropping out in Tuscany (Tuscan Succession). They considered these lithofacies as a part of the substratum of the overlying "flysch succession", which includes *Pietraforte*-like sandstones (Turonian-Santonian) and a Maastrichtian-Ypresian comprehensive succession, containing grey marly limestones rich in oxidized joint systems ("*pietra paesina*"), siliceous marly limestones (*"palombino"*), calcarenites, and reddish marly limestones (*"scaglia"*). According to sheet 143-Bracciano of the geological map of Italy (scale 1:100.000), the "flysch succession" surrounding *Bagni*, *il Casone*, and *Monte delle Fate* transgressively overlies the Meso-Cenozoic formations with Tuscan affinity (see cross section IV in sheet 143-Bracciano; Servizio Geologico d'Italia, 1971).

Subsequently, Fazzini et al. (1972), although confirming the occurrence in "*Pian della Carlotta*" of some formations of the Tuscan Succession (*Calcare Massiccio*, *calcari selciferi*, and *scaglia toscana*), suggested a complete different relationship between them and the surrounding *Flysch della Tolfa*. According to Fazzini et al. (1972), the formations with Tuscan affinity, which pertain to an autochthonous (?) basal complex, crop out in tectonic windows of the overlying allochthonous "flysch tolfetani" (Fig. 2A).

A similar interpretation was subsequently proposed by de Rita et al. (1989) in the Geological map of the Sabatini volcanic complex (Fig. 2B). Despite some differences with respect to the previous authors (Bertini et al., 1971; Fazzini et al., 1972) in the typology of the calcareous formations cropping out in *Bagni*, *il Casone*, and *Monte delle Fate*, also de Rita et al. (1989) recognized in *"Pian della Carlotta"* a tectonic boundary between a "basal carbonatic succession" and an overlying allochthonous unit (*Flysch della Tolfa*). In this framework, they recognized two major tectonic windows: "il Casone" and "Monte delle Fate" (Fig. 2B). According to these authors, within "il Casone" tectonic window the "basal carbonatic succession" crops out with Upper Triassic formations, *Calcare Massiccio*, *Monte delle Fate* formation, and *Scaglia*, whereas the "Monte delle Fate" tectonic window exhibits only the *Monte delle Fate* and *Scaglia* formations.

Considering that the "basal carbonatic succession" should crop out within "il Casone" and "Monte delle Fate" tectonic windows, the analysis and interpretation of gravity anomalies performed by Di Filippo & Toro (1993) call into question the autochthony of these Meso-Cenozoic carbonate outcrops. Di Filippo & Toro (1993) show a wide gravimetric depression bordered to the west by the positive residual anomalies of the Civitavecchia and "Monte delle Fate" gravimetric highs. Since the areas of gravimetric maxima are characterized by the outcrop of *Flysch della Tolfa,* Di Filippo & Toro (1993) hypothesized a remarkable rising of the "basal carbonatic succession" near the Tyrrhenian coast to explain those anomalies (Fig. 3). However, the maximum value of the "Monte delle Fate" positive residual anomaly (+9 mGal) is shifted of ca. 4 km to the west of the "il Casone" and "Monte delle Fate" outcrops (Fig. 3), rising some doubts on the autochthony of those Meso-Cenozoic carbonate rocks. To explain this inconsistency, Di Filippo & Toro (1993) suggested a tectonic duplication of the Meso-Cenozoic "basal carbonatic succession" due to late Miocene compressional tectonics (Fig. 3).

In Pian della Carlotta, two boreholes (Cinquare 1, 126.56 m t.d.; Cinquare 2, 251.30 m t.d.) were drilled in the 1950's by "Montecatini - Società generale per l'industria mineraria e chimica" for water research (see location in Fig. 2B). Beside the gravity profile by Di Filippo & Toro (1993), the stratigraphy of these boreholes (Vighi, 1955) are the only data on the subsurface geology of the study area.

Following the detailed description of the borehole stratigraphy by Vighi (1955), the Cinquare 1 borehole penetrated into: (1) 53 m of Quaternary deposits, mainly consisting of pebbles and blocks of limestones and marly-limestones in an argillaceous-sandy matrix; (2) 3 m of Pliocene whitish marly-clays; (3) 52 m of grey and beige marly limestones, limestones with intercalations of marls, sandstones, and shales, referable to the *Flysch della Tolfa*; (4) 16 m of dark-grey and grey brecciated limestones, referred by Vighi (1955) to the Lower Jurassic limestones cropping out in the Bagni area.

The Cinquare 2 borehole penetrated into: (1) 8.50 m of Quaternary cover, mainly consisting of detrital grains, containing both carbonate and volcanic rocks, in an argillaceous-sandy matrix; (2) 2.5 m of Quaternary travertine; (3) 122 m of a Pliocene cover consisting mainly of clays, sandy clays, clays with pebbles, marly clays, sands, pebbles, sandstones, and conglomerates; (4) 118 m of grey-beige, grey, and dark-grey limestones, sometimes brecciated, similar to the limestones drilled in the basal part of Cinquare 1 borehole, which Vighi (1955) referred to the Lower Jurassic limestones of the "Bagni" area.

MATERIAL AND METHODS

In the *"Pian della Carlotta"* area, we performed a geological survey, starting from a 1:5000 topographic map, using the FieldMOVE software, a map-based digital field mapping app for geological data capture. From the outcropping stratigraphic units, we collected rock samples to perform microfacies analysis on thin sections, and clayey and marly samples for the biostratigraphic analysis of the calcareous nannofossil assemblages.

In particular from the "il Casone" and "Monte delle Fate" areas, we collected fourty-one samples of marl and clays to perform the biostratigraphic analyses on nannofossil assemblages. Thirty-three samples out of fourty-one (SS 1-SS 33) were collected as a single sample, whereas eight samples (SS 34-SS 41) are from a stratigraphic section of *Flysch della Tolfa*. The location of the collected samples is shown in Tab. S1 (supplementary materials).

For the calcareous nannofossil analysis, we prepared slides according to the pipette strew slide method, and we performed the species determination using a microscope (Zeiss Axioplan) with transmitted crossed-polarized and plane-polarized light at 1200× magnification.

We performed only a qualitative analysis of the marker species since the preservation state of the calcareous nannofossil

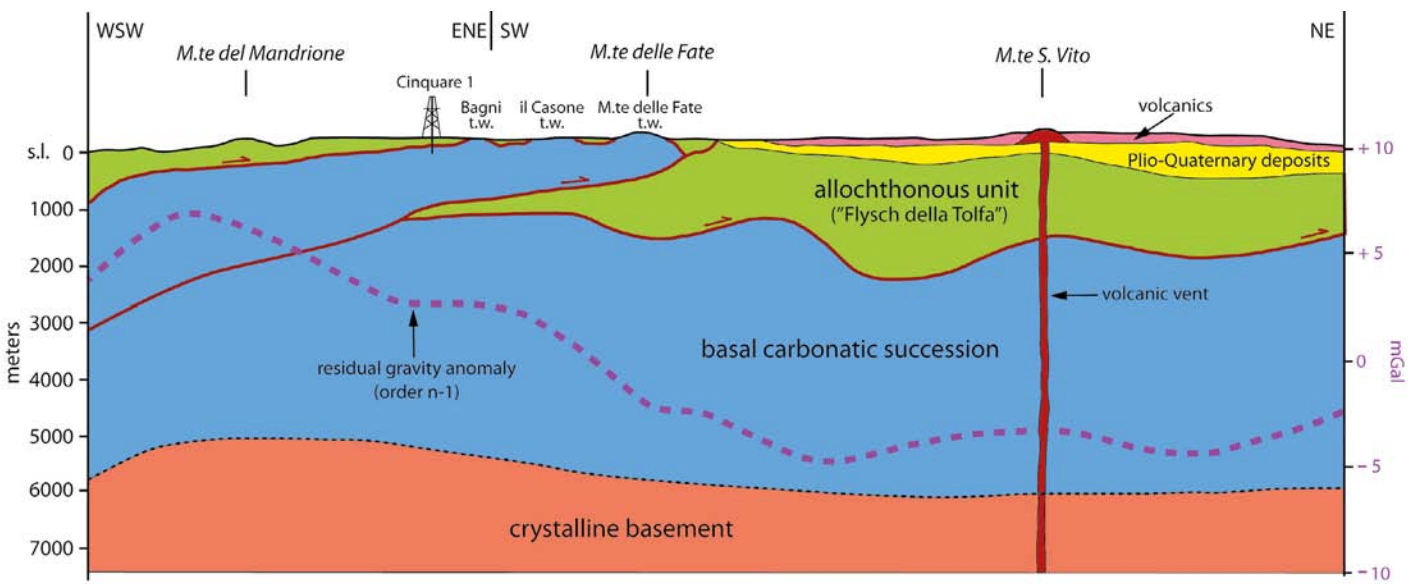

Fig. 3 - Gravimetric profile crossing "il Casone-Monte delle Fate" area with the "Bagni", "il Casone", and "Monte delle Fate" tectonic windows. The position of the Cinquare 1 borehole is also shown. The trace of the gravimetric profile is shown in Fig. 1. Redrawn and modified after Di Filippo & Toro (1993).

assemblage was poor due to reworking, dissolution, and overgrowth phenomena. We evaluated the reworking percentage by counting, in the better-preserved samples, 500 specimens larger than 3 µm (see Tab. S1 in supplementary materials).

For the calcareous nannofossil biostratigraphy, we referred to the zonal schemes proposed by Martini (1971), Okada & Bukry (1980), Fornaciari et al. (2010), Agnini et al. (2007; 2014), for Paleogene, and Thibault et al. (2012) for Cretaceous biozonations.

To detect the elemental composition of the crust coating the carbonate olistoliths, we used a Zeiss Signa300 Scanning Electron Microscope with an EDS detector Bruker XFlash 6160 at the LIME of Roma Tre University.

RESULTS

"il Casone-Monte delle Fate" olistostrome

The field work carried out in the "il Casone" and "Monte delle Fate" areas, where previous works suggested the presence of a basal carbonate succession with Tuscan affinity either in the footwall of tectonic windows (Fazzini et al., 1972; de Rita et al., 1989) or trasgressively overlain by the "flysch succession" (Bertini et al., 1971; Servizio Geologico d'Italia, 1971), leads us to consider a complete different relationship between these carbonates and the surrounding *Flysch della Tolfa*.

In the "il Casone" and "Monte delle Fate" areas, the field stratigraphical and geometrical relationships point to different and randomly distributed blocks of both carbonates, mainly made of massive dark-grey limestones, *Calcari selciferi* and *Scaglia toscana*, and *Flysch della Tolfa*, within a highly deformed argillaceous matrix (Figs. 4, 5, and 6).

The massive dark-grey limestones from "il Casone" consist of different irregular-shaped blocks of limestones, ranging from tens of metres down to a few centimetres, with both oolitic and micritic textures, containing large spicules of sponges, bivalves, and gastropods, which can be referred to the *Calcari ad Angulati* of the Tuscan Succession. In a different area of "il Casone", tabular-shaped and randomly distributed blocks of limestones and marly limestones are from Lower Cretaceous calpionellid limestones (*Maiolica* fm.) and Upper Cretaceous and upper Paleocene-lower Eocene *Scaglia toscana* fm. Therefore, in both "il Casone" and "Monte delle Fate" areas, the carbonates with Tuscan affinity are not part of a carbonate succession, but crop out as different sizes olistoliths wrapped in a highly deformed argillaceous matrix. The matrix consists mainly of varicoloured clays with brecciated and tectonised fabric, showing widespread slickenlines. Limestone blocks embedded in this matrix are often bordered by slip surfaces, evidenced by prominent slickenlines. This stratally disrupted chaotic complex, which contains exotic blocks with respect to the matrix (i.e., extrabasinal blocks), led us to define it as a sedimentary mélange (olistostrome, *sensu* Festa et al., 2016), here called "il Casone-Monte delle Fate" olistostrome (Fig. 4), subsequently overprinted by tectonics.

This olistostrome also crops out in the "Bagni" area, where to the west of "Bagni" a small portion of the olistostrome, characterized by olistoliths of *Calcare Massiccio* and *Calcari ad Angulati* wrapped in an argillaceous matrix, crops out below the Quaternary cover of the travertine plateau. In the same area, beneath some Plio-Quaternary covers, "il Casone-Monte delle Fate" olistostrome was drilled by the Cinquare 1 and Cinquare 2 boreholes (Fig. 5). Starting from 104 m depth, the Cinquare 1 borehole drilled 16 m of dark-grey and grey brecciated limestones, referred by Vighi (1955) to the Lower Jurassic limestones cropping out in the "Bagni" area, and interpreted in this work as olistoliths of *Calcare Massiccio* and *Calcari ad Angulati* within "il Casone-Monte delle Fate" olistostrome. The Cinquare 2 borehole, starting from 133 m depth, drilled 118 m of grey-beige, grey, and dark-grey limestones, sometimes brecciated, similar to the limestones drilled in the basal part of Cinquare 1 borehole. It is worth noting that the recovery ratios of these limestones were really low for a carbonate succession. In the Cinquare 1, the dark-grey limestones were recovered with 61% of recovery ratio, whereas in the Cinquare 2 the recovery ratio was only 30% (Vighi, 1955). Thus, according to our field results (Fig.4) and the recovery ratio of the Mesozoic limestones in Cinquare 1 and Cinquare 2 wells (see Fig. 5), both these boreholes drilled "il Casone-Monte delle Fate" olistostrome, which in the "Bagni" area shows a minimum thickness of ca. 120 m.

The stratigraphic position of "il Casone-Monte delle Fate" olistostrome is clear to the north of Pian della Carlotta, near Vejano (VT), where the geological survey for the 364-Bracciano sheet (CARG project) indicates that it lies stratigraphically above the *Mignone clays*.

Typically, the "il Casone-Monte delle Fate" olistostrome is made of olistoliths of different sizes and lithologies (from decimetric to decametric sizes) wrapped by a highly tectonized clayey matrix (Fig. 6A, B). The olistoliths crop out with disparate bedding attitudes and show lithologies mostly pertaining to the Tuscan Meso-Cenozoic carbonate succession and to the *Flysch della Tolfa*. According to the macroscopic and microscopic features of the Meso-Cenozoic carbonate olistoliths, we referred them to the corresponding lithostratigraphic units of the Tuscan Succession.

Hereafter we report a brief description, in terms of both macroscopic and microscopic features, of the most representative olistoliths cropping out in the "il Casone" and "Monte delle Fate" areas. The presentation follows a stratigraphic order, from the oldest stratigraphic unit to the youngest.

"Calcare Massiccio" (Hettangian; Decandia et al., 1968; Dallan Nardi & Nardi, 1974; Fazzuoli et al., 1985, 1994; Costantini et al., 1993): although this stratigraphic unit was extensively reported in the previous geological maps of the area (Fig. 2), the olistoliths referable to this formation are poorly represented in the olistostrome, and occur only in the "Bagni" and "il Casone" areas. The *Calcare Massiccio* olistoliths are metric sized, and are mainly characterized by massive whitish grainstones. Usually, they are deeply fractured and karstified.

"Calcari ad Angulati" (Hettangian *p.p.*-Sinemurian; Decandia et al., 1968; Dallan Nardi & Nardi, 1974): the olistoliths referred to this formation consist of greyish massive mainly micritic limestones, characterized by diffuse cavities due to karst processes (Fig. 6D, E). These olistoliths display mudstone, wackestone, and subordinately packstone textures containing large spicules of sponge and small gastropods (Fig. 7A, B). The spicules of sponge are mm-sized and show a hexagonal transversal contour. The microprobe analysis

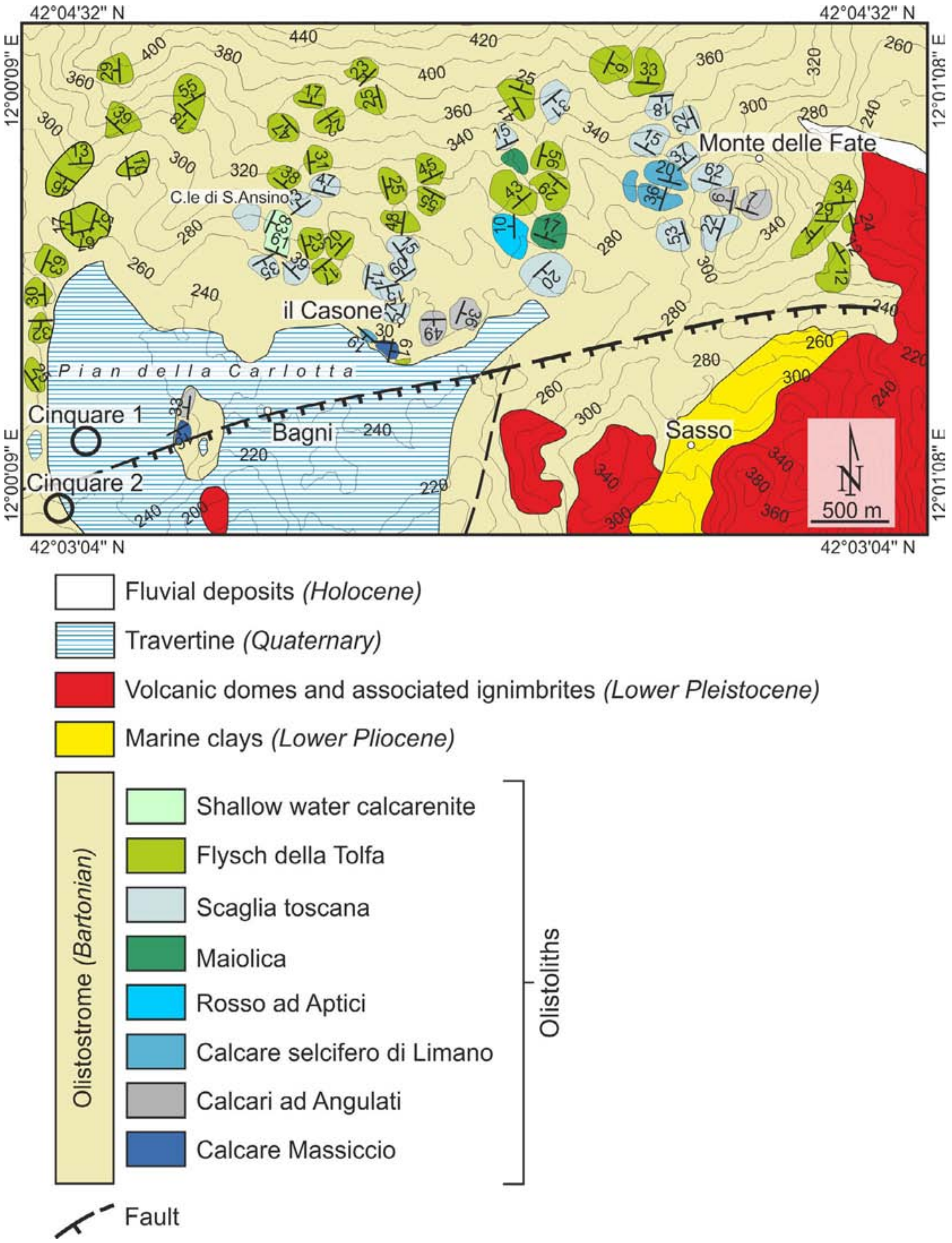

Fig. 4 - Geological map of the "il Casone-Monte delle Fate" area showing the occurrence of a stratally disrupted chaotic complex containing exotic olistoliths, mainly pertaining to the Tuscan Succession. This stratally disrupted chaotic complex is here defined as "il Casone-Monte delle Fate" olistostrome.

performed on these spicules through an EDS detector confirmed they pertain to siliceous sponges (Fig. 8A). These greyish limestone blocks show a weathered surface, usually covered by a cm-thick phyllosilicate crust (Figs. 6D and 8B), likely in relation with the clayey matrix embedding the olistoliths. All the olistoliths from *"Calcari ad Angulati"* show pervasive calcite veins with different orientations and thicknesses (Fig. 7B).

"Calcare selcifero di Limano" (lower Pliensbachian-Toarcian; Perilli & Reale, 1998; Costantini et al., 1993; Fazzuoli et al., 1994): the olistoliths referred to this formation largely outcrop in the "Monte delle Fate" area. The presence of nodules and bands of grey chert well characterize these limestones, which are also rich in radiolarians of large size.

"Rosso ad Aptici" (middle Tithonian; Kalin et al., 1979; Conti et al., 1985; Fazzuoli et al., 1985, 1994; Costantini et al., 1993; Perilli & Reale, 1998): the olistoliths referred to this formation consist of finely laminated limestones or marly limestones rich in *Aptychus*, radiolarians, and calcite plates (Fig. 7C).

"Maiolica" (upper Tithonian-Barremian; Fazzuoli et al., 1985, 1994; Costantini et al., 1993; Cerrina Feroni & Patacca, 1975): several olistoliths referred to this formation were collected in the "Monte delle Fate" area. They mainly consist of whitish mudstones and wackestones with radiolarians. Some olistoliths provided a rich microfacies characterized by abundant *Calpionella alpina* (Fig. 7D), radiolarians, and some *Aptychus*. One olistolith referred to this formation shows the

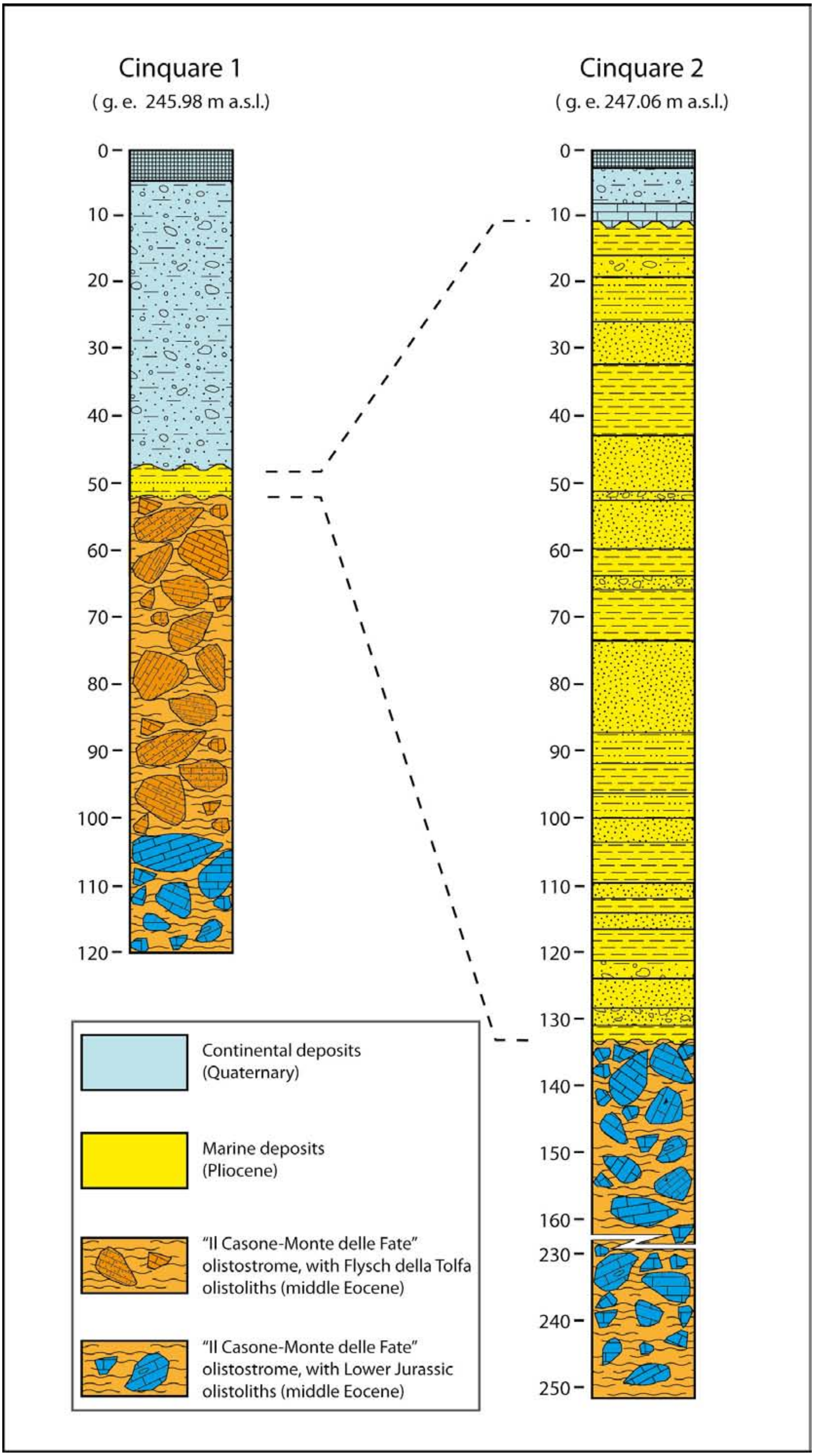

Fig. 5 - Stratigraphic logs of the Cinquare 1 and Cinquare 2 boreholes, drilled in 1950' by "Montecatini - Società generale per l'industria mineraria e chimica". The stratigraphy of these boreholes has been reinterpreted according to the results of this work, and following the detailed original description by Vighi (1955), especially for the indications of the recovery ratios in the Mesozoic limestones drilled in the basal part of the boreholes (61 % in Cinquare 1 and 30% in Cinquare 2).

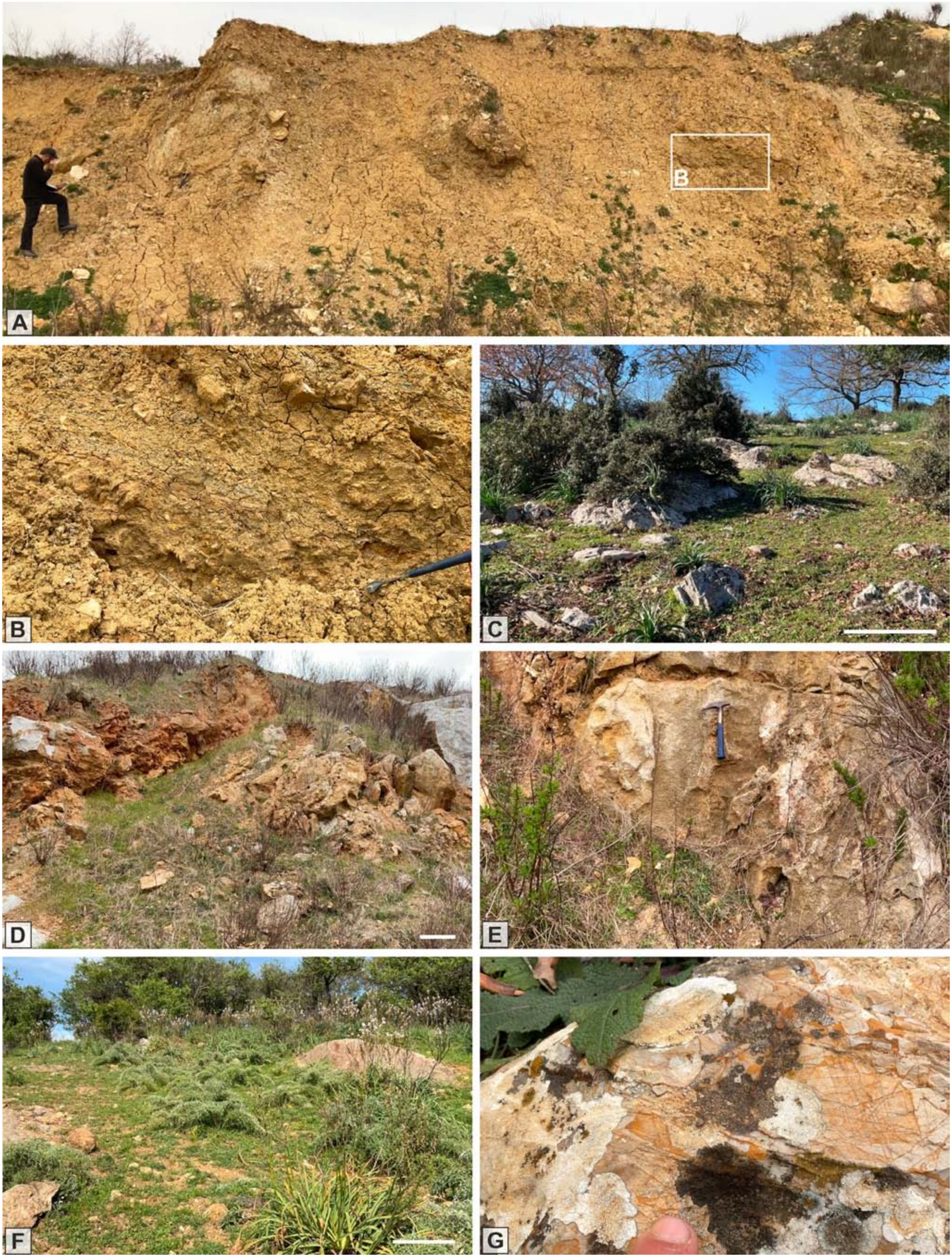

Fig. 6 - Field photographs showing some details of "il Casone-Monte delle Fate" olistostrome. A) Outcrop of "il Casone-Monte delle Fate" olistostrome at "il Casone" (42°03'48''N, 12°01'48''E), showing different olistoliths embedded within a tectonized argillaceous matrix; B) Close up of the previous photograph showing a detail of the argillaceous matrix of the olistostrome embedding some small carbonate olistoliths; C) stratally disrupted beds of *Scaglia toscana* (42°03'45''N, 12°01'37''E); D) disrupted massive beds of *Calcari ad Angulati* (42°03'42''N, 12°01'46''E); E) detail of an olistolith of *Calcari ad Angulati* (42°03'46''N, 12°01'52''E); F) stratally disrupted beds of *Flysch della Tolfa* (42°02'33''N, 12°00'09''E); G) detail of a *"pietra paesina"* olistolith (*Flysch della Tolfa*) (42°03'50''N, 12°01'07''E). White scale bar is 0.5 m.

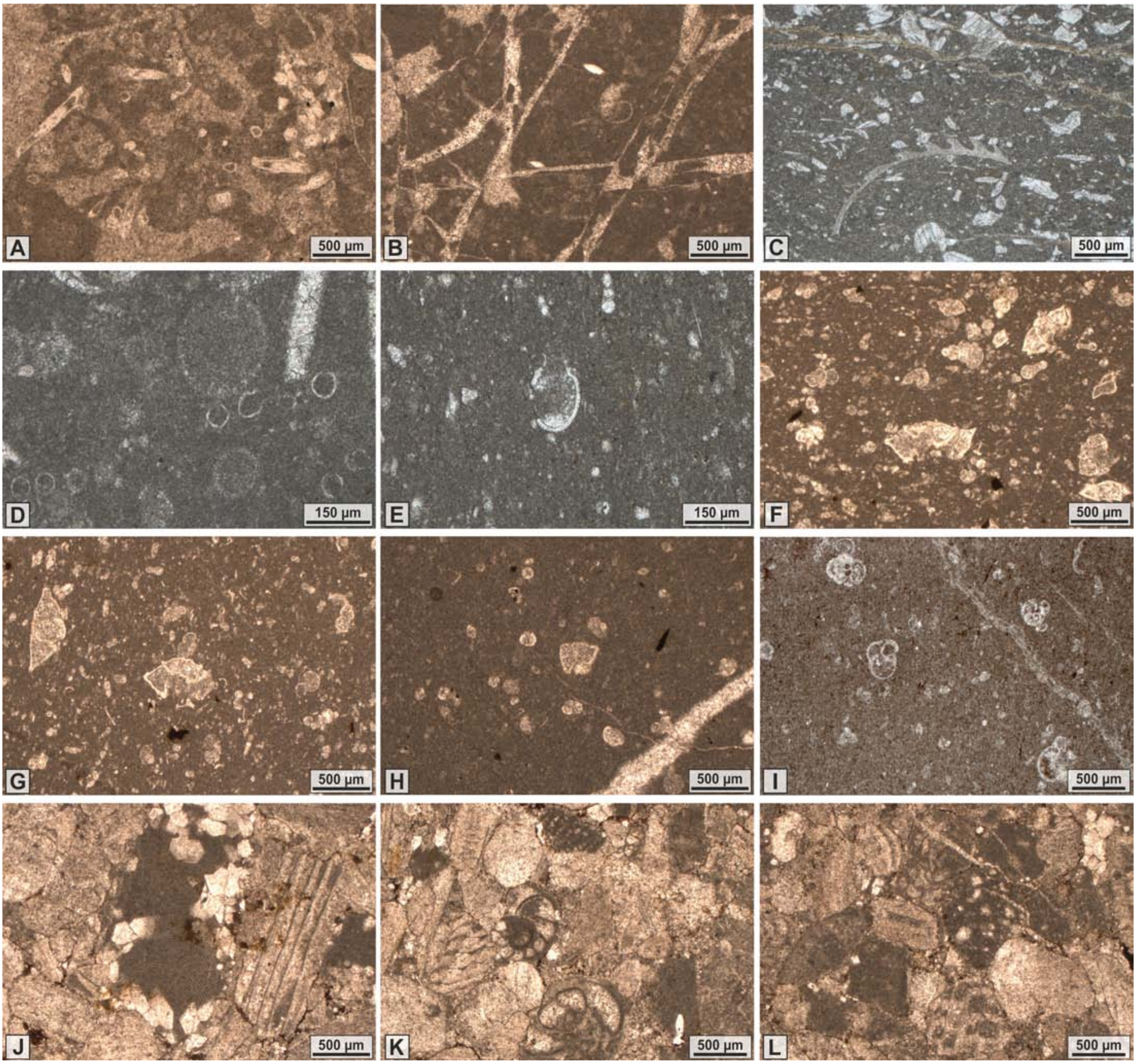

Fig. 7 - Thin section microphotographs of the most representative olistoliths of "il Casone-Monte delle Fate" olistostrome. A) packstone with large spicules of sponge (*Calcari ad Angulati*); B) packstone/wackestone with gastropod and sponge spicules (*Calcari ad Angulati*); C) wackestone with *Aptychus* and calcite plates (*Rosso ad Aptici*); D) wackestone with radiolarians and calpionellids (*Calpionella alpina*) (*Maiolica*); E) wackestone with radiolarians and *Calpionella elliptica* (*Maiolica*); F) wackestone with planktonic foraminifers (*Globotruncana stuarti, Heterohelix* sp.) and radiolarians (*Scaglia toscana*); G) wackestone with planktonic foraminifers (*Globotruncana conica*) and radiolarians (*Scaglia toscana*); H) wackestone with planktonic foraminifers (*Acarinina topilensis*) and radiolarians (*Scaglia toscana*); I) wackestone with planktonic foraminifers (globigerinids) and radiolarians (*Scaglia toscana*); J) packstone with bryozoans and red algae (Shallow-water calcarenite); K) packstone with bryozoans, benthic foraminifers (rotalidae), and red algae (shallow-water calcarenite); L) packstone with benthic foraminifers (orbitoids) and fragments of echinoids (shallow-water calcarenite).

occurrence of *Calpionella elliptica* (Fig. 7E), together with *Calpionella alpina*.

"Scaglia toscana" (Aptian-Rupelian; Fazzuoli et al., 1985, 1994; Catanzariti, 1988; Costantini et al., 1993; Catanzariti et al., 1996; Coccioni & Perilli, 1997; Perilli, 1997): the olistoliths referred to this formation crop out as sparse blocks, with different attitudes (Fig. 6C). As for other olistoliths, they are embedded within a highly deformed clayey matrix. They mainly consist of reddish and whitish micritic limestones containing abundant planktonic foraminifers. In thin section, they show mainly wackestone textures characterized by planktonic foraminifer assemblages pointing to two different ages: Late Cretaceous (e.g., *Globotruncana conica*, *G. linneiana*, *G. stuarti*) (Fig. 7F, G) and early Eocene (*Acarinina topilensis*, *Globigerinatheka* sp.) (Fig. 7H, I). In some samples, well-defined large pyrite crystals are also present.

"Flysch della Tolfa" (upper Albian-upper Eocene; Nappi et al., in press): the olistoliths referred to this formation (Fig. 6F) are the most common in "il Casone-Monte delle Fate" olistostrome. They

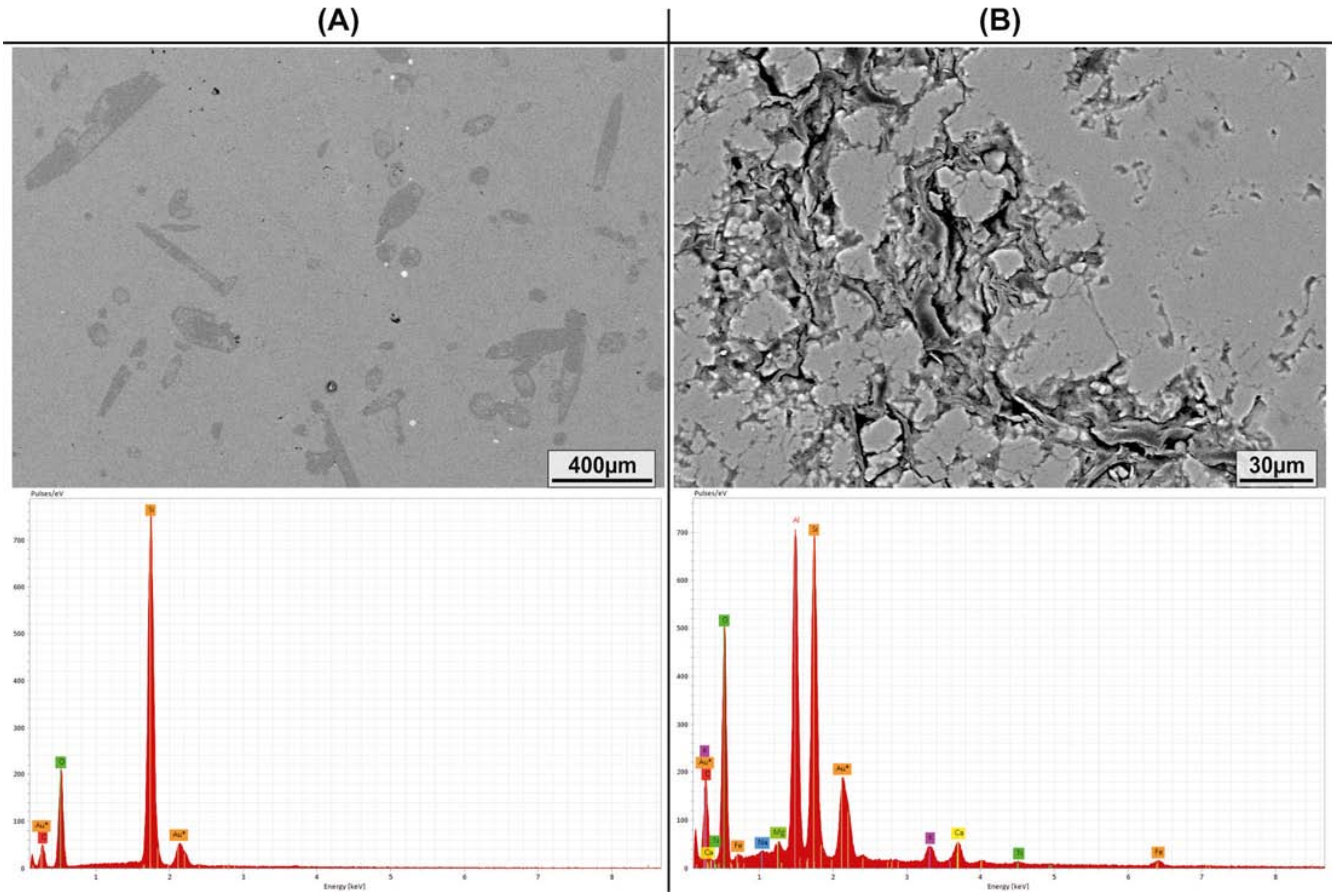

Fig. 8 - Scanning electron micrographs, and relative EDS microprobe analysis, of thin sections from *Calcari ad Angulati* samples. A) (above) the SEM micrograph shows several spicules of sponge; (below) EDS microprobe spectrum showing the silica composition of the spicules of sponge; B) (above) SEM micrograph of the argillaceous crust coating a *Calcari ad Angulati* olistoliths; (below) EDS microprobe spectrum showing the phyllosilicate composition of the crust coating the olistolith.

consist of reddish and brownish mudstones, cut by several calcite vein systems that provide the classical aspect of the *"pietra paesina"* lithofacies (Fig. 6G), which are interbedded with carbonate-clastic turbiditic layers, with tractive sedimentary structures, and marly limestones.

***"Shallow-water calcarenite"*:** these olistoliths are mainly represented by metric-sized calcarenite blocks. In thin section, these calcarenites show the presence of shallow-water fossil fragments such as bryozoans, fragments of echinoderms, benthic foraminifers, and red algae (Fig. 7J, K, L). These calcarenites are similar to the detrital horizons interbedded into the *Flysch della Tolfa* fm.

Calcareous Nannofossil Biostratigraphy

In the "il Casone-Monte delle Fate" area, fourty-one samples were collected from both the argillaceous matrix containing the olistoliths and the clayey intercalations of a large olistolith of *Flysch della Tolfa*. Twenty-five samples out of fourty-one are barren, and the remaining sixteen samples present calcareous nannofossil assemblages affected by a huge amount of reworked species and poor preservation. Despite that, the qualitative analysis provided some relevant results in terms of chronostratigraphy, such as the presence of the *Reticulofenestra umbilicus* group (samples SS 4, SS 24, and SS 33) (Fig. 9 A and B), *Dictyococcites bisectus* (samples SS 7, SS 10, and SS 26) (Fig. 9 C, D), the marker species *Sphenolithus obtusus* (sample SS 14) (Fig. 9 E, F), and *Sphenolithus radians* (SS 28). In addition to these species, the assemblages show the presence of long-ranging species such as *Coccolithus pelagicus, Sphenolithus moriformis, Discoaster deflandrei,* and *Ericsonia formosa.*

As mentioned above, all the calcareous nannofossil assemblages consist mainly of reworked species. In this regard, the quantitative analyses performed on the better preserved and abundant assemblages (samples SS 4, SS 14, and SS 33) show reworking percentages varying from 91% to 96 %, with a dominant presence of Late Cretaceous species. The presence of the few marker species shows abundance ranging from 0.5% to 0.7%.

The more abundant reworked species, grouped according to their distribution range, are the following: *Watznaueria barnesiae* (Middle Jurassic – Late Cretaceous); *Zeugrhabdotus embergeri* (Late Jurassic – middle Paleocene); *Cyclagelosphaera platyaspis, Nannoconus fragilis* (Early Cretaceous); *Rhagodiscus asper* (Early Cretaceous-Late Cretaceous *p.p.*); *Arkhangelskiella cymbiformis, Aspidolithus parcus parcus, Broinsonia parca,*

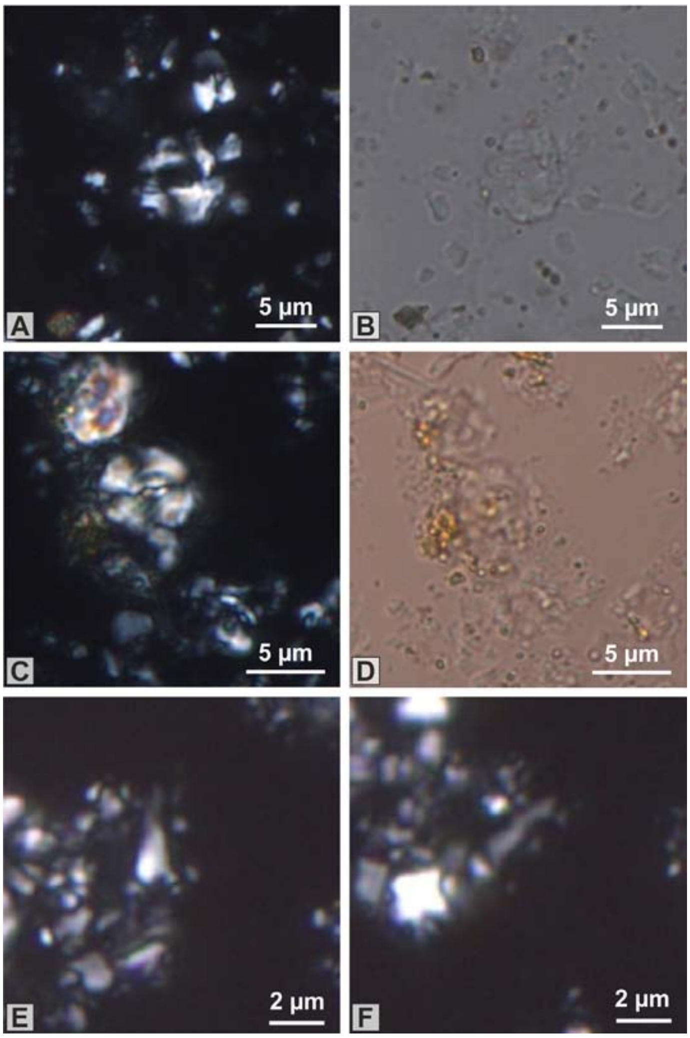

Fig. 9 - Microphotographs of some calcareous nannofossils marker species from the argillaceous matrix of "il Casone-Monte delle Fate" olistostrome. A) *Reticulofenestra umbilicus* group (crossed nicols) (sample SS 33); B) *Reticulofenestra umbilicus* group (parallel light) (sample SS 33); C) *Dictyococcites bisectus* (crossed nicols) (sample SS 7); D) *Dictyococcites bisectus* (parallel light) (sample SS 7); E) *Sphenolithus obtusus* (crossed nicols, 0°) (sample SS 14); F) *Sphenolithus obtusus* (crossed nicols, 45°) (sample SS 14).

Ceratolithoides aculeus, Cribrosphaerella ehrenbergii, Lithraphidites acutus, Microrhabdulus decoratus, Micula decussata, Micula murus, Micula prinsii, Nephrolithus frequens, Placozygus fibuliformis, Quadrum gartneri, Reinhardites levis, Watznaueria sp. large (Late Cretaceous); *Discoaster backmanii, Ericsonia robusta, Fasciculithus magnus, Neochiastozygus modestus* (Paleocene).

Finally, the samples collected from a stratigraphic section of a large olistolith of *Flysch della Tolfa* (SS 34 – SS 41) provided abundant calcareous nannofossil assemblages. In all samples, we detected the presence of *Micula prinsii*, *Micula murus*, and *Reinhardtites levis*. The assemblages also include reworking and long-ranging taxa such as *Lithraphidites acutus*, *Microrhabdulus decoratus*, *Nannoconus fragilis*, *Neochiastozygus modestus*, *Nephrolithus frequeus*, *Placozycus fibuliformis*, *Rhagodiscus asper*, *Watzanaueria barnesiae*, *Watzanaueria* sp., and *Zeugrahabdotus embergri*.

DISCUSSION

Age of "il Casone-Monte delle Fate" olistostrome: new constraints on the geodynamic evolution of the northern Apennines

The age of "il Casone-Monte delle Fate" olistostrome is well defined by the calcareous nannofossil assemblages from the argillaceous matrix that embed the different olistoliths of this sedimentary mélange. The presence of *Sphenolithus radians* in the argillaceous matrix of "il Casone-Monte delle Fate" olistostrome provides a pretty broad age estimation since its distribution ranges between the biozones NP 11 (54.2 Ma, Ypresian) and NP 23 (32.02 Ma, Rupelian) of Martini (1971) (Agnini et al. 2007; Bown & Dunkley Jones, 2012). Moreover, the occurrence of *Reticulofenestra umbilicus* in the calcareous nannofossil assemblage from the argillaceous matrix reduces the age uncertainty for "il Casone-Monte delle Fate" olistostrome, since its presence in the sample SS 33, estimated at 3% of the entire assemblage (highly diluted by reworking), points to an age younger than its First Common Occurrence (FCO). This latter bioevent occurs at the base of CNE 13 (Agnini et al., 2014) or at the base of CP 14a (Okada & Bukry, 1980), and its age is estimated at 43.06 Ma (Lutetian; Agnini et al., 2014) (Fig. 10).

Additionally, the presence of *Dictyococcites bisectus* in the calcareous nannofossil assemblages of samples SS 7, SS 10, and SS 26 provides a further age constraint for "il Casone-Monte delle Fate" olistostrome. Due to reworking dilution, we assume it occurring in a time interval younger than its First Occurrence (FO) (i.e., younger than 40.34 Ma; Agnini et al., 2014).

Finally, a more robust time constraint on the age of "il Casone-Monte delle Fate" olistostrome is the presence of *Sphenolithus obtusus* in the calcareous nannofossil assemblage of sample SS 14. A short time interval defines the distribution of this marker species, which is enclosed within the MNP 17a biozone (Fornaciari et al., 2010), or within the CNE 15 biozone (Agnini et al., 2014) (Fig. 10). In the Central Tethys, the calibrated age for the *Sphenolithus obtusus* FO is 39.63 Ma (Fornaciari et al., 2010). The Last Occurrence (LO) of *Sphenolithus obtusus* is quite synchronous, since in the Central Tethys it occurs at 38.25 Ma and in the western Atlantic its age is 38.45 Ma (Fornaciari et al., 2010). According to Agnini et al. (2014) the LO of *Sphenolithus obtusus* occurs at 38.47 Ma (Bartonian).

The calcareous nannofossils bioevents identified in the samples from the argillaceous matrix of "il Casone- Monte delle Fate" sedimentary mélange let us to refer this olistostrome to a Bartonian age (middle Eocene) (Fig. 10), more precisely, to a time interval spanning from 39.63 Ma to 38.47 Ma, that is the distribution range of *Sphenolithus obtusus*.

Regarding the total assemblage found in the good preserved samples (SS 34-SS 41) collected from a large olistolith of *Flysch della Tolfa*, the presence of *Micula prinsii* points to the upper Maastrichtian, within the upper part of the UC 20 biozone (Thibault et al., 2012). The Late Cretaceous nannofossil assemblages recognised in all these samples reinforce our field evidence that the sampled section is from an exotic block with respect to the middle Eocene (Bartonian) argillaceous matrix of the "il Casone-Monte delle Fate" olistostrome.

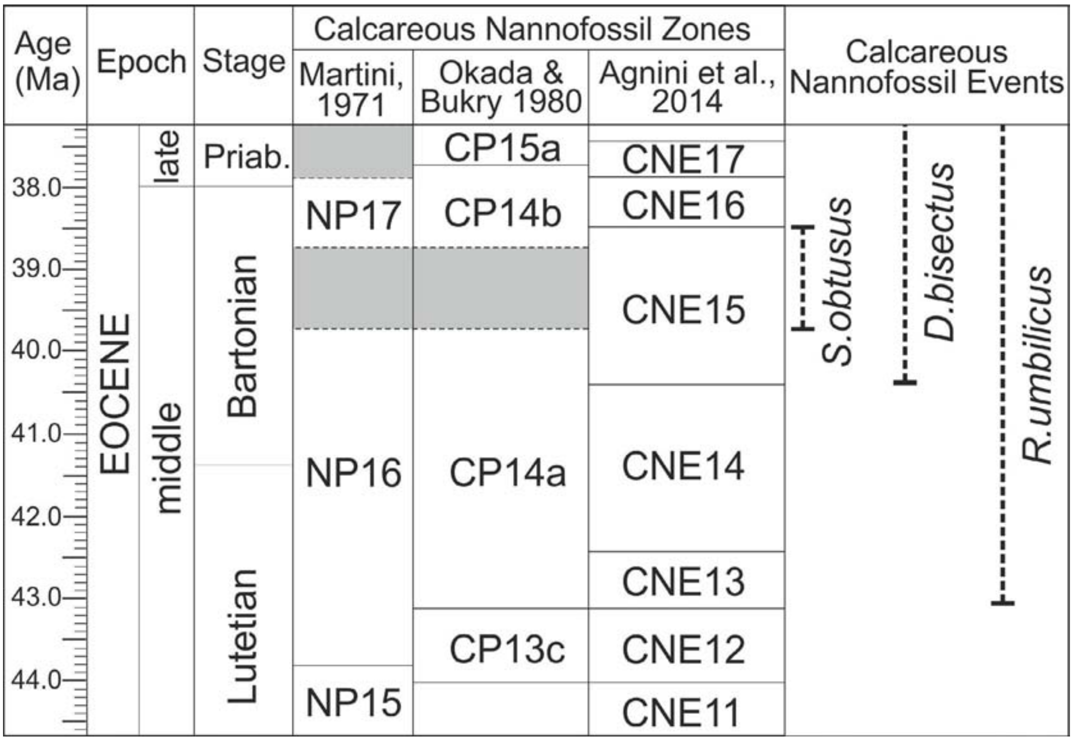

Fig. 10 - Middle to late Eocene calcareous nannofossil biozonations, according to Martini (1971), Okada & Bukry (1980), and Agnini et al. (2014). The distribution of the marker species from "il Casone-Monte delle Fate" olistostrome is also shown.

Bartonian ages were never reported in the stratigraphies of the Ligurian Units, given that the thinned continental margin of Adria, containing the External Ligurian Domain, since the middle Eocene (Ligurian Tectonic Phase; Elter, 1975) was involved in the west-dipping Apennine subduction zone, which was responsible for the building of the External Ligurian accretionary wedge (e.g., Molli et al., 2010; Marroni et al., 2010). In the Ligurian-Emilian Apennines, the accretionary stage of the External Ligurian Units is well constrained to the early-to-middle Lutetian by the age of the unconformity at the base of the Epiligurian Units and the Tertiary Piedmont Basin (e.g., Ricci Lucchi, 1986; Mutti et al., 1995), sedimented in a wedge-top setting above the External Ligurian accretionary wedge.

In the Ligurian-Emilian Apennines, the base of the wedge-top basin succession (Epiligurian Units) is commonly characterized by a middle Eocene sedimentary mélange known as the "*brecce argillose di Baiso*" (e.g., Bettelli et al., 1987; Bettelli & Panini, 1989; Festa et al., 2020). This sedimentary mélange, which was mainly sourced by the Basal Complex of the External Ligurian Units, is age constrained to the middle(?) to late Lutetian to early Bartonian (e.g., Bettelli et al., 1987; Cerrina Feroni et al., 2002; Panini et al., 2002; Papani et al., 2002; Vescovi, 2002; Di Dio et al., 2005; Gasperi et al., 2005) (Fig. 11). The "*brecce argillose di Baiso*" is the evidence that during the Bartonian the External Ligurian Domain was already involved in the building phase of the Ligurian-Emilian Apennines.

At a regional scale, the Bartonian age of the "il Casone-Monte delle Fate" olistostrome, within the External Ligurian Tolfa Unit, points to a younger tectonic phase for the deformation of the External Ligurian Domain in northern Latium. In this regard, it is worth noting that to the north of the study area, in the surroundings of Sutri (VT), the pre-orogenic succession of the Tolfa Unit includes, ontop of the *Flysch della Tolfa*, the *Arenarie di Poggio San Benedetto* (Oligocene) (ISPRA-Servizio Geologico d'Italia, 2016). In that contex, the *Arenarie di Poggio San Benedetto* could represent the siliciclastic deposition in an early Oligocene foredeep basin developed ontop of the External Ligurian Domain of northern Latium.

The presence of a middle Eocene sedimentary mélange in the stratigraphy of the Eastern External Ligurian Domain in northern Latium (Fig. 11), containing olistoliths with Tuscan affinity, points to a major tectono-sedimentary event that affected the Adria passive margin at the transition between the External Ligurian Domain and the Tuscan Domain.

PROVENANCE OF THE OLISTOLITHS OF "IL CASONE-MONTE DELLE FATE" OLISTOSTROME

The stratally disrupted chaotic complex cropping out in "Bagni", "il Casone", and "Monte delle Fate" areas, which contains both native (i.e., intraformational) and exotic (i.e., extraformational) blocks, might have resulted from various mass transport events (e.g., Festa et al., 2016, with references therein). As evidenced by the lithologies of the different olistoliths embedded within the highly tectonized argillaceous matrix of "il Casone-Monte delle Fate" olistostrome, the provenance area of the olistoliths is both from a pelagic domain with Tuscan affinity and the Eastern External Ligurian Domain (*Flysch della Tolfa* olistoliths). Almost all the formations of the stratigraphic succession of the Tuscan Domain, starting from the *Calcare Massiccio* (Lower Jurassic) up to the *Scaglia toscana* (Upper Cretaceous-Eocene) are represented as olistoliths in "il Casone-Monte delle Fate" olistostrome (Fig. 12).

To explain the occurrence of Lower Jurassic up to Eocene olistoliths with Tuscan affinity, a source area characterized by a complete exposure of the Tuscan Succession, from the *Calcare*

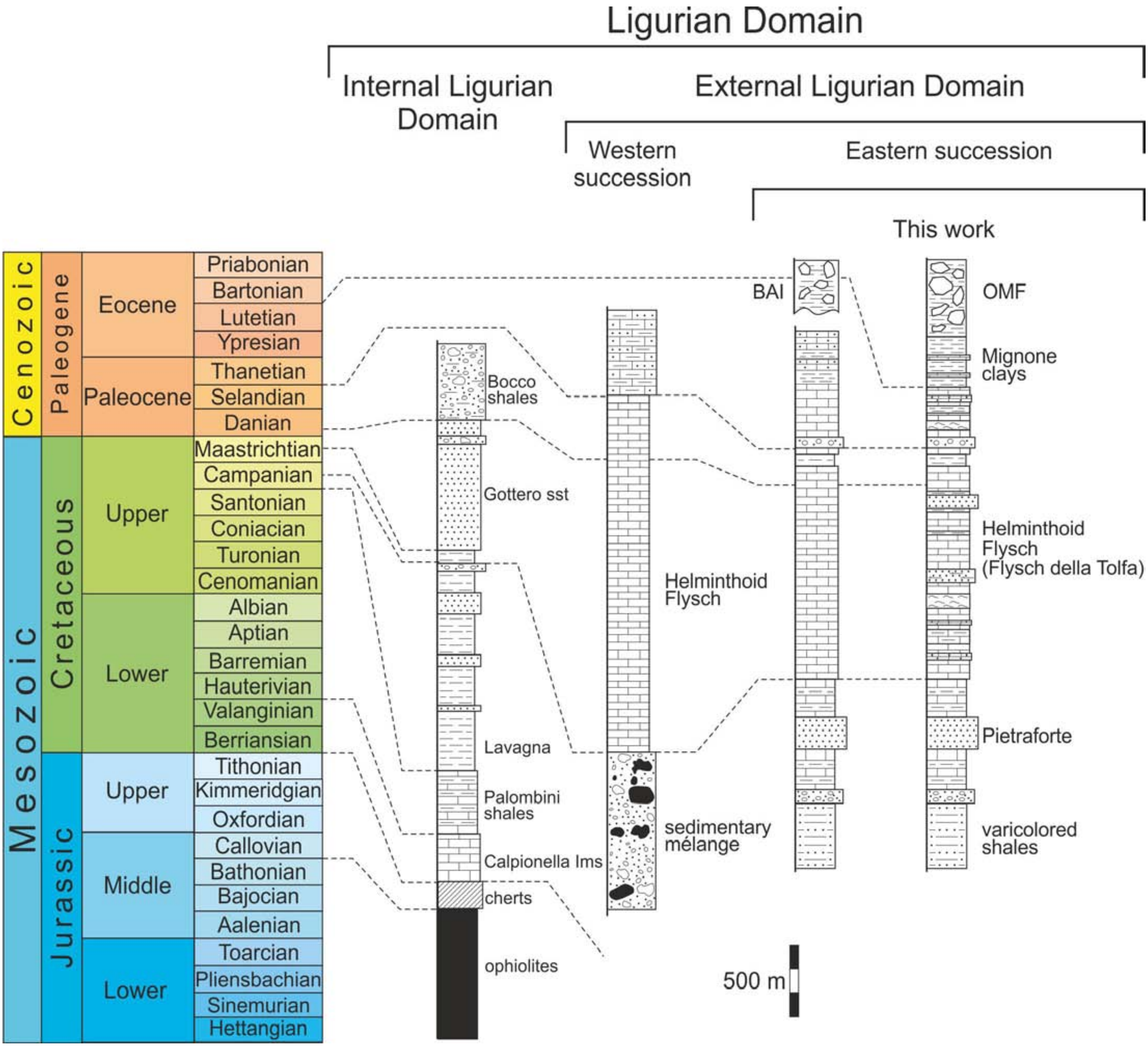

Fig. 11 - Stratigraphy of the Ligurian Domain, after Marroni *et alii* (2001, 2017), Conti et al. (2020), and Festa (2020), modified according to the results from this work and including the basal portion of the Epiligurian succession of the Ligurian-Emilian Apennines. BAI – *brecce argillose di Baiso* (Epiligurian succession of the Ligurian-Emilian Apennines); OMF – *il Casone-Monte delle Fate olistostrome.*

Massiccio (Lower Jurassic) up to the Cenozoic part of the *Scaglia toscana*, is needed. Such an upper crust configuration is possibly related to the reactivation of pre-existing extensional faults responsible for the footwall exhumation of the whole Tuscan Succession.

The palaeogeographic position of an area that includes the source-to-sink system of "il Casone-Monte delle Fate" olistostrome, characterized by blocks from both the Eastern External Ligurian Unit (*Flysch della Tolfa*) and the Tuscan Succession, has to be placed on the thinned crust of the ocean-continent transition zone (OCT) (Fig. 13), which marks the transition between the continental crust of the Tuscan Domain and the oceanic crust of the Piedmont-Ligurian Ocean (Internal Ligurian Unit). The reactivation of pre-existing low-angle extensional faults of the thinned continental crust at the OCT zone and/or at the western margin of Adria is a possible triggering mechanism for slope instability and mass transport events (e.g., Festa et al., 2016) responsible for the emplacement of "il Casone-Monte delle Fate" olistostrome in the stratigraphic succession of the Eastern External Ligurian Unit (Tolfa Unit).

GEODYNAMIC FRAMEWORK FOR TRIGGERING "IL CASONE-MONTE DELLE FATE" OLISTOSTROME

The middle Eocene is one of the key periods for the geodynamic reconstruction of the central Mediterranean area. At that time, the consumption of the E- to SE-subducting oceanic

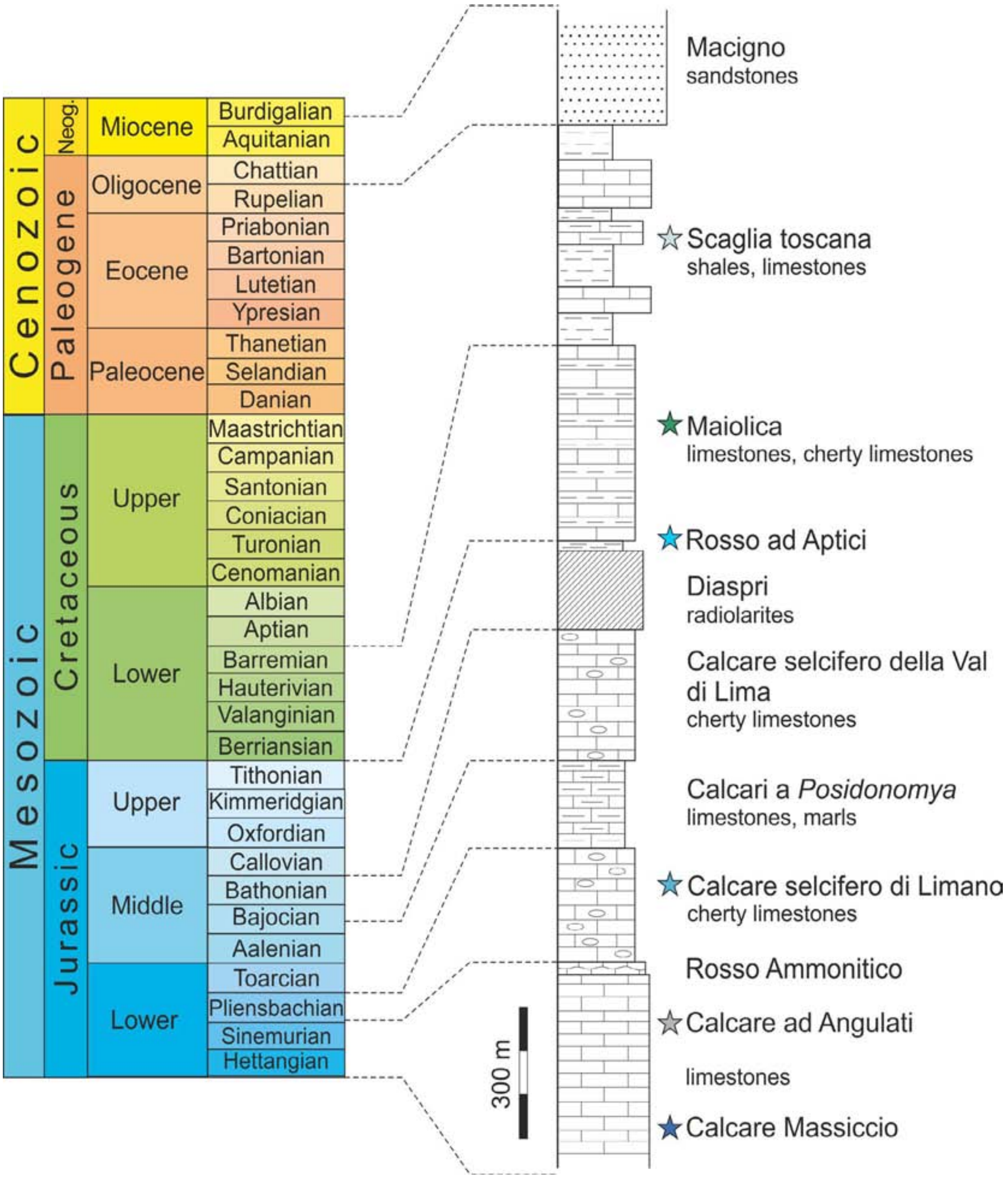

Fig. 12 - Stratigraphic log of the Tuscan Succession (modified after Conti et al., 2020). The coloured stars indicate the formations of the Tuscan Succession found as olistoliths within "il Casone-Monte delle Fate" olistostrome.

lithosphere was almost completely ceased (e.g., Marroni et al., 2010, 2017; Carminati et al., 2012), bringing the continental crust of the Southern European palaeo-margin to collide with the continental crust of the Adria microplate (Fig. 13). After the continent-continent collision, the Adria microplate started to subduct underneath the intra-plate margin (post-collisional subduction), defining both the W-directed (Apennines) and the E-directed (Dinarides) subduction zones (e.g., Channell et al., 1979; Doglioni et al., 1999; Carminati et al., 2012; Marroni et al., 2017; Cicala et al., 2021). In a such geodynamic setting, the lower plate is usually affected by an intraplate stress field (Fig. 13) that leads to pronounced lithosphere folding (e.g., Luth et al., 2010; Reece et al., 2013), with regional wavelength of 200-400 km (e.g., Mc Adoo & Sandwell, 1985; Nikishin et al., 1993; Burov et al., 1993). A middle Eocene lithosphere bulging of the Adria microplate, as a consequence of the collision between Adria and the European plate, has been indicated as the cause of the formation of the Paleogene gap affecting the carbonate platform areas on the Adria microplate (e.g., Cipollari & Cosentino, 1995).

The intraplate stress field affecting the lower plate is generally responsible for the formation or reactivation of pre-existing normal faults to accommodate the growth of the lithosphere bulging (e.g., Reece et al., 2013). We infer that the post-collision lithosphere bulging of the Adria microplate may have reactivated the Mesozoic normal fault system responsible for crustal thinning at the ocean-continent transition zone located between the Ligurian and Tuscan domains (Figs. 13 and 14).

According to Festa et al. (2016), the reactivation of pre-existing extensional faults is the most common triggering mechanism for mass transport deposits (olistostrome) in a passive margin at the ocean-continent transition (OCT). Olistostromes formed in OCT zones are well documented from different areas of the Circum-Mediterranean Region: Apennines (e.g., Naylor,

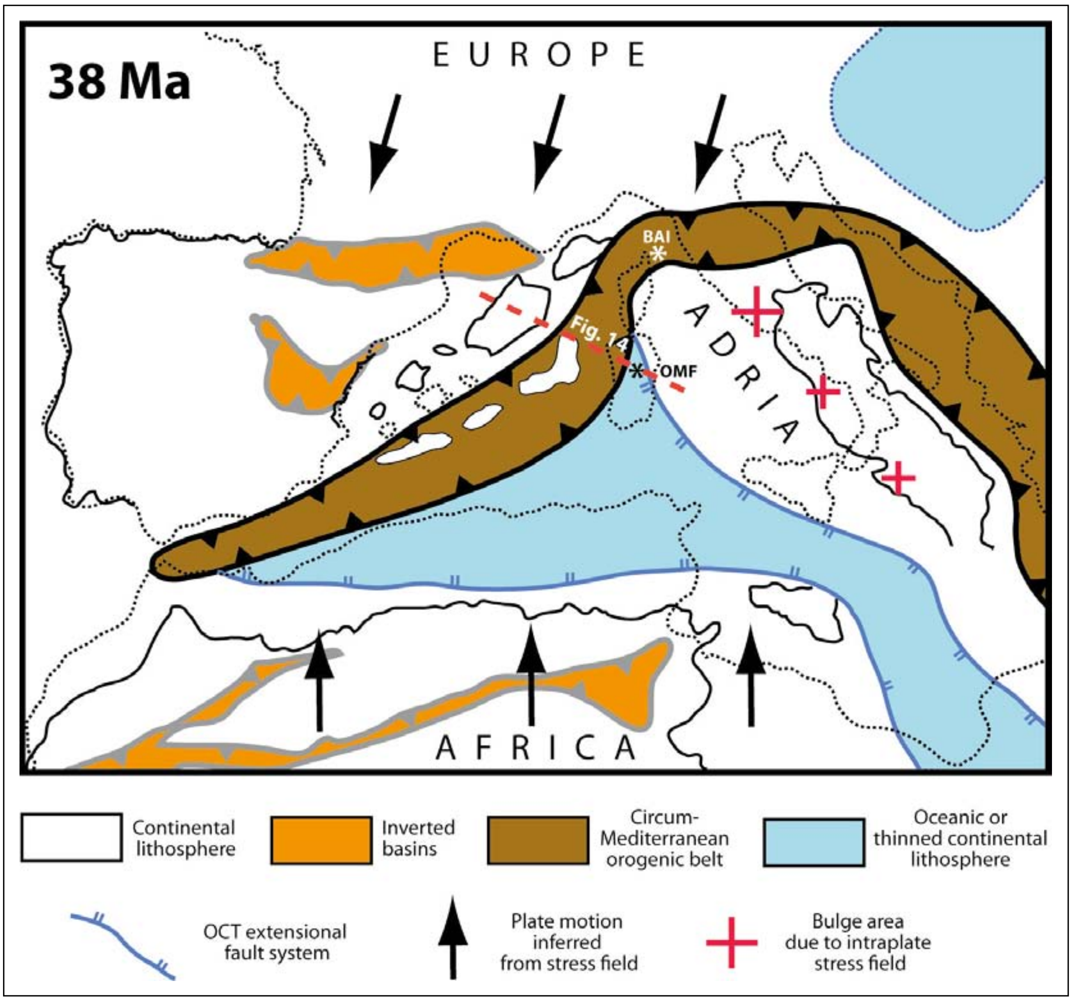

Fig. 13 - Geodynamic reconstruction of the central-western Mediterranean area at 38 Ma, during the European-Adria continental collision (modified from Carminati et al., 2012). The inferred bulge of the Adria microplate due to intraplate stress field is also shown. The white asterisk shows the position of the "*brecce argillose di Baiso*" (BAI) Epiligurian Unit; the black asterisk shows the position of the "il Casone-Monte delle Fate" olistostrome (OMF) in the Eastern External Ligurian Domain of northern Latium, not yet involved in the orogenic deformation; the red dashed line indicates the trace of the geodynamic section of Fig. 14.

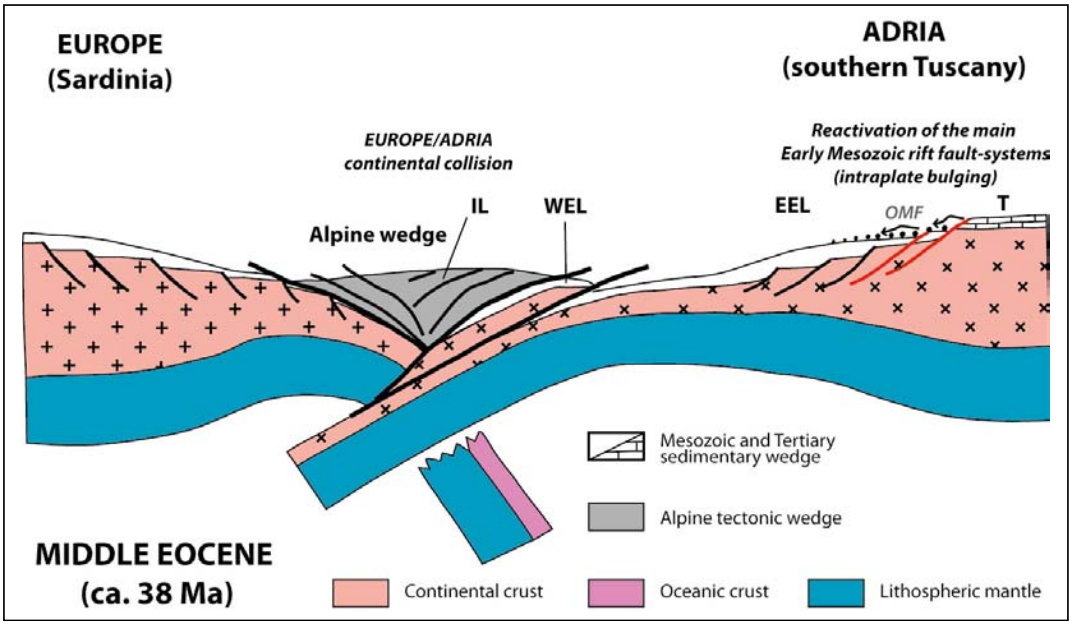

Fig. 14 - Possible geodynamic section (see location in Fig. 13) for the ocean-continent transition in the Adria microplate (Ligurian and Adria domains) after the middle Eocene European-Adria continental collision. Modified from Marroni et al. (2010). The reactivation of pre-existing extensional faults at the Adria passive margin is suggested as a possible mechanism for triggering the "il Casone-Monte delle Fate" olistostrome (OMF). IL – Internal Ligurian Domain; WEL – Western External Ligurian Domain; EEL – Eastern External Ligurian Domain; T – Tuscan Domain.

1982; De Libero, 1998; Pini et al., 2004), Hellenides-Albanides (e.g., Smith et al., 1979; Shallo, 1990; Shallo & Dilek, 2003), and Taurides (Dilek & Rowland, 1993).

Since “il Casone-Monte delle Fate” olistostrome contains olistoliths ranging from the Lower Jurassic (*Calcare Massiccio*) up to the Eocene (*Scaglia toscana*), the Mesozoic fault system at the ocean-continent transition must have been reactivated in the post-collisional phase (middle Eocene) with substantial throws to allow exhumation in the footwall of the oldest units of the Tuscan Succession.

CONCLUSIONS

The field work carried out in the "il Casone", "Bagni", and "Monte delle Fate" areas, where previous works suggested the presence of tectonic windows showing a basal carbonate succession with Tuscan affinity, led us to recognize a stratally disrupted chaotic complex, consisting of exotic blocks (extrabasinal blocks with Tuscan affinity) randomly distributed within a highly tectonized varicoloured argillaceous matrix. For this reason, we define it as a sedimentary mélange (olistostrome), here called "il Casone-Monte delle Fate" olistostrome, affected by tectonics during its eastwards orogenic transport.

The calcareous nannofossil assemblages from the "il Casone-Monte delle Fate" olistostrome point to a Bartonian age (middle Eocene) for this mass transport deposit. In particular, the presence of *Sphenolithus obtusus*, allows us to constrain it between 39.63 Ma (FO of *S. obtusus*) and 38.47 Ma (LO of *S. obtusus*).

This chronostratigraphical result points to the presence of a middle Eocene sedimentary mélange (olistostrome) in the stratigraphy of the Eastern External Ligurian Domain, which characterizes the Tolfa Unit. Bartonian ages were never reported in the literature of the Ligurian Units, whereas it defines the base of the Epiligurian Units in the Ligurian-Emilian Apennines. At a regional scale, this finding shows a younger compressional phase responsible for the orogenic deformation of the Eastern External Ligurian Domain in northern Latium, in comparison with the Ligurian Tectonic Phase (Lutetian) in the Ligurian-Emilian Apennines.

The reactivation of pre-existing extensional faults at the ocean-continent transition zone of the Adria passive margin (Ligurian Domain-Tuscan Domain), due to the Adria lithosphere bulging, is the suggested triggering mechanism for explaining the emplacement of the middle Eocene "il Casone-Monte delle Fate" olistostrome.

ELECTRONIC SUPPLEMENTARY MATERIAL

This article contains electronic supplementary material which is available to authorised users.

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