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The Late Oligocene to Early Miocene foredeep basin system evolution of the Northern Apennines (Emilia-Tuscany, Italy): review and new litho- and biostratigraphic data

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ABSTRACT

The Oligocene-Miocene turbidite successions of the Emilia-Tuscany Apennines are one of the most intriguing aspects of the geology of the Northern Apennines (NA) in Italy. To better understand the stratigraphic and tectonic evolution of this sector of the NA, we conducted a detailed field-mapping and stratigraphic study of turbidite successions of the most critical areas of this sector of the chain, which are composed of Mt. Modino Sandstone, Mt. Cervarola Sandstone, Gova Sandstone and associated marly units. Our contribution encompasses a review of the regional geology and field-relationships of arenaceous and marly formations, with a particular focus on new biostratigraphic data. This new biostratigraphic study is coupled with a compositional characterization of sandstone, with a view to producing a paleogeographic and evolutionary model of the thrust-foredeep system of the NA during the late Oligocene-early Miocene. This system was structured in a first stage during the Chattian-Aquitanian with the development of different inner turbidite systems (the Mt. Modino Sandstone in the frontal thrust-top basin, the Macigno, the Torre degli Amorotti System of the Mt. Cervarola Sandstone and the Gova Sandstone in the foredeep). The orogenic wedge was then affected by a later important deformation event during the earliest Burdigalian (Tuscan phase), developing the wider foredeep of the Mt. Cervarola Sandstone basin.

Key Words: *nannofossil biostratigraphy, turbidite system, foredeep basin, Oligocene-Miocene, Northern Apennines.*

INTRODUCTION

The Emilia-Tuscany sector of the Northern Apennines (NA) is a debated portion of the orogen, due to: the complex relationships between the tectonics and sedimentation in a migrating thrust wedge-foredeep system; the poorly constrained differences between orogenic landslides (olistostrome) vs. tectonic chaotic complexes; the controversial significance of the associated marly deposits; and the emplacement timing and kinematics of the thrust sheets.

The aim of this paper is to present new stratigraphic data and a review of the literature concerning some of the most studied and still discussed Oligo-Miocene turbidite successions of the Emilia-Tuscan sector of the NA, with the goal being to frame them in a coherent and homogeneous regional scenario. The research mainly focuses on some of the problematic successions, due to their still controversial position in regional paleogeographic reconstructions. This is because their relationships with overlying and underlying successions are still a matter of debate, or because the ages of the rocks are poorly defined.

The investigated successions crop out in tectonic windows in the Gova, Gazzano and Civago areas, lying below the Ligurian and Sestola-Vidiciatico units. Integrating data on these successions with additional data from nearby areas has also produced a more complete discussion.

This research uses a multidisciplinary approach (lithostratigraphy, biostratigraphy, sandstone composition) in order to better define the peculiar features of the turbidite successions. First, a major review of the data in the literature was performed, and this data was then integrated with new data obtained for this research, especially with respect to: field relationships among the lithostratigraphic and tectonic units; and biostratigraphy through an analysis of nannofossils.

Finally, more accurate information about the age and paleogeographic position of these rocks is utilized, which is crucial for reconstructing the stratigraphic and tectonic evolution of this important sector of the NA.

GEOLOGICAL OVERVIEW

The NA are a fold-thrust belt formed during the Cenozoic by the thrusting from west to east (in present day coordinates) of the Ligurian units onto the Tuscan-Umbria units (Fig. 1a). The Ligurian units represent remnants of the Ligurian-Piedmont Ocean (or Alpine Tethys), and also suffered deformation during the Cretaceous-Paleogene tectonic phases that are well documented in the Alps (Trümpy, 1975; Frisch, 1979). The Tuscan-Umbria Domain represents the continental margin of the Adria (Apulia) plate and consists of a Hercynian basement and its Permian-Mesozoic to Cenozoic cover (Carmignani *et alii*, 2004 *cum bib)*. The eastwards motion of the European Plate with respect to Adria during the middle Eocene led to continental collision, with the closure of the Ligurian-Piedmont Ocean, the overthrusting of the Ligurian units above the Tuscan-Umbria units, and deformation in the Apulia margin (see Elter, 1973; Vai & Martini, 2001 for an overview and reference list). Later, back-arc rifting led to the extension in the Tyrrhenian Sea and the NA, with the eastwards migration of subduction, deformation and extensional tectonics (Boccaletti *et alii*, 1971; Kligfield, 1979; Principi & Treves, 1984; Jolivet *et alii*, 1998;

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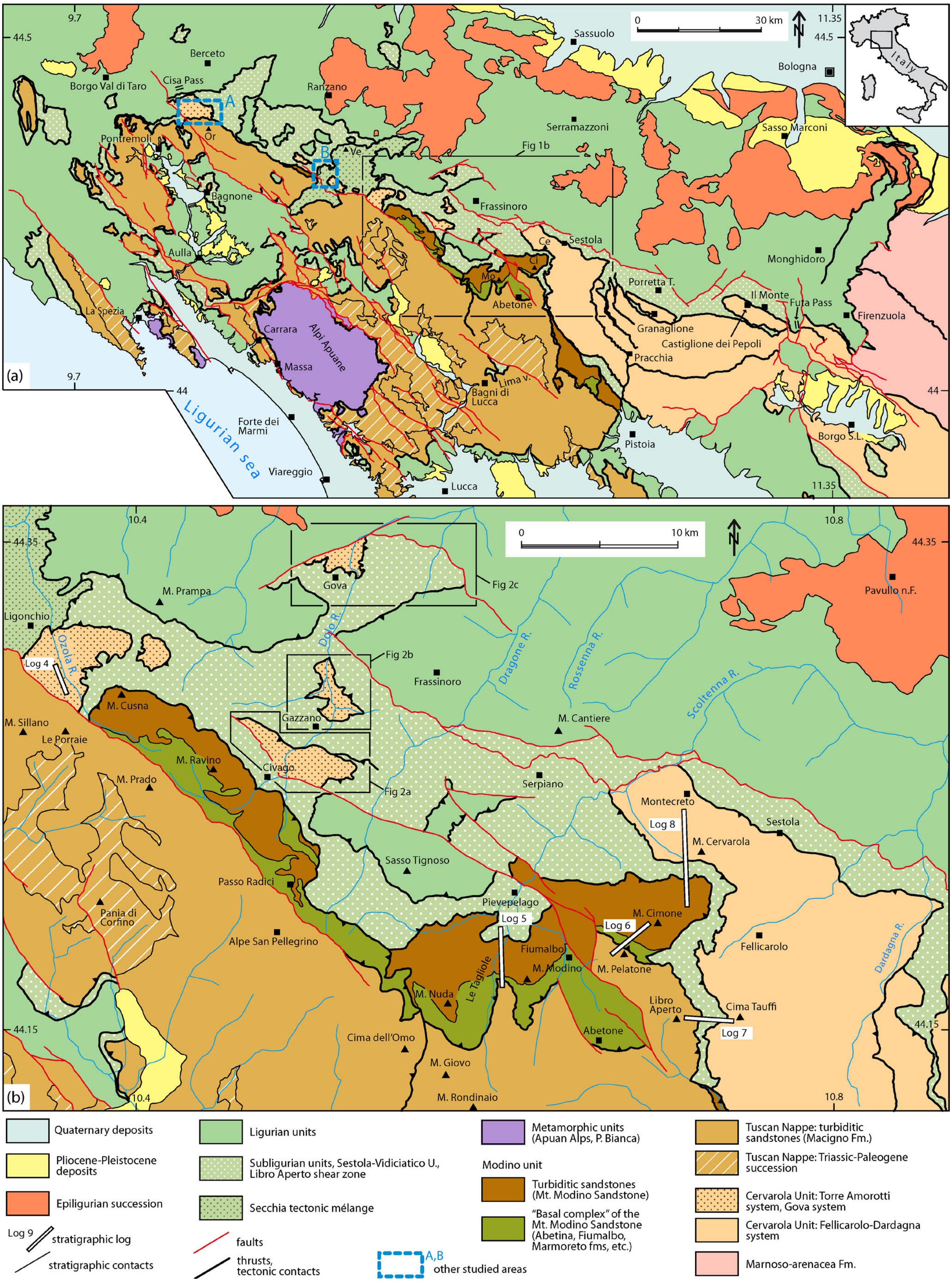

Fig. 1 - (a) Tectonic map of the Northern Apennines. (b) Tectonic map of the studied Emilia-Tuscany Northern Apennines. Boxes indicate the study areas.

CARMIGNANI *et alii*, 2001, 2004; VAI & MARTINI, 2001; ARGNANI, 2002; MARRONI *et alii*, 2010; MOLLI & MALAVIEILLE, 2011; CORNAMUSINI & PASCUCCI, 2014, and references therein).

The following main tectonic units are exposed (from top to bottom) in the study area (Fig. 1b):

1. the Ligurian units.
2. the Sestola-Vidiciatico and Subligurian units.
3. the Modino Unit.
4. the Tuscan Nappe Unit.
5. the Cervarola Unit.

The Ligurian units are represented here by successions characterized by Helminthoid flysch deposits and sedimentary melanges with blocks of ophiolite rocks (External Ligurian Domain: MARRONI *et alii*, 2001; ARGNANI *et alii*, 2006). These units are not investigated in this study.

The Sestola-Vidiciatico Unit (REMITTI *et alii,* 2007; VANNUCCHI *et alii,* 2008) is a thick (up to 500 m), strongly deformed tectonic unit, and represents a regional shear zone developed in the Miocene during a continental collision between the European and Adria plates. This unit is composed of juxtaposed tectonic slivers of different rock types that are detached from the overriding Ligurian units and underlying tectonic units and incorporated into the shear zones. Moving towards the northwestern areas, from Alpe di Cerreto to Pracchiola (Fig. 1a), the Sestola-Vidiciatico Unit is replaced by the Subligurian Unit (see also in ELTER *et alii*, 2003; REMITTI *et alii*, 2007). This latter unit is formed by stacked thrust sheets of Upper Cretaceous to Upper Oligocene shale, limestone and sandstone (PLESI *et alii*, 1998; CATANZARITI *et alii*, 2002).

The Modino Unit is represented by a succession that starts with a complex of Cretaceous Helminthoid Flysch (with Ligurian affinity) that is unconformably overlain by: Eocene-Oligocene shales, marls and marly limestones (Fiumalbo Shale and Marmoreto Marl); and in turn arenaceous turbidite deposits of Mt. Modino Sandstone. This unit is now overthrusted above the Tuscan Nappe tectonic unit.

The Tuscan Nappe Unit crops out extensively in the NA and comprises a calcareous to shaly succession that is Triassic-Oligocene in age, with at the top the Macigno Fm., a thick arenaceous turbidite succession that is late Oligocene-early Miocene in age.

The Cervarola Unit covers wide areas in the NA and is mainly formed by a thick arenaceous turbidite succession (Mt. Cervarola Sandstone). In the study area, the Civago Marl is considered to be the unit's stratigraphic base (GHELARDONI *et alii*, 1962); outside the study area, the Villore Shale Fm. (varicoloured shale) is regarded as the base of the Mt. Cervarola Sandstone.

The turbidite and marly successions studied here belong to the Modino and Cervarola tectonic units.

PREVIOUS WORKS AND INTERPRETATIONS

A long-lasting debate is documented in the Italian geological literature about the geological setting of this sector of the NA, particularly with respect to: the palinspastic position of the Modino and Tuscan Nappe-Cervarola units and their relative locations; and the nature of their boundaries (tectonic vs. stratigraphic). A comprehensive overview of the different interpretations was presented by CHICCHI & PLESI (1991a).

Extensive investigations in the Emilia-Tuscany NA, which produced a modern geological model following the fundamental paper by MERLA (1952), were first carried out by NARDI (1965) and BALDACCI *et alii* (1967), and then by geologists from Berlin University (GÜNTHER & RENTZ, 1968; REUTTER, 1969; GÜNTHER & REUTTER, 1985), who envisaged a single (albeit complicated) stratigraphic succession for the Modino-Cervarola succession.

The stratigraphic and structural position of the Modino Unit has led to a debate that is still ongoing, but different interpretations can be brought back to two end-members: a) the Mt. Modino Sandstone is in a stratigraphic succession above the Macigno Fm. of the Tuscan Nappe, with the interposition of a thick gravitational chaotic complex called "Monte Modino Olistostrome" (ABBATE & BORTOLOTTI, 1961; NARDI, 1965; BALDACCI *et alii*, 1967; MARTINI & SAGRI, 1977; BOCCALETTI *et alii*, 1980; ABBATE & BRUNI, 1987; LUCENTE & PINI, 2008); and b) the Mt. Modino Sandstone is in a tectonic relationship with the underlying Macigno Fm., through the interposition of a tectonic basal complex (REUTTER, 1969; PLESI, 1975; MARTINI & PLESI, 1988; BETTELLI *et alii*, 1987; CHICCHI & PLESI, 1991a; CERRINA FERONI *et alii*, 2002a; PLESI *et alii*, 2002).

Also reported herein are the data and interpretations of earlier literature works on the successions here studied in detail (Civago-Torre Amorotti, Gazzano, Gova and Ozola) (Figs. 1, 2). The arenaceous succession outcropping in the Civago-Torre Amorotti area has been studied by several authors, is referred to as the "Torre degli Amorotti" succession, and has been interpreted as belonging to the Mt. Cervarola Sandstone that lies stratigraphically on the Civago Marl (NARDI, 1965; BERTOLLI & NARDI, 1966; REUTTER & SCHLÜTER, 1968; REUTTER, 1969; RENTZ, 1971; CHICCHI & PLESI, 1991a; ANDREOZZI, 1991; ANDREOZZI *et alii*, 1995; PLESI, 2002b; VESCOVI, 2005; PIAZZA, 2016). This sandstone depositional unit is referred to by FAZZINI (1965) as Civago Sandstone and by ANDREOZZI (1991) as Torre degli Amorotti system of the Mt. Cervarola Sandstone, separated by the Scoltenna and Fellicarolo systems outcropping in the Mt. Cervarola-type locality. This succession was studied in detail from a sedimentological point of view by ANDREOZZI *et alii* (1991) and PIAZZA (2016).

The arenaceous succession in the Gazzano area was regarded as belonging to the Mt. Modino Sandstone by FAZZINI (1965), NARDI (1965), BERTOLLI & NARDI (1966), and MARCUCCI (1967), and to the Mt. Cervarola Sandstone by REUTTER (1969), RENTZ (1971), CHICCHI & PLESI (1991a, 1995), and ANDREOZZI (1991). This unit has been subdivided by PLESI (2002) into two lithofacies based on the sand/mud ratio and is overlain by tectonic slices of Civago Marl.

The Gova Sandstone succession was first described in detail by PLESI (1989), especially its structural features. The correlation of the Gova Sandstone with nearby successions is still a matter of debate, and for this reason this lithostratigraphic unit has been proposed as an *incertae sedis* formation by PLESI (2002). In the literature, it has been tentatively correlated with the Mt. Cervarola Sandstone (RENTZ, 1971; CHICCHI & PLESI, 1991a; VESCOVI, 2005), whereas NARDI (1965) and BERTOLLI & NARDI (1966) correlated it with the Mt. Modino Sandstone.

The succession outcropping in the Ozola Valley was described as Cerreto Sandstone by REUTTER (1968), and

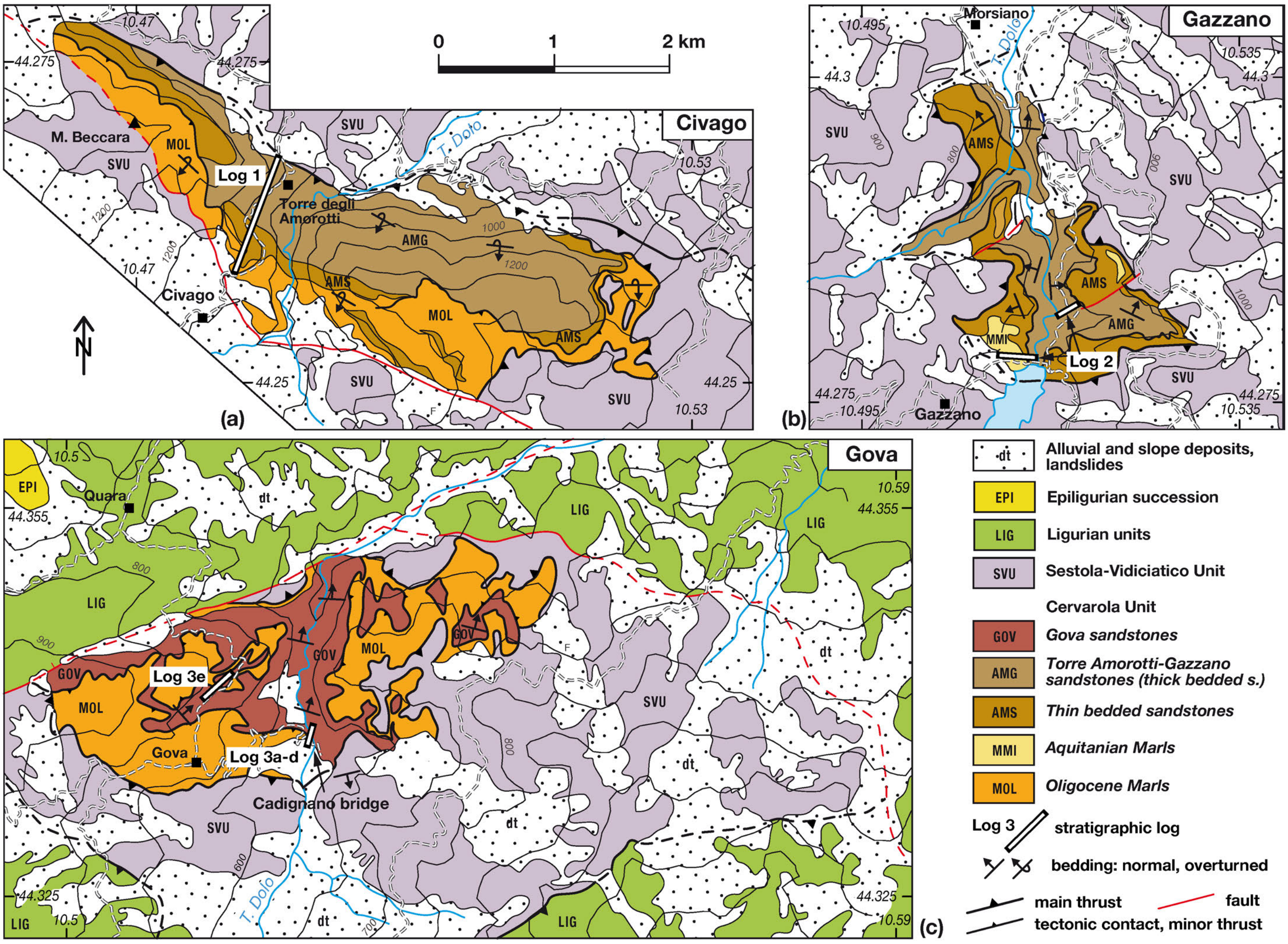

Fig. 2 - Geological maps of the investigated areas, see fig. 1b for location; scale is the same for all areas. (a) Geological map of the Civago - Torre degli Amorotti area. (b) Geological map of the Gazzano area. (c) Geological map of the Gova area. Log localities are indicated. Maps compiled from original field work integrated with data from Plesi (1989; 2002), Chicchi & Plesi (1995).

was then correlated by Chicchi & Plesi (1988, 1991b) with the Mt. Cervarola Sandstone. Andreozzi (1991) and Piazza (2016) refer this succession to the Mt. Cervarola Sandstone of the Torre degli Amorotti system.

REVIEW OF SANDSTONE PETROGRAPHY

In the following, we briefly review the more significant petrographic studies regarding the investigated arenaceous successions and those in adjacent areas, including modal analysis researches (Fig. 3).

Cipriani & Malesani (1964) first characterized the sandstones of the Emilia-Tuscan NA, where they recognized some primary compositional trends: the calcite and dolomite content is low or absent, respectively, in the Macigno Fm.; it increases in the Mt. Modino Sandstone; and is relatively high in the Mt. Cervarola Sandstone.

The composition of the Mt. Cervarola Sandstone in the Torre degli Amorotti section was studied by Mezzadri & Valloni (1981). They identified lithic arkoses with prevailing clasts of metamorphic rocks (micaschists) and subordinate carbonate lithoclasts, enabling the notion of a correlation with the Macigno Fm. to be rejected. Further regional studies were later performed by Cibin *et alii* (1993), Bruni *et alii* (1994a) and Pandeli *et alii* (1994). In terms of the sandstones of the Macigno and Mt. Modino Sandstone fms, these authors recognized more content of metamorphic lithics, chlorite and quartz with undulose extinction with respect to the Mt. Cervarola Sandstone. Meanwhile, the Mt. Modino Sandstone has more carbonatic content than the Macigno Fm.

Bruni *et alii* (1994b) focused their studies on the Macigno and Mt. Modino Sandstone of the Abetone area, highlighting strong similarities, although there were minor differences in the higher amount of serpentinite and carbonate content in the Mt. Modino Sandstone. Di Giulio (1999) confirmed the high compositional maturity of these sandstones in the Abetone area, with similar QFL+C (quartz, feldspar, lithic fragments and carbonate fragments) patterns and trends.

The Mt. Cervarola Sandstone was then investigated in the study area by Andreozzi & Di Giulio (1994), Valloni *et alii* (2002), Plesi (2002) and Botti *et alii* (2002; 2009). Plesi (2002) performed modal analysis for the sandstone of the Gazzano succession and of the Mt. Modino Sandstone (Fig. 3) showing similar composition, as well as for the Gova Sandstone, with an average detrital modal composition of $Q_{58}F_{29}L+CE_{13}$ and $Lm_{82}Lv_4Ls+CE_{14}$, with abundant calcite cement and patches.

REVIEW OF THE REGIONAL BIOSTRATIGRAPHIC AND CHRONOSTRATIGRAPHIC DATA

In this section, we briefly review the most recent biostratigraphic and chronostratigraphic data of the literature on the different lithostratigraphic units. The cited biozones are those used in the relevant papers.

The Fiumalbo Shale at the base of the Mt. Modino succession has been dated to a wide interval ranging from the Lutetian (CNE12 Zone of Agnini *et alii*, 2014, in Marchi *et alii*, 2017) or the Bartonian (NP16-NP17 zones of Martini, 1971), to the Rupelian p.p. (MNP23 Zone of Fornaciari & Rio, 1996 and Catanzariti *et alii*, 1997), by Plesi *et alii* (2000), Catanzariti *et alii* (2002) and Marchi *et alii* (2017). The overlying Marmoreto Marl has been ascribed by Plesi *et alii* (2000) and Plesi (2002) to the MNP23-MNP25b interval (Rupelian to Chattian), while Catanzariti *et alii* (2002), Catanzariti & Perilli (2009) and Marchi *et alii* (2017) extended the top to the MNN1a Zone. Catanzariti *et alii* (1991) assigned the Mt. Modino Sandstone to the NN1-NN2 interval (late Oligocene - early Miocene) for the study area, and later more precisely to the MNP25b - MNN1d interval (late Chattian - late Aquitanian) (Plesi *et alii,* 2000; Plesi, 2002; Botti *et alii,* 2009; Catanzariti & Perilli, 2009; Marchi *et alii,* 2017).

The Macigno Fm., representing a wider turbidite system, has a significant bottom to top internal diachrony between northern and southern Tuscany, ranging overall from the MNP24 to the MNN1d intervals (late Rupelian/early Chattian to Aquitanian) (Costa *et alii*, 1992; Catanzariti *et alii*, 1996; 2010; Plesi *et alii*, 1998; 2000; Cornamusini *et alii*, 1999; Botti *et alii*, 2002; Cornamusini, 2001, 2002). In terms of sections closer to the studied area, the MNP25a - MNN1d interval (early Chattian - late Aquitanian) has also been recognized (Plesi *et alii*, 2000; Plesi, 2002; Catanzariti & Perilli, 2009; Botti *et alii*, 2009).

The Civago Marl lithostratigraphic unit has been established by Ghelardoni *et alii* (1962; 1965), who recognized a microfauna assemblage of foraminifera within a section south of Torre Amorotti, indicating a late Oligocene-early Miocene age, whereas the overlying arenaceous unit was referred to the early-middle Miocene. Plesi (2002) and Catanzariti *et alii* (2002), on the basis of nannofossil analyses, dated the Civago Marl to the MNN1 Zone (late Chattian-Aquitanian), with the upper part restricted to the MNN1d subzone. In terms of the outcrops of Gazzano and Gova, where the marl lays tectonically on top of the sandstone, Chicchi & Plesi (1991a) and Catanzariti *et alii* (1991) reported a lower Miocene age, namely the NN1-NN2 zones of Martini (1971) (corresponding to the MNP25b-MNN2b zonal scheme adopted here).

Nardi & Tongiorgi (1962) first indicated a Miocene age for the Mt. Cervarola Sandstone, with Nardi (1964b) asserting (in agreement with Ghelardoni *et alii*, 1962) that its age was located between the late Oligocene and early Miocene on the basis of the macroforaminifera assemblage. Meanwhile, in other areas, the age could cover the entire Early-Middle Miocene (Nardi, 1965). In particular, the wide outcrop extending from Montecreto to Cima Tauffi in the studied area (Fig. 1) was dated to the early Miocene (early Aquitanian) (Gelmini, 1965, 1966, Serpagli & Sirotti, 1968; Reutter, 1969).

On the basis of nannofossil analyses, the whole Mt. Cervarola Sandstone system, which extends over the entire Emilia Apennines, has been ascribed to a wide time-span, ranging from the Chattian (MNP25) for the Pracchiola area to the Langhian (MNN5) for the more eastern Castiglione dei Pepoli area (Andreozzi, 1991; Andreozzi *et alii*, 1991; Plesi, 2002; Catanzariti *et alii,* 2002). The same authors showed that the Mt. Cervarola Sandstone close to the type-area (Mt. Cervarola) is constrained between the MNN1a and MNN2b intervals (latest Chattian to early Burdigalian), while Fornaciari (1996) reported a younger interval (MNN1d-MNN2a) for the lower part. A younger Burdigalian age (MNN3a Zone) has been recognized for the same area by Botti *et alii* (2002; 2009),

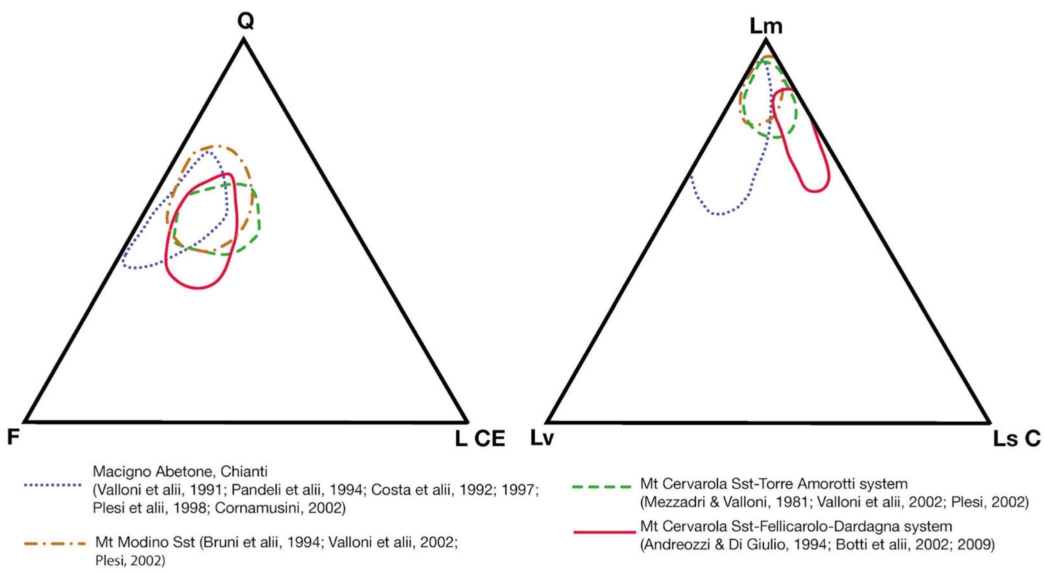

Fig. 3 - Compositional ternary diagrams (main composition: QFLCE and fine-grained texture lithic composition: LmLvLsC) of the main arenaceous units of the study area, from literature data.

who analyzed the two members (T. Fellicarolo and T. Dardagna) of the Mt. Cervarola Sandstone. The Serpiano Sandstone that lies below the Mt. Cervarola Sandstone has been dated to the MNN1-MNN2b interval by Botti *et alii* (2009). The sandstone succession of Civago-Torre degli Amorotti studied here (Log1 in Fig. 4) has been dated by Plesi (2002) to the MNN3a Zone of Fornaciari & Rio (1996) and ascribed to the middle Burdigalian as Mt. Cervarola Sandstone. Regarding the Gazzano area (Log 2 in Fig. 4), Fazzini (1965) indicated a probable Late Oligocene age on the basis of the microfauna assemblage.

The Gova Sandstone was first attributed to the Aquitanian by Bertolli & Nardi (1966) on the basis of its foraminifera content, while more recent nannofossil analyses suggested doubtfully a late Burdigalian-early Langhian age (MNN3b-MNN4b interval, in Andreozzi *et alii,* 1991; Fornaciari & Rio, 1996; Catanzariti *et alii,* 2002; Plesi, 2002).

MATERIALS AND METHODS

This research benefits from an integrated approach that first consists of an extensive field survey aimed at the revision and homogenization of the several available 1:10.000 scale regional-geological maps of the study area. Numerous literature maps, often showing contrasting geological settings, have also been used. This has allowed us to define the geometrical and stratigraphic vs. tectonic relationships among the units and a coherent geological setting. Logs were reconstructed through outcrop (logs 1 and 2 of Fig. 4) and bed by bed measures (logs 3 of Fig. 5) and integrated by way of geological cross-sections (logs 4 to 8 of Fig. 6). The collected samples along the logs have been used for biostratigraphic and petrographic analyses. A total of 67 samples have been used for the study of the nannofossil content, coming from the Civago-Torre Amorotti, Gazzano and Gova sections (Fig. 2), and other from secondary sections such as Ligonchio-Ozola, Mt. Modino, Mt. Cimone, Cima Tauffi, Mt. Cervarola, Pracchiola, and Collagna (Fig. 1), which have marly-sandstone units. The samples were prepared using standard techniques (Rio *et alii*, 1990; Fornaciari & Rio, 1996), and were examined through an Olympus BX-50 polarized microscope (transmitted light and crossed nicols) at a magnification of 1000x. In this work, we refer to a biostratigraphic scheme that combines the zonations of Fornaciari & Rio (1996), Sprovieri *et alii* (2002), Raffi *et alii* (2003), Iaccarino *et alii* (2011) and Baldassini & Di Stefano (2017).

A qualitative petrographic analysis of the sandstone has been conducted on selected samples from all the sections, with the aim being to define the major compositional features that are characteristic of lithostratigraphic units.

All the new data, along with the literature data, were then inserted into a regional frame, which enabled us to better understand the stratigraphic and tectonic evolution of this portion of the NA.

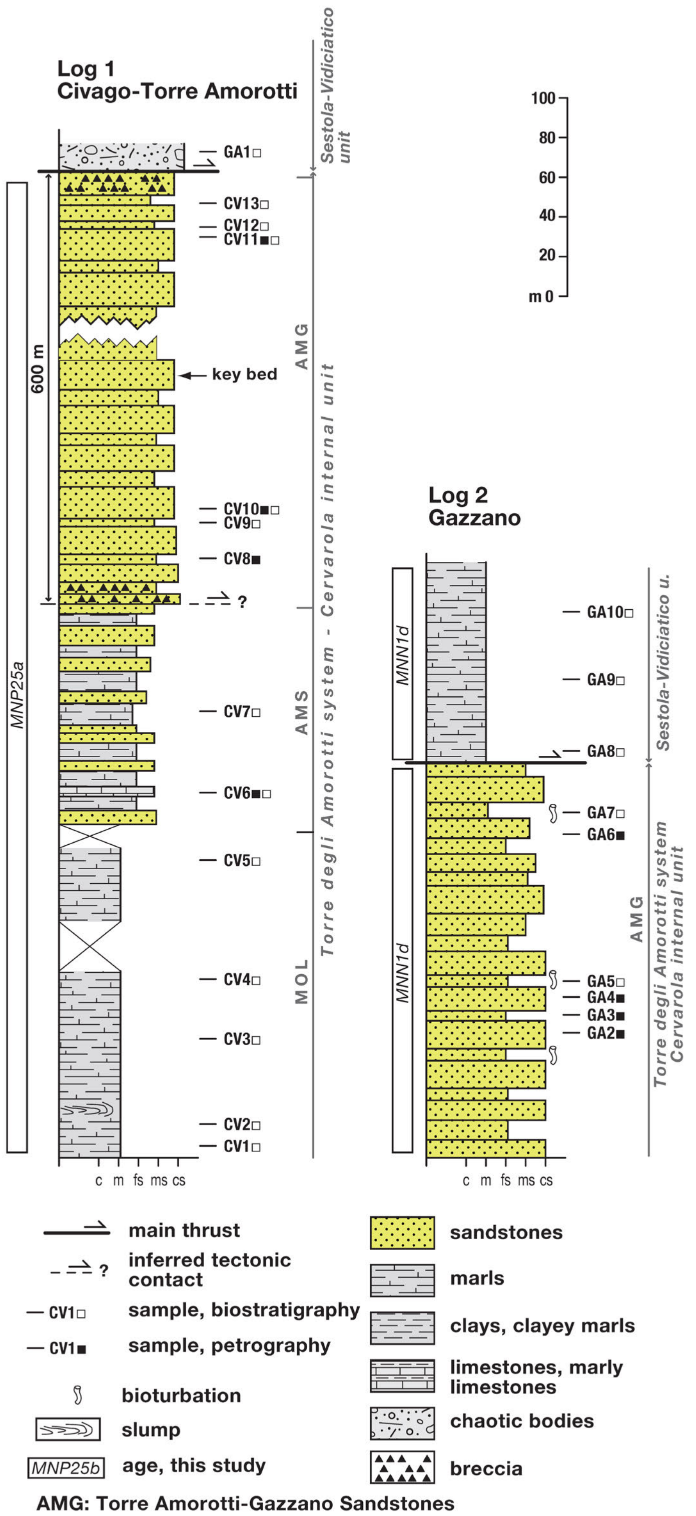

Fig. 4 - Lithostratigraphic logs for the Civago - Torre Amorotti and the Gazzano sections, see location in fig. 2.

STRATIGRAPHY

In this section, we present our results from the investigated areas, providing evidence with respect to differences with earlier interpretations and open questions. The study area is geographically located between the Secchia Valley to the northwest and the Dardagna Valley to the southeast. In more detail, the following successions are studied here (see location in figs. 1b and 2):

– Civago - Torre Amorotti (Log 1 in Fig. 4).
– Gazzano (Log 2 in Fig. 4).
– Gova (Log 3a-e in Fig. 5).

In addition, we present data from further subsidiary stratigraphic-tectonic logs (Fig. 6) from:
– Ozola Valley (Log 4).
– Mt. Modino - Le Tagliole (Log 5).
– Mt. Pelatone - Mt. Cimone (Log 6).
– Libro Aperto - Cima Tauffi (Log 7).
– Mt. Cimone - Mt. Cervarola - Montecreto (Log 8).

CIVAGO - TORRE AMOROTTI SUCCESSION

This section is located along the road between the village of Civago and the Torre degli Amorotti locality (Fig. 2a). This succession belongs to the Torre degli Amorotti system that is part of the Cervarola Unit, which is overlain tectonically by the Sestola-Vidiciatico Unit (Fig. 1). The stratigraphic succession can be partitioned into three depositional units:
– A lower marly unit (MOL in figs 2 and 4), corresponding to the Civago Marl of Ghelardoni et alii (1962, 1965) and Plesi (2002).
– An intermediate thin-bedded sandstone unit (AMS in figs 2 and 4), corresponding to the Serpiano Fm. of Plesi (2002).
– An upper sandstone unit (AMG in Fig. 4), corresponding to the Mt. Cervarola Sandstone of Plesi (2002).

The basal stratigraphic contact of the depositional unit MOL is not exposed, since the tectonic contact

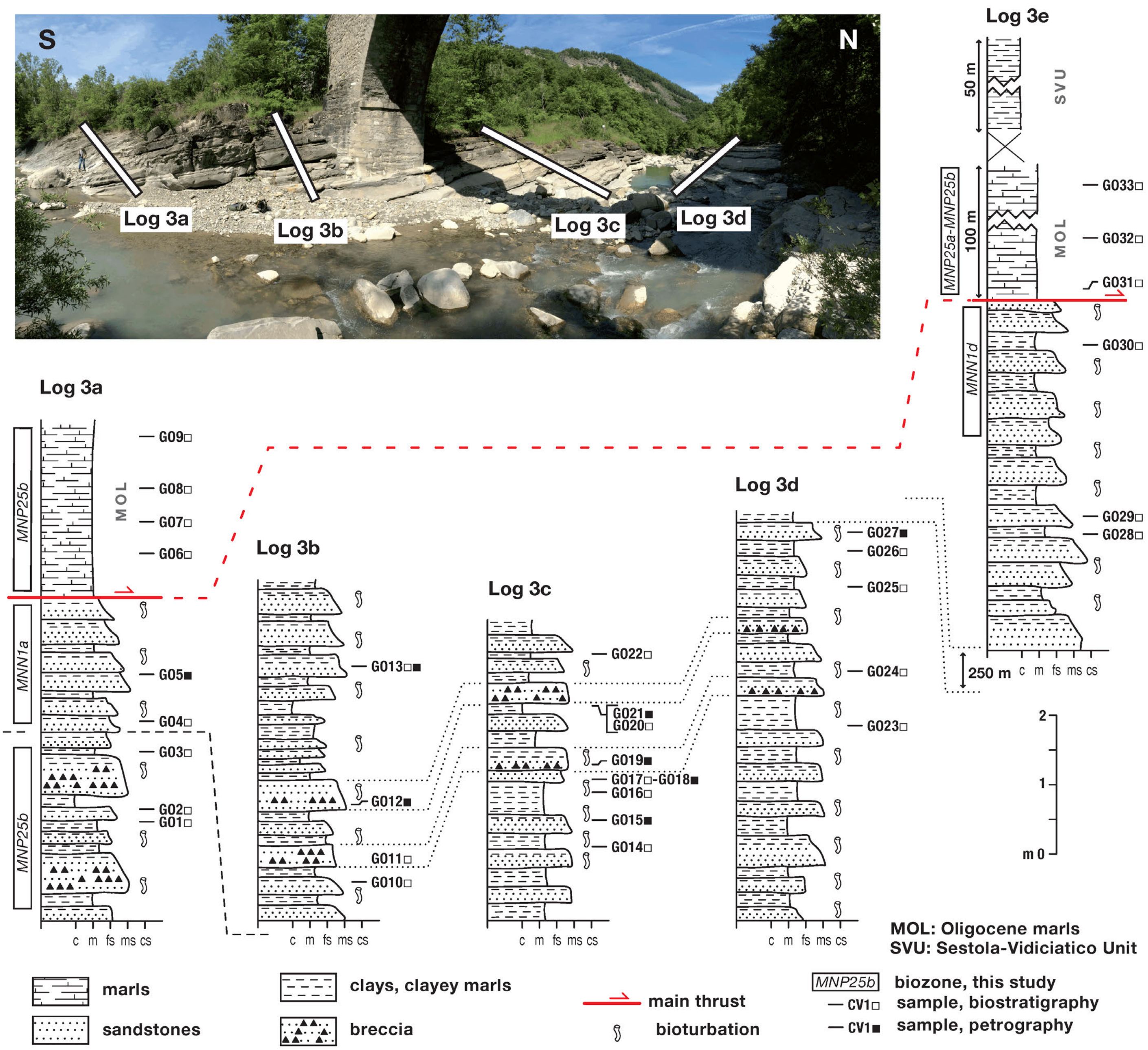

Fig. 5 - Studied logs in the Gova area: logs 3a-3d are from the Cadignano Bridge area (see above photograph for details). The Log 3e is located North of the Gova village along the Gova - Quara road, about 250 m stratigraphically above the logs 3a-d. See logs location in fig. 2c.

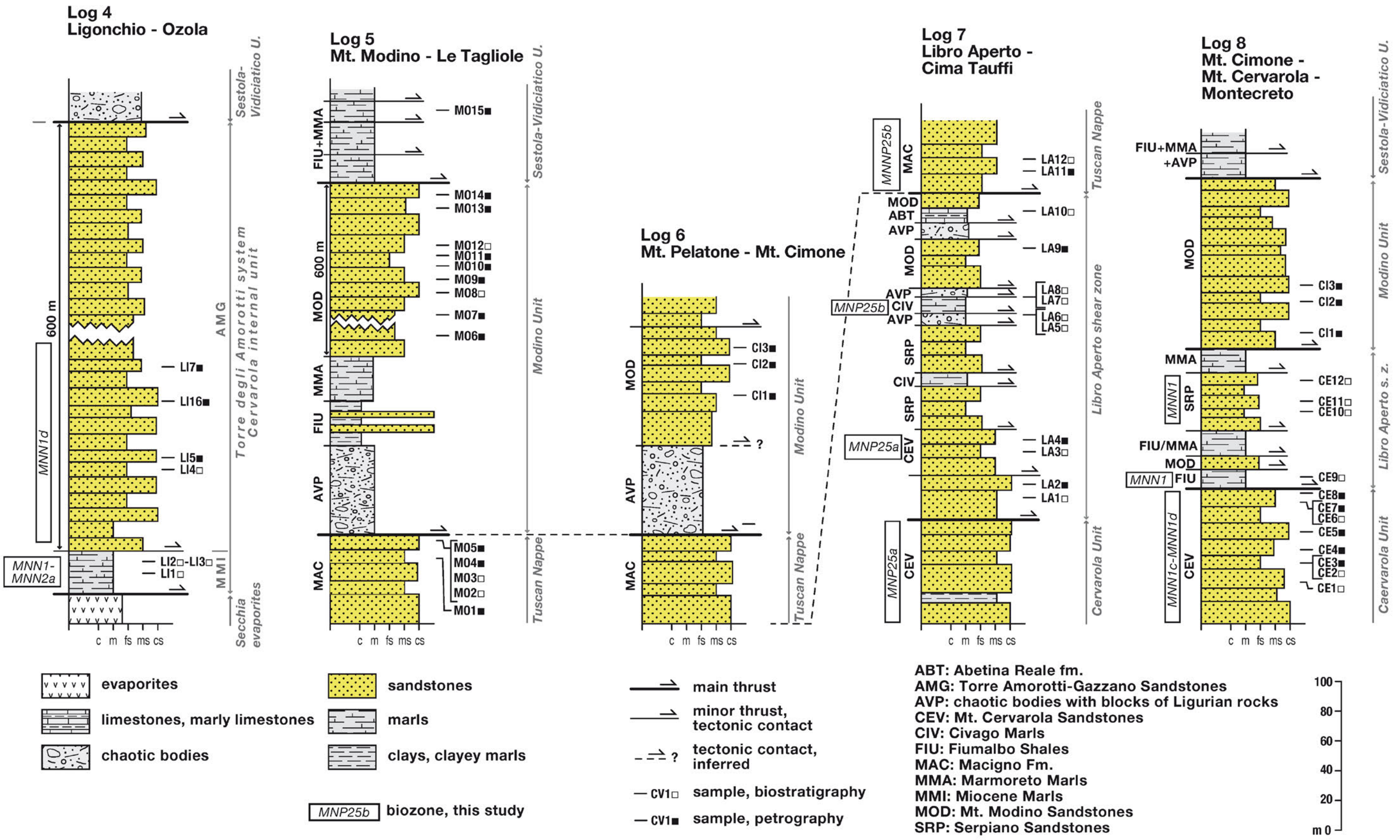

Fig. 6 - Studied stratigraphic logs of additional sections, see logs location in fig. 1b.

(normal fault) is with formations belonging to the Sestola-Vidiciatico Unit. This tectonic contact is observable at Mt. Beccara (Fig. 2a). The stratigraphic upper boundary of the depositional unit AMG is not exposed, as this succession has tectonic relationships (overthrust) with the overlying Sestola-Vidiciatico Unit.

The marly depositional unit MOL is well exposed along the road cut; it is a 160 m thick succession (Log 1 in Fig. 4), with an overall overturned attitude and a constant dip direction towards the southwest. Some cataclastic levels parallel to the bedding testify to localized deformation. Plesi (2002) reported some levels of polygenic sedimentary breccia in this succession (Rio Rumale Breccia). This unit is composed of marls and silty marls, which are grey in colour and have widespread bioturbation, alternating with thin silty layers and fine-graded sandstone, often with laminated and fluid-flow structures. A 1 m thick chaotic layer with slumping structures outcrops just 20 m above the base. The contact with the overlying depositional unit AMS is not clearly exposed, but is most likely to be stratigraphic, as the bedding shows the same attitude (vertical) and there is no evidence of widespread deformation.

The sandstone depositional unit AMS is about 120 m thick and is composed of alternating sandstones and silty marls. The sandstone is the "Thin-bedded-turbidite, TBT" facies of Mutti & Ricci Lucchi (1972), with a fine and very fine grain size, usually showing the incomplete Bouma sequence T_{b-e} and T_{c-e} (F9 facies of Mutti *et alii*, 2003), and with typical structures such as cross-lamination and convolute lamination. Locally, some more carbonatic turbidites (such as calcarenite or hybrid arenite, *sensu* Zuffa, 1980) are intercalated. The interbedded marly levels are often bioturbated.

The sandstone depositional unit AMG is 600 m thick and represented by turbiditic sandstones with interbedded marls and siltstones (Chicchi & Plesi, 1991a; Andreozzi, 1991; Plesi, 2002; Vescovi, 2005; Piazza, 2016). The sandstone succession is well exposed (Fig. 7a) and formed by thick sandstone layers with a very coarse to fine grain size and wide facies variability (mostly the F5 to F8 facies of Mutti *et alii*, 2003). Some of these layers contain the typical Bouma sequence, as described in detail by Piazza (2016). Mixed facies (slurry beds) from ponding basins, with deflection and reflection structures, are present. The bases of the sandstone beds are often characterized by flute casts and groove casts, indicating currents flowing from the northwest towards the southeast. Piazza (2016) also reports the presence of paraconglomerates, sedimentary breccias and thick chaotic beds with slumping (mass transfer deposits).

The upper contact of the depositional unit AMG is tectonic in origin and the sandstone is directly juxtaposed with deformed and chaotic formations of the Sestola-Vidiciatico Unit (Fig. 7b). It is also important to report some cineritic intervals that are present at different levels in the succession, as described by Andreozzi *et alii* (1995).

The sharp upwards change of the facies from F9 of the AMS unit to F5-F8 of the AMG unit, along with the occurrence of chaotic and slump deposits of channel and ponding structures, indicate the progradation of a turbidite fan within a confined basin (see also Tinterri & Tagliaferri, 2015 and Tagliaferri & Tinterri, 2016 for similar structures in the Marnoso-arenacea Fm.).

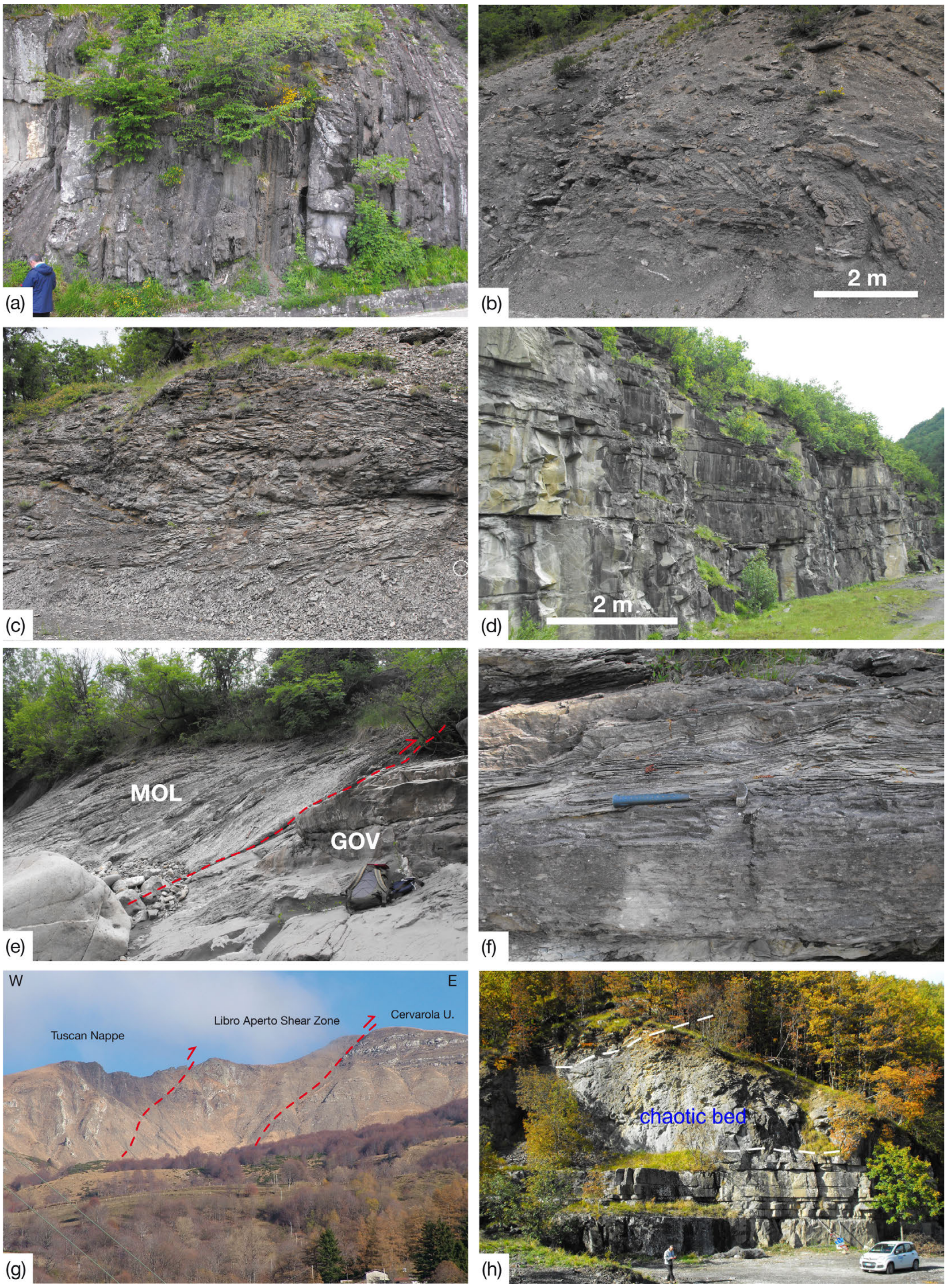

Fig. 7 - (a) Torre Amorotti Sandstone with vertical attitude (younging to the right), Log 1. (b) Deformed Sestola-Vidiciatico Unit thrust above the Torre Amorotti Sandstone, Log 1. (c) Deformed Aquitanian marlstones (Civago Marl) part of the Sestola-Vidiciatico tectonic unit above the Gazzano-Torre Amorotti Sandstone (Cervarola internal Unit), Log 2. (d) Thick turbidite sandstone beds of the Gazzano-Torre Amorotti Sandstone, Log 2. (see man in circle for scale) (e) Thrust between Marmoreto Marl (MOL) and Gova Sandstone (GOV), Cadignano Bridge locality, Log 3. (f) Turbidite bed with ripples on top, Gova Sandstone, Log 3. (g) Tectonic slices of the Libro Aperto Shear Zone (in the middle) overlying the Mt. Cervarola Sandstone at Cima Tauffi, Log 7. (h) Cerreto Sandstone (area A of fig. 1a) with horizontal attitude and interlayered thick marly-sandy chaotic bed, rich in bioturbation.

GAZZANO SUCCESSION

The studied section is located northeast of the village of Gazzano along the Dolo River, north of the Fontanaluccia dam (Fig. 2b, Log 2 in Fig. 4). The succession outcrops in a tectonic window and belongs to the Torre degli Amorotti system of the Cervarola Unit (Fig. 1). Its stratigraphic base is not exposed and the upper boundary is tectonic with the Sestola-Vidiciatico Unit (Fig. 7c). For a detailed geological overview of the area, see Chicchi & Plesi (1995) and Plesi (2002).

Only the sandstone depositional unit AMG outcrops in this area, and has a thickness of about 200 m, normal horizontal bedding and local open folding.

The lower portion of the succession has thick sandstone beds (Fig. 7d) with a coarse to medium grain size, mudstone intercalations and a sandstone/mudstone ratio >> 1; the upsections comprise thinner sandstone beds with a fine grain size and thicker mudstone layers (sandstone/mudstone ratio>= 1). The sandstone beds (mostly in the lower portion) have amalgamation and channel structures, clay-chip rich layers, normal grading and evident Bouma sequences (F8-F9 facies of Mutti *et alii*, 2003). Also frequent are layers with ripples and convolute lamination, flute casts and groove casts are also evident at the bottom of the bed surface, indicating current flows towards east-southeast.

The Civago Marl and Serpiano Sandstone (respectively MMI and AMS of Fig. 2) form tectonic slices on top of the turbiditic AMG succession (Fig. 2, Fig. 7c), which are in turn overlain by the Sestola-Vidiciatico Unit.

GOVA SUCCESSION

The investigated sections are located along the Dolo River below the Cadignano Bridge, and north of Gova Village, along the Gova - Quara road (Fig. 2c, Fig. 5). The Gova arenaceous succession belongs to the Gova system of the Cervarola Unit (Fig. 1). The sandy unit outcrops in a thick (about 230 m) succession at the core of an open antiformal tectonic window (Fig. 2c); the stratigraphic base does not outcrop and is tectonically topped by tectonic slices of the MOL marly unit and by the Sestola-Vidiciatico Unit (Fig. 7e) (Plesi, 1989, Vannucchi *et alii*, 2012).

The sandy succession is represented by sandstone in thick to thin tabular beds with a grain size ranging from coarse to very fine, alternating with marl and laminated clayey-silty marl. The sandstone contains characteristic turbidite structures (Fig. 7f), often developing the typical Bouma sequence of normal gradation, plane-parallel lamination and ripples that characterize the F8-F9 facies of Mutti *et alii* (2003). Convolute lamination and other fluid-escape structures occur. The bottom of the sandstone beds is usually flat, with occasional sole marks and a sharp transition to the mudstone below, while the top shows a gradual transition to laminated mudstone. Sandstone and marl are strongly bioturbated, mainly with *Ophiomorpha* type fossil traces. Some beds show chaotic or brecciated structures with mudstone intraclasts and rafts embedded in a marly-sandy matrix, particularly within the upper part of the bed. These structures range from a few cm to 50 cm in size and can show fold-slump features. These beds are referable to the so-called slurry-beds, and are probably linked with bipartite, cohesive debris-flow processes and analogously to co-genetic, debrite-turbidite beds of the Marnoso-arenacea Fm. (Talling *et alii*, 2004; Tinterri & Tagliaferri, 2015), indicating a complex basin morphology.

OTHER SECTIONS

Additional and complementary sections have been investigated through field surveys and sampled for biostratigraphy and petrography, in order to integrate the geological framework of the logs, and to better reconstruct the geological setting of this sector of the NA.

Ozola Valley area

The studied section (Log 4 in Fig. 6) outcrops along the Ozola River, south of the village of Ligonchio (Fig. 1b). The arenaceous succession belongs to the Torre degli Amorotti system of the Cervarola Unit (Fig. 1). Its bedding constantly gently dips (10°- 20°) towards the north and shows a vertical or reverse attitude near the tectonic contact with the underlying unit (Triassic Secchia anhydrite and cataclasite of the Secchia tectonic melange, Fig. 1b). The succession is covered tectonically by the Sestola-Vidiciatico Unit, which is in turn overlain by a later thrust of the Modino Unit (Fig. 1).

The lower marly succession (MMI in Log 4 of Fig. 6) is characterized by well-cemented silty marl, with intercalations of fine-grained sandstone, and is in tectonic contact with the arenaceous succession. This last part (AMG in Log 4 of Fig. 6) is about 600 m thick and is characterized by medium and thick beds, with a very fine to coarse grain size and turbiditic structures such as the F5 to F9 facies of Mutti *et alii* (2003); amalgamation structures and channels are also present, as are slumping levels. For a more detailed description of this succession, see Andreozzi (1991) and Piazza (2016).

Mt. Modino area

Log 5 (Fig. 6) shows the section of Mt. Modino-Le Tagliole (Fig. 1b), where relationships between the Modino Unit and the underlying Tuscan Nappe Unit are exposed. The lower part of the section shows a thick arenaceous succession that is referable to the Macigno Fm. of the Tuscan Nappe tectonic unit, overlain by a thick chaotic complex formed by rocks, mainly limestone and shale, that are Ligurian in origin (AVP in Fig. 6) (see Perilli, 1994 and De Libero, 1998 for details of the internal structure). This complex is overlain by a shaly succession (Fiumalbo Shale) formed by: red-green shales with a few polygenic breccia interlayers and marlstones in the upper part. Upsection follows the Marmoreto Marl formed of marlstones and silty marlstones, with an upwards increase in thin-bedded sandstones. In some areas, this part of the succession is deformed tectonically, forming imbricated slices, as in the Fiumalbo area. The upper part of the unit is represented by Mt. Modino Sandstone, some hundred metres thick, formed by siliciclastic turbidite sandstones, with thin to thick beds and a thickening-upwards trend (Marchi *et alii*, 2017). The Modino Unit in the Mt. Modino-Pievepelago area is overlain by a complicated stack of tectonic slices of Fiumalbo Shale and Marmoreto Marl, which are part of the Sestola-Vidiciatico Unit.

Mt. Cimone - Libro Aperto area

Log 6 (Fig. 6) represents a transect from Mt. Pelatone to Mt. Cimone (fig. 1b), where the Macigno Fm. of the Tuscan Nappe is overlain by the Modino Unit. The Modino Unit is represented here by a Ligurian chaotic complex at the base (AVP), with the Mt. Modino Sandstone above. In the upsection, the sandstone is then deformed by a thrust, with an overturned slice at the top.

Log 7 (Fig. 6) shows a stack reconstructed across a highly deformed zone along the ridge from Libro Aperto to Cima Tauffi. This belongs to the Libro Aperto Shear Zone (Fig. 7g), which is composed of: a complex stack of imbricated thrust-slices of Mt. Cervarola Sandstone; Serpiano Sandstone; Civago Marl; Mt. Modino Sandstone; and chaotic Ligurian units, including the carbonate mudstones of the Abetina Reale Fm., which originally belonged to the Modino Unit. This shear zone is interposed tectonically between the Macigno Fm. of the Tuscan Nappe above and the Cervarola Unit below, consisting here of a thick turbidite arenaceous succession, called the Fellicarolo-Dardagna System (Andreozzi, 1991; Botti *et alii*, 2002).

Mt. Cervarola area

Log 8 (Fig. 6) represents a reconstructed unit stack succession from Mt. Cimone to Mt. Cervarola and Montecreto (Fig. 1b). This shows the Cervarola Unit formed by Mt. Cervarola Sandstone that belongs to the Fellicarolo-Dardagna System (Andreozzi, 1991). This system is overlain by: thrust-slices of highly deformed Marmoreto Marl; Fiumalbo Shale; Mt. Modino Sandstone and a thick thin-bedded-turbidite horizon of Serpiano Sandstone (originating from the deformation of the Modino and Cervarola units) in the northwestern area that belongs to the Libro Aperto Shear Zone. The overturned arenaceous succession of the Modino Unit of Mt. Cimone outcrops above the shear zone (see Log 6). The uppermost unit is represented by the Sestola-Vidiciatico Unit formed here by a Ligurian chaotic complex (AVP), highly tectonized Fiumalbo Shale and Marmoreto Marl (Nardi, 1964a; Bettelli *et alii*, 1987; Chicchi & Plesi, 1995).

Cerreto - Pracchiola areas

Supplementary unlogged, but surveyed and sampled areas are located in the northwestern sector of the study area, such as those of Collagna-Alpe di Cerreto and Monchio delle Corti-Marra-Pracchiola (respectively, areas B and A of Fig. 1a).

The geological setting of the Cerreto area (area B) is characterized by a lower turbidite sandstone succession (Cerreto Sandstone *Auctt*., Fig. 7h), which is correlated by most authors with the Ozola, Gazzano and Torre degli Amorotti outcrops and the Mt. Cervarola Sandstone of the Torre degli Amorotti system (see the review in Piazza, 2016). The sandstone succession belonging to the Cervarola Unit is overlain by the “Secchia tectonic mélange” and the Mt. Ventasso slice stack (Fig. 1a). The former is a tectonic complex containing: rocks from the Ligurian units; lenticular slices of Marmoreto Marl and Fiumalbo Shale; Triassic evaporites (Sassalbo Evaporite) belonging to the lower part of the Tuscan Nappe (see Plesi *et alii*, 2000; Vescovi, 2005; Puccinelli *et alii*, 2009); and scattered amphibolite bodies (Ricci, 1968; Di Sabatino *et alii*, 1979).

Differently, in the Pracchiola area (area A of Fig. 1a), a thick siliciclastic-carbonate succession mainly formed of thin-bedded-turbidites and marlstones (Pracchiola Sandstone *Auctt.*) crops out. We consider this to be part of the inner Cervarola Unit. This unit occurs in a tectonic window delimited at the top by tectonic slices of deformed marlstone (Marra Marl or Marmoreto Marl); it is then overlain by the highly deformed Subligurian Unit, laterally replacing the Sestola-Vidiciatico Unit towards the northwest, which is in turn overlain by Ligurian units (see Plesi *et alii*, 1998; Vescovi, 2002; Cerrina Feroni *et alii*, 2002b).

PETROGRAPHIC COMPOSITION OF THE SANDSTONES

The main compositional framework of the sandstone of the studied sections is illustrated here based on a petrographic analysis (comprehensive, detailed, modal, quantitative analyses of these rocks, such as evaluations of compositional trends or provenance studies, are beyond the scope of this work).

All the samples we investigated in this study are characterized by an arkosic to arkosic-litharenitic composition, often with a relatively high carbonate content (Fig. 8, see table in the Supplementary Material). Usually, the samples were composed of siliciclastic sandstone with a low matrix content (arenites), and rarely graywackes. The General Composition and Main Composition (following Di Giulio & Valloni, 1992) were similar (see the literature’s plotted data in Fig. 3), but with some distinctive features that allow us to define three main petrographic facies (based on a qualitative analysis and compositional markers): Petrofacies A, Petrofacies A’ and Petrofacies A”. Although modal petrographic analysis using QFL+C lithic ternary diagrams can highlight detailed compositional differences, vertical trends and provenance insights, as emphasized by several authors (e.g. Valloni *et alii*, 2002, with references therein), the use of some compositional markers enables us to easily distinguish qualitative petrofacies (i.e. carbonate fragments, sedimentary and volcanic lithics, serpentinite clasts).

All the recognized petrofacies (Fig. 8) are characterized by: detrital quartz (Q); plagioclase (Pl); K-feldspar (Kf); muscovite and biotite; lithic fragments from metamorphic rocks (Lm: gneisses, micaschists, phyllites, quartzites); carbonate lithic fragments (Lc); clasts from volcanic rocks (Lv: from rhyolite to andesite); and bioclasts. The quartz clasts are mono- and polycrystalline, with undulose extinction. Meanwhile, the feldspars (plagioclase and K-feldspars) are frequently altered (often sericitized) and the K-feldspars are mainly orthoclase and microcline, with white mica and biotite altered to chlorite, and opaque and heavy minerals.

Petrofacies A consists of arkoses, lithic arkoses and arkosic litharenites with clasts of Q, Kf, Pl, and Lm, minor Lv and rare Lc, micas, and chlorite. Petrofacies A’ is distinguished from Petrofacies A mainly in terms of the higher carbonate content (lithic fragments, bioclasts) and the rare presence of dolomite and serpentinite clasts. The sandstones, meanwhile, are arkoses and arkosic litharenites. Petrofacies A” is characterized by the abundance of carbonate fragments (lithic clasts and bioclasts), and the overall composition of the arenites is mixed siliciclastic-carbonatic and hybrid (*sensu* Zuffa, 1980). Glauconite grains appear occasionally.

It is evident from the studied samples and the comparison with the literature data (Fig. 3) that:

- Petrofacies A characterizes the sandstone of the Macigno Fm. and some beds of the Mt. Modino Sandstone (Alpe San Pellegrino, Pracchia, Libro Aperto, Le Tagliole, Mt. Cimone, Ozola River; Fig. 1).
- Petrofacies A’ characterizes: most of the Mt. Modino Sandstone; the sandstone of the Ozola-Ligonchio, Torre degli Amorotti and Gazzano successions; minor part of the Gova succession; and Cerreto-Collagna (area B in Fig. 1a).
- Petrofacies A” mainly characterizes: the sandstone of the Fellicarolo-Dardagna System of the Mt. Cervarola Sandstone (Andreozzi, 1991); part of the Ozola-Ligonchio succession; most of the Gova succession; the Pracchiola

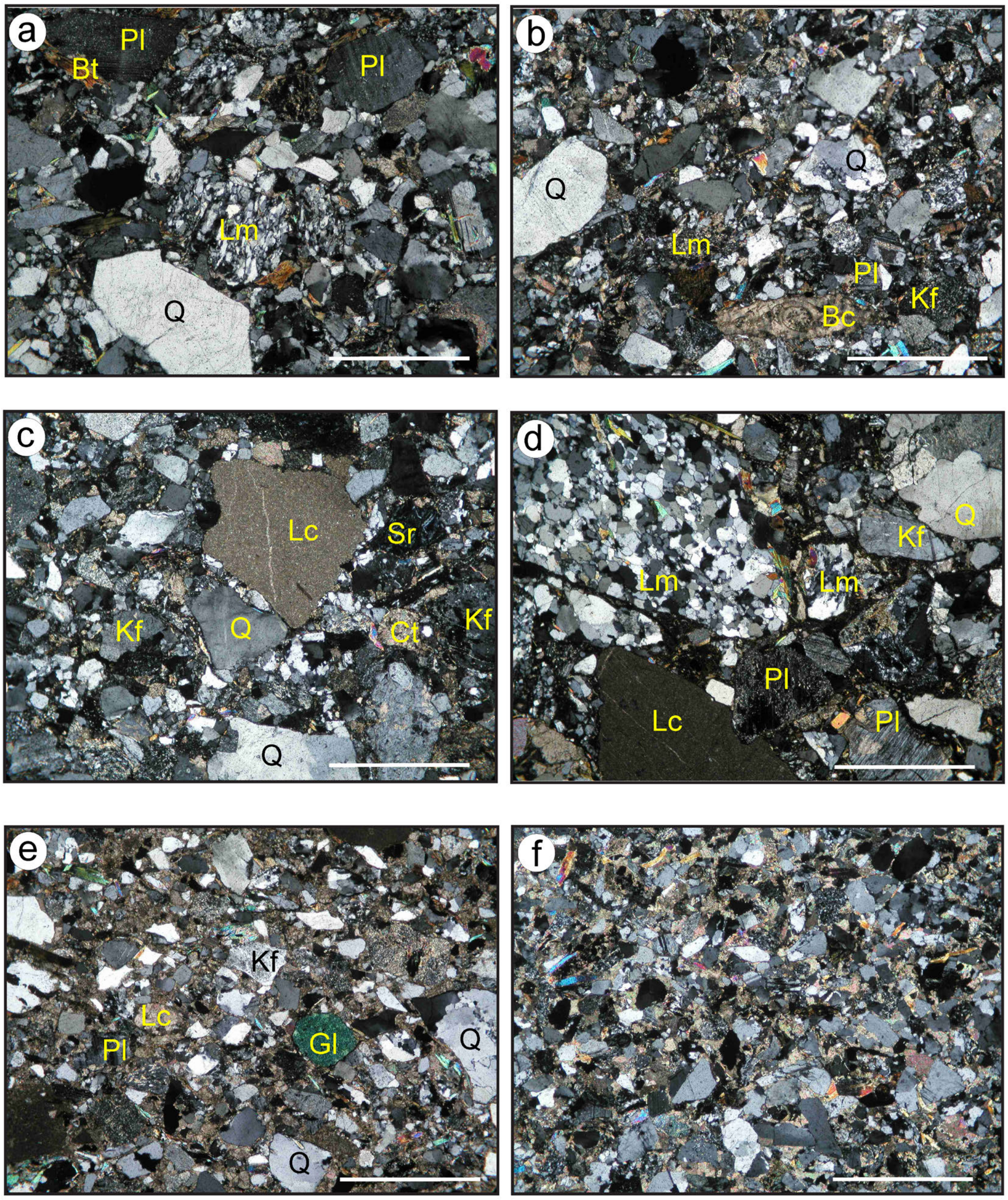

Fig. 8 - Photomicrographs of the sandstone samples: (a) medium-coarse arenite (arkose) Petrofacies A, sample PRA7, Macigno Fm.; (b) medium-coarse arenite (lithic arkose) Petrofacies A', sample MO7, Mt. Modino Sandstone; (c) medium-coarse arenite (lithic arkose) Petrofacies A', sample CV8, Civago-Torre Amorotti Sandstones; (d) coarse arenite (arkosic litharenite) Petrofacies A', sample GA4, Gazzano Sandstone; (e) medium-fine hybrid arenite with abundant calcite recrystallization (hybrid arkose) Petrofacies A", sample GO13, Gova Sandstone; (f) fine-medium arenite with abundant calcite recrystallization (hybrid arkose) Petrofacies A", sample CE7, Mt. Cervarola Sandstone. Grains: Q - quartz, Kf - k-feldspar, Pl - plagioclase, Lm - metamorphic lithic, Lc - carbonate lithic, Sr - serpentinite lithic, Gl - glauconite, Bt - biotite, Bc - bioclast, Ct - calcite grain, patch and cement (bar for scale is 1 mm).

Sandstone (area A in Fig. 1a); and the carbonate rich keybeds in the Torre degli Amorotti succession.

BIOSTRATIGRAPHIC DATA

The results of the analysis of the nannofossil content are subdivided for study sections. The figure 9 shows the bio-chronostratigraphic scheme here adopted and the abundance of the *taxa* for each sample are reported in Table 1 and in the Online Supplementary Material 2.

CIVAGO-TORRE AMOROTTI AREA

We collected 13 samples in this area (Fig. 4). The studied section, along the road Civago-Torre Amorotti, contains well preserved nannofossil assemblages (Tab. 1, Fig. 10), with *Sphenolithus ciperoensis* distributed in low frequencies and the almost continuous and common occurrence of *Dictyococcites bisectus*.

More in detail the marlstone depositional unit MOL defined by most authors as Civago Marl, shows a nannofossil assemblage referable to the MNP25a Zone (Figs. 4, 9, Tab. 1), as well as the overlying thin-bedded-sandstone depositional unit AMS (mapped as Serpiano Sandstones Fm. by Plesi, 2002) and the above thicker arenaceous depositional unit AMG. This allows the attribution of the marlstone-sandstone section all inside the MNP25a Subzone (Chattian, Oligocene).

The sample GA1 (from deformed mudstone of the overlying Sestola-Vidiciatico Unit) contains a rich Cretaceous assemblage to testify a Ligurian origin for some of the rocks of such tectonic unit.

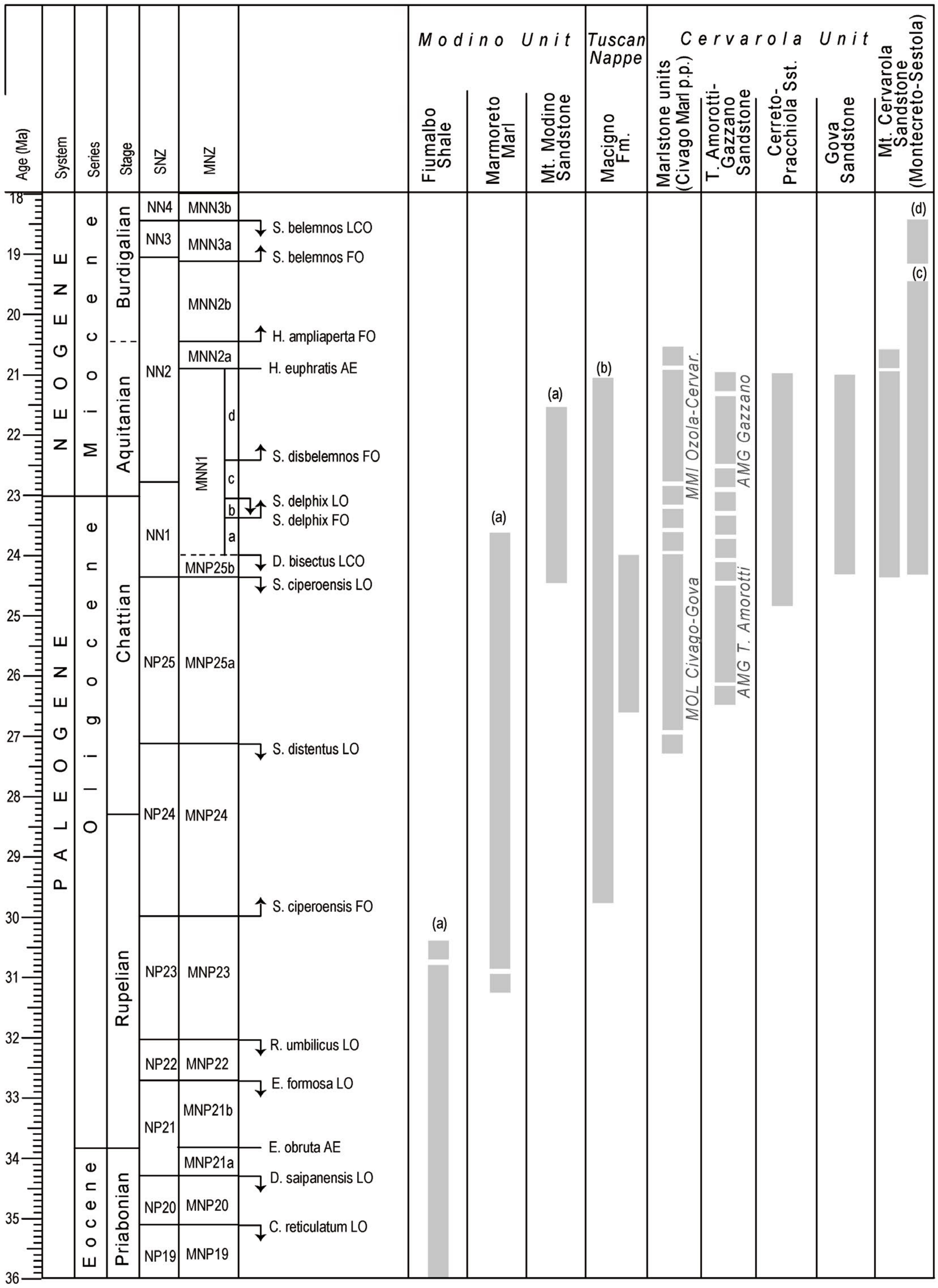

Fig. 9 - Bio-chronostratigraphic framework adopted in this study and distribution of the data here obtained: (a) data from Marchi *et alii* (2017); (b) data for the whole NA, from Costa *et alii*, (1992; 1997); (c) and (d) data for the Fellicarolo-Dardagna system, from Catanzariti *et alii* (2002) and Botti *et alii* (2002) respectively. Bioevents chronology from: Sprovieri *et alii* (2002), Aziz *et alii* (2008), Turco *et alii* (2011), Backman *et alii* (2012), Agnini *et alii* (2014), and Foresi *et alii* (2014). SNZ=Standard Nannofossil Zonation of Martini (1971); MNZ=Mediterranean Nannofossil Zonation. MNP: Mediterranean Nannoplankton Paleogene; MNN: Mediterranean Nannoplankton Neogene. FO: first occurrence; LO: last occurrence; FCO: first common occurrence; LCO: last common occurrence; AE: acme ending; PB: paracme beginning; PE: paracme ending.

GAZZANO AREA

The collected 5 samples from the sandstone unit (AMG of Fig. 4) and the overlying marlstone tectonic slices, contain scarce assemblages (Tab. 1) with moderately good preservation. The occurrence of index *taxa Sphenolithus disbelemnos*, the co-occurrence of well represented *Helicosphaera euphratis* and *H. carteri*, abundant *Triquetrorhabdulus* genera (*T. serratus*, *T. challengeri*, *T. carinatus*), and very rare *Discoaster druggii*, allow attribution of the Gazzano sandstone succession and the tectonically overlying deformed marlstones to the MNN1d Subzone (Aquitanian) (Fig. 9).

GOVA AREA

For this work in the Gova area we collected 26 samples in 5 logs (Figs. 5, 10, Tab. 1). Analyzed samples of Log3a contain common to abundant nannofossils with good preservation. Logs 3b, 3c, 3d and 3e show samples with worse preservation and abundance. As a whole, the assemblages are dominated by placoliths and sphenoliths, while discoasterids and helicoliths are rare.

In summary, fossil content of the sandstone of Log 3a (samples GO1 to GO3, Fig. 5, Tab. 1) shows a characteristic assemblage with the common occurrence of the index *taxon Dictyococcites bisectus* (Fig. 10), indicating the Oligo-Miocene boundary, in particular the MNP25b Subzone of Chattian age. Starting from GO4 the drop of frequency of *D. bisectus* marks the beginning of MNN1a Subzone. Sandstones of the Logs 3b, 3c, 3d contain assemblages similar to previous Log 3a, but the clear absence or rare and discontinuous occurrence of *D. bisectus*, as well as the absence of *C. abisectus* (> 11µm) and the occurence of *H. carteri*, delineate the MNN1a Subzone (Chattian, Oligocene) for all the samples. The lower samples of the upper part of the Gova Sandstone of Log 3e (GO28 and GO29 of Fig. 5) revealed scarce association with bad preservation of nannofossil. Only the uppermost sample GO30 shows a good and enough rich assemblage, where *D. bisectus*, *C. abisectus* and *Z. bijugatus* seems to be absent while there are *H. carteri* and abundant sphenoliths, but mostly *S. disbelemnos* occurrence allow to indicate the MNN1d subzone (Aquitanian-Early Miocene).

Therefore the Gova section shows, through the nannofossil association analysis (Tab. 1, Fig. 9), a distribution from MNP25b to MNN1a zones for the lower part of the sandstone outcrop at Cadignano bridge (Logs 3a-d in Fig. 5), to the MNN1d for the upper part of the outcropping section along the Gova-Quara road (Logs 3e in Fig. 5).

The marlstones and shales (MOL) of both Log 3a and Log 3e, forming tectonic slices overlying the sandstone depositional unit have shown well preserved nannofossil association, with abundant to common *D. bisectus* (Tab. 1), allowing an attribution to the MP25a-MNP25b interval (late Chattian).

This allows the attribution of the Gova Sandstone to a late Chattian - late Aquitanian interval (uppermost Oligocene to lowermost Miocene).

OTHER SECTIONS

Ozola area

We collected 4 samples along this section (Log 4 in Fig. 6). The sandstone succession of the Ligonchio-Ozola area revealed only one significant sample, the others are barren or with not-significant associations (Tab. 1).

The marly succession (MMI of Log4 in Fig. 6) placed at the base of the sandstone unit and in tectonic contact

TABLE 1

Distribution and frequency of the nannofossil *taxa* for each investigated log. A- abundant, C- common, R- rare, RR- very rare. Samples are positioned within the respective logs.

		Braarudosphaera sp	Braarudosphaera regularis	Ceratolithoides sp	Coccolithus miopelagicus	Coccolithus pelagicus	Cyclagelosphaera margerellii	Cyclicargolithus abisectus <10 micron	Cyclicargolithus abisectus >10 micron	Cyclicargolithus floridanus	Dictyococcites bisectus	Dictyococcites scrippsae		Discoaster spp	Discoaster deflandrei	Discoaster druggii	Ellipsogelosphaera sp.	Fasciculithus sp.	Helicosphaera sp	Helicosphaera carteri	Helicosphaera euphratis	Helicosphaera truempyi	Reticulofenestra daviesii	Reticulofenestra dictyoda	Spenolithus ciperoensis	Sphenolithus conicus	Sphenolithus disbelemnos	Sphenolithus dissimilis	Sphenolithus moriformis	Triquetrorhabdulus sp.	Triquetrorhabdulus carinatus	Triquetrorhabdulus challengeri	Triquetrorhabdulus serratus	Watznaueria barnesae	Watznaueria biporta	Zygrabilithus bijugatus
LOG1 – Civago	CV1					RR		R		R	R	R		RR							RR		RR		RR	R		R		C		C				
	CV2																																			
	CV3									R	R	C			RR						RR		R		RR	R		R				C				C
	CV4					RR				R	R	R			RR																					
	CV5					RR				C	C	C			RR								R			C		R								C
	CV6									RR															RR											RR
	CV7					R			R	R	C	C												C	R	C					C					C
	CV9										RR	RR														RR							RR			R
	CV10																																			
	CV11					RR																	RR									RR	RR			R
	CV12					R				R	C	C		RR					RR				RR		R	C		R				C				C
	CV13					RR			RR		R	C			RR							RR			R	C		R	RR			C		rew.		C
	GA1	RR	R	C			RR										RR	R																A	C	

		Braarudosphaera sp	Braarudosphaera regularis	Ceratolithoides sp	Coccolithus miopelagicus	Coccolithus pelagicus	Cyclagelosphaera margerellii	Cyclicargolithus abisectus <10 micron	Cyclicargolithus abisectus >10 micron	Cyclicargolithus floridanus	Dictyococcites bisectus	Dictyococcites scrippsae	"small" Dictyococcites	Discoaster spp	Discoaster deflandrei	Discoaster druggii	Ellipsogelosphaera sp.	Fasciculithus sp.	Helicosphaera sp	Helicosphaera carteri	Helicosphaera euphratis	Helicosphaera truempyi	Reticulofenestra daviesii	Reticulofenestra dictyoda	Spenolithus ciperoensis	Sphenolithus conicus	Sphenolithus disbelemnos	Sphenolithus dissimilis	Sphenolithus moriformis	Triquetrorhabdulus sp.	Triquetrorhabdulus carinatus	Triquetrorhabdulus challengeri	Triquetrorhabdulus serratus	Watznaueria barnesae	Watznaueria biporta	Zygrabilithus bijugatus
LOG2 – Gazzano	GA5					R				R		C	C											R		C	RR				R	C				C
	GA7									R				RR	RR																R	R	R			
	GA8					R		RR		R		R	C							RR	RR		R									C				C
	GA9				RR					R		R	C			RR							R				R	R		C		C	C			R
	GA10					R				C		R			RR	RR				C	C					C	R	R				C				R

TABLE 1

LOG3 – Gova																										
GO33	GO32	GO31	GO30	GO29	GO28	GO26	GO25	GO24	GO23	GO22	GO20	GO17	GO16	GO14	GO13	GO11	GO10	GO9	GO8	GO7	GO6	GO4	GO3	GO2	GO1	
			RR																							*Braarudosphaera sp*
																						RR				*Braarudhospahera bigelowii*
											rew.															*Calculites obscurus*
																	RR		RR		RR					*Clausicoccus fenestratus*
R					R	RR	R		C		RR	RR	RR			R			R		R	RR	R		C	*Coccolithus miopelagicus*
R	R		R		R	R	R	R	C	R	R	R	R	R	R	R	R	R	R	A	R	R	R	R	R	*Coccolithus pelagicus*
RR						RR					RR						RR						RR			*Coronocyclus nitescens*
	R																			C	C		R	RR		*Cyclicargolithus abisectus <10 micron*
R													R					C			R				R	*Cyclicargolithus abisectus >10 micron*
C	C		R		R	R	R	RR	C	R	R		R	R			C	R	C	C	C		R		R	*Cyclicargolithus floridanus*
C	C		RR				RR	RR	RR	RR	RR	RR	RR				RR	C	C	C	C	RR	R	RR	A	*Dictyococcites bisectus*
A	C				R	R	R	R	A	R	R	R	C	R	R	C	A	C	C		A	C	R	C	C	*Dictyococcites scrippsae*
			C								C	C						C					C			*small Dictyococcites*
R				RR	RR						RR															*Discoaster spp*
																						rew.			rew.	*Discoaster barbadiensis*
																								RR		*Discoaster calculosus*
RR	RR		RR			RR					RR	RR		RR			RR		RR	RR	RR	RR	RR	RR	RR	*Discoaster deflandrei*
																	RR									*Discoaster druggii*
rew.											rew.					rew.									rew.	*Eiffellithus turriseiffellii*
														rew.						rew.						*Ericsonia formosa*
							rew.		rew.														rew.			*Ericsonia robusta*
																rew.										*Fasciculithus sp.*
																							rew.			*Fasciculithus tympaniformis*
R										RR						R			RR			R	R			*Helicosphaera sp*
	R		C			R	R	R	RR				RR	RR		R	R		R		RR	RR		RR	RR	*Helicosphaera carteri*
R	R		R						RR								R	R	R		R					*Helicosphaera euphratis*
											RR													RR		*Helicosphaera perch-nielseniae*
							rew.																			*Lanternithus minutus*
																						RR				*Micrantolithus vesper*
																							rew.			*Nannocuns steinmannii*
																								rew.		*Octolithus multiplus*
	R		RR	RR	C				R		R	R					R		R		R		R		R	*Reticulofenestra daviesii*
						R	R	R	R		R	R	R	R						R			R		R	*Reticulofenestra dictyoda*
											RR															*Reticulofenestra lockeri*
			RR																							*Reticulofenestra retiformis*
rew.	rew.				rew.							rew.							rew.				rew.		rew.	*Reticulofenestra umbilica*
C	C							R	R															R	R	*Sphenolithus calyculus*
									RR																	*Sphenolithus capricornutus*
C					RR					RR							RR						R		R	*Spenolithus ciperoensis*
C	C		R			C	C	C	C			C					C		C		C			R	C	*Sphenolithus conicus*
											RR															*Sphenolithus cf delphix*
			C						C							RR										*Sphenolithus disbelemnos*
C	C		C			R	R	R	C						RR		R		A		R	R		R		*Sphenolithus dissimilis*
	R		R				R		C	C		R	R	R		R		C		C	R		R	R	R	*Sphenolithus moriformis*
																									C	*Triquetrorhabdulus sp.*
C	C										R	R	C		C							R				*Triquetrorhabdulus carinatus*
	C	RR	R		R	C	C	C	C						C		R		C		R	C		C		*Triquetrorhabdulus challengeri*
R			R								C	C										C		R		*Triquetrorhabdulus serratus*
											rew.		rew.												rew.	*Waztnaueria barnesae*
																rew.							rew.			*Waztnaueria biporta*
C	C	RR	R	RR	R	C	C	RR	R			R	R		C		C	C	C		C	R	C	C	C	*Zygrablithus bijugatus*

TABLE 1

		Calculites obscurus	*Calculites ovalis*	*Coccolithus miopelagicus*	*Coccolithus pelagicus*	*Cyclagelosphaera margerelli*	*Cyclicargolithus abisectus <10 micron*	*Cyclicargolithus abisectus >10 micron*	*Cyclicargolithus floridanus*	*Dictyococcites bisectus*	*Dictyococcites scrippsae*	*small Dictyococcites*	*Discoaster deflandrei*	*Ellipsogelosphaera sp.*	*Helicosphaera sp*	*Helicosphaera carteri*	*Helicosphaera euphratis*	*Helicosphaera intermedia*	*Helicosphaera paleocarteri*	*Helicosphaera perch-nielseniae*	*Helicosphaera recta*	*Lucianorhabdus maleformis*	*Micula sp*	*Nannocuns steinmannii*	*Reticulofenestra daviesii*	*Reticulofenestra dictyoda*	*Sphenolithus calyculus*	*Sphenolithus capricornutus*	*Spenolithus ciperoensis*	*Sphenolithus conicus*	*Sphenolithus disbelemnos*	*Sphenolithus dissimilis*	*Sphenolithus furcatolithoides*	*Sphenolithus moriformis*	*Triquetrorhabdulus sp.*	*Triquetrorhabdulus carinatus*	*Triquetrorhabdulus challengeri*	*Triquetrorhabdulus serratus*	*Waztnaueria barnesae*	*Zygrablithus bijugatus*
LOG4 – Ligonchio-Ozola	LI1								R			C			RR										R							R				C		C		
	LI2								R			C					R													C		R					R	C		R
	LI3																																	RR			RR			
	LI4			RR	RR				R			R				R														C	R	R				R	C	A		R
LOG5 – M. Modino-Le Tasgliole	MO2				R				RR		C																													
	MO3				R		R		R	R	C		RR			RR											R		R	C				R		R	C	R		R
	MO8																																							
	MO12							RR				RR																					rew.						rew.	
LOG6 – Pelatone – Cimone	CI1																																							
	CI2																																							
LOG7 – Libro Aperto – Cima Tauffi	LA1				R			R	C	C	C		RR												R				R	R	RR			R					rew.	
	LA3			RR					R	R	C														R	R						R		R	C		R			C
	LA5	RR																				R		R															R	
	LA6	R	R			R								R									R																C	
	LA7	R				R																RR	R																R	
	LA8			R	R			R	R	C	C	C																		C		C		R	C	C				C
	LA10				RR						R																							RR						
	LA12			R	R		C		R	C	C	C	RR				R			RR										C		C		R			R			C
LOG8 – M. Cimone – M. Cervarola – Montecreto	CE1				R				A		A														R					C				R			C			R
	CE2				R				R	RR	C	C	RR				R				RR				R			RR		C	R	C		R	C	R	C	C	rew.	C
	CE5			R	R				R	C	C						R								R		R		RR			C				R	C	R		C
	CE6			R	R						C	C				R									R		R			C		C		R			R			RR
	CE9				RR			R	R	RR	R	C						RR	RR							R				C		C					R	R		RR
	CE10																																		R		R			
	CE11				R				R		RR	R			R												R					C				R	R	R		RR
	CE12				R				R	RR	RR				RR																					R	R	R		R

with it, revealed very poor and badly preserved association. Anyway, the few forms allow to establish an undifferentiated MNN1 Zone - MNN2a Subzone interval of the Aquitanian.

Differently, the only good sample (LI4) of the above AMG depositional unit (Fig. 6), particularly due to the presence of *S. disbelemnos*, allows the attribution, at least of the lower part of the arenaceous succession, to the MNN1d Subzone (Aquitanian, Miocene).

Mt. Modino area

Only one (sample MO3) of the 3 samples (Log 5 in Fig. 6) collected for nannofossils analysis from rare carbonate beds of the Macigno Fm. contains an association probably referable to the MNP25a Subzone (Chattian, Oligocene) for the presence of *Sphenolithus ciperoensis* in addition to *Dictyococcites bisectus*.

The samples collected in sandstones of the overlying Mt. Modino Sandstone resulted barren or showing poorly preserved and poorly representative associations (Tab.1).

Libro Aperto - Cima Tauffi

Some of the samples collected along Log 7 in Fig. 6 have been collected in tectonic slices part of the Libro Aperto Shear Zone. The lowest slices belong to the Mt. Cervarola Sandstone and the respective samples LA1 and LA3, due to the presence of *S. ciperoensis* (Tab. 1) allows its attribution to the MNP25a Subzone (Chattian, Oligocene). Upper tectonic slices made of deformed mudstone and limestone, revealed Cretaceous (Campanian) nannofossil association, indicating a Ligurian origin (Tab. 1). Samples from a tectonic slice formed of marlstone, lying below the Mt. Modino Sandstone and Macigno Fm. on top of the stack, show very abundant and well preserved nannofossil association. They, on the base of the common occurrence of very large and well preserved *D. bisectus* and the absence of the *S. ciperoensis*, are indicative of the MNP25b Subzone (Chattian, Oligocene). The Macigno Fm. lying tectonically on top of the stack of Log 7, revealed nannofossil association indicative of the MNP25b Subzone.

Mt. Cervarola area

Other samples come from the section reconstructed along Mt. Cimone-Mt. Cervarola-Montecreto of Log 8 in Fig. 6. The lowest unit of the stack is here represented by the Cervarola Unit formed by the Cervarola Sandstone of the type-area. The assemblages from the samples (from CE1 to CE6) are characterized by the abundant and continuous occurrence of nannofossils (Tab. 1). The collected data allows to recognize lower Aquitanian biozones, likely MNN1c-MNN1d on the basis of the absence of *C. abisectus* (>10μm) and the presence of *S. delphix* and *S. disbelemnos* similar forms. Instead, the drop of *D. bisectus* frequency (<1%), in addiction to *H. paleocarteri* (CE9) and the occurence of *C. abisectus* (>10μm) indicate that the overlying deposits (CE9-CE12), belonging to the above tectonic slices of the Libro Aperto Shear Zone, are younger, to date back to the Chattian-Aquitanian transition. Unfortunately, poor and badly preserved nannofossil

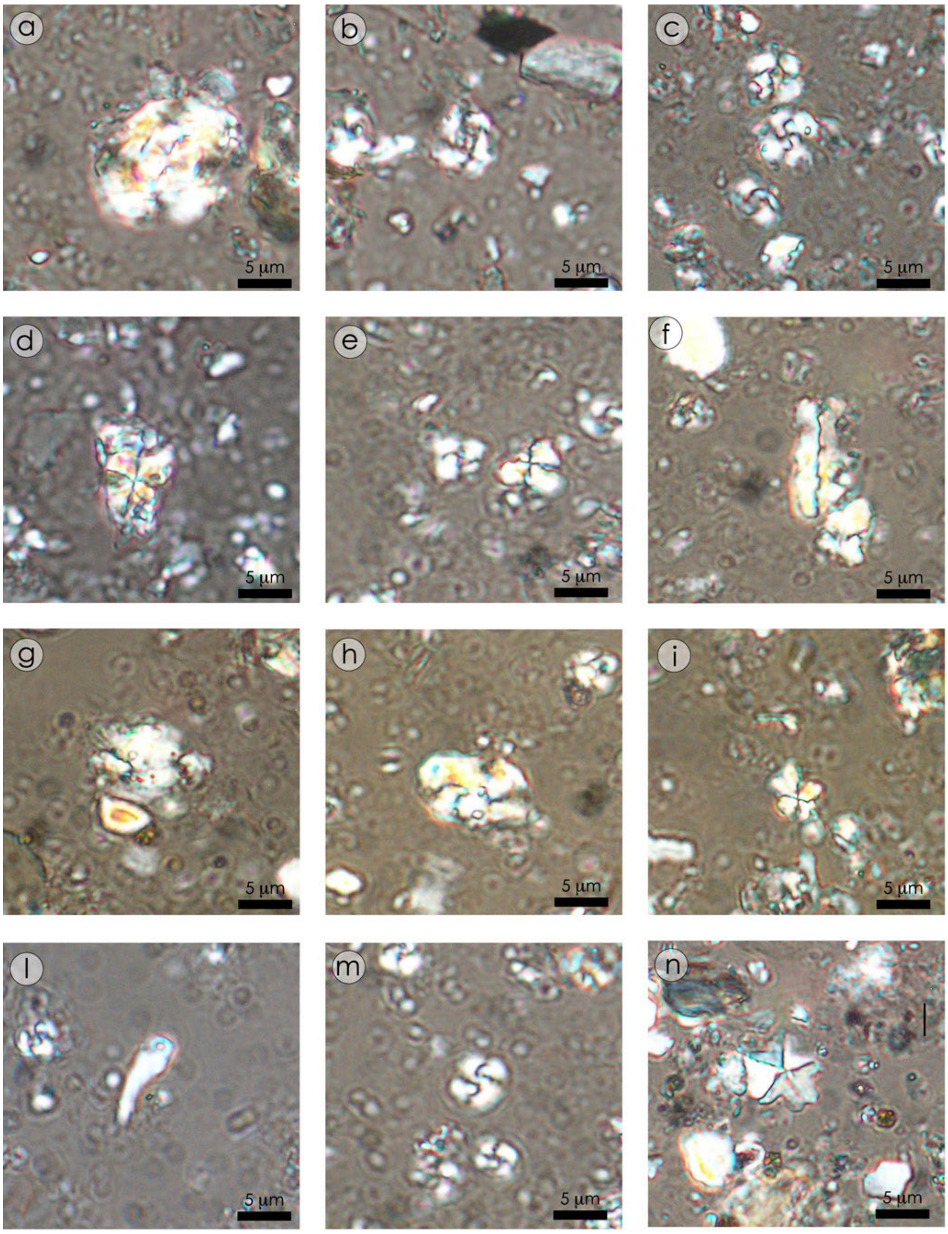

Fig. 10 - Specimens of calcareous nannofossils recognized in the studied samples characterizing the Oligo-Miocene interval. a) h) *Dictyococcites bisectus* (Hay, Mohler & Wade, 1966) Bukry & Percival, 1971 (samples GO1, GO33); b) *Reticulofenestra daviesii* (Haq, 1968) Haq, 1971 (sample GO1); c) *Cyclicargolithus floridanus* (Roth & Hay, in Hay *et alii*, 1967) Bukry, 1971 (sample GO33); d) *Sphenolithus conicus* Bukry, 1971 (sample LA12); e) i) *Sphenolithus dissimilis* Bukry & Percival, 1971 (sample GO33); f) *Zygrhablithus bijugatus* (Deflandre in Deflandre & Fert, 1954) Deflandre, 1959 (sample GO23); g) *Helicosphaera* sp. (sample GO2); l) *Triquetrorhabdulus serratus* (Bramlette & Wilcoxon, 1967) Olafsson, 1989 (sample CV5); m) *Dictyococcites scrippsae* Bukry & Percival, 1971 (sample GO33); n) *Micrantholithus vesper* Deflandre, 1950 (sample GO4).

assemblages in the marlstones and sandstones induce to refer such deposits to an undifferentiated MNN1 Zone.

Cerreto - Pracchiola areas

In these two areas 12 scattered samples (Online Supplementary Material 2) have been collected. The sample COL11 from the Collagna-Cerreto area (Area B in Fig. 1a) reveals a significant nannofossil association referable to the MNN1c-MNN1d interval of the Aquitanian (Miocene) for the sandstone succession (Cerreto Sandstone) placed at the base of the unit stack and correlated with the sandstones cropping out at Ozola-Gazzano-Torre degli Amorotti. The marlstones involved in the slices near the Mt. Ventasso (Marmoreto Marl) have been attributed to the MNP25a-MNP25b interval recording the Chattian (Oligocene).

Differently, in the Pracchiola window (Area A in Fig. 1a), the succession of the Pracchiola Sandstone has been dated to the MNN1 Zone of the Chattian-Aquitanian transition.

Few samples from the Macigno Fm. close to the Pracchiola window, showed a scarce presence of nannofossils; the few specimens recovered seem indicate an undifferentiated MNN1 Zone.

DISCUSSION

The geological framework emerging from this study reveals a complex unit stack setting, where the analyzed arenaceous-marly successions are part of different tectonic units. In particular, whereas the Macigno Fm. belongs to the Tuscan Nappe, the Mt. Modino Sandstone, the Marmoreto Marlstone and the Fiumalbo Shale belong to the Modino Unit or occur as tectonic slices incorporated within the Sestola-Vidiciatico Unit or the Libro Aperto Shear Zone. Differently, the marly-arenaceous successions of the Torre Amorotti system (Torre Amorotti, Gazzano, Ozola, Cerreto), the Gova system (Gova Sandstone and Pracchiola Sandstone), and the Fellicarolo-Dardagna system (Mt. Cervarola Sandstone), as well as the lower Miocene marlstones (i.e. Civago Marl), are all part of the Cervarola Unit. Tectonic slices of Mt. Cervarola Sandstone and of marlstones have been recognized within the Libro Aperto Shear Zone and in the Sestola-Vidiciatico Unit.

Geometrical and age relationships of all these successions allow us to reconstruct the evolution of the sedimentation and the deformation of this sector of the NA.

During the Oligocene-Miocene time-span, the system was diachronous with a progressive eastwards migration of the basin depocentres (linked with the eastwards migration of Apennine subduction). It is also clear that the foredeep basin system was complex and subdivided into some cohabiting and coeval basins that progressively underwent deactivation and cannibalization by the advancing orogenic wedge and by the contemporaneous development of new basins towards the foreland.

The Macigno turbidite system represents the first large foredeep system settled onto the Adria microplate during the late Oligocene-early Miocene, and its paleogeographic setting and stratigraphic-structural relationships are well defined. Differently, the Mt. Modino turbidite system still does not have a well constrained setting (see models in Chicchi & Plesi, 1991a and Bettelli *et alii*, 2002).

In this regard, on the basis of the results of our investigations and literature data, the following evidences can be summarized:

1. The Mt. Modino Sandstone lies conformably on a marly-shaly succession (Marmoreto Marl and Fiumalbo Shale, respectively), which spans from the Lutetian to the late Chattian (Catanzariti & Perilli, 2009; Marchi *et alii*, 2017), and has lithological and chronostratigraphical similarities with the marly-shaly succession lying below the Macigno Fm., such as the Rovaggio Marl and the Scaglia Toscana Fm.
2. The field relationships clearly show the tectonic superposition of the Mt. Modino Sandstone (with Fiumalbo Shale and Marmoreto Marl fms at the base) onto the Macigno Fm., as is well evident in the Mt. Modino-Mt. La Nuda-Fiumalbo-Mt. Cimone area (Fig. 1b), through the interposition of a chaotic complex containing Ligurian-derived blocks and slices coming from the accretionary wedge.
3. The chaotic complex at the base of the Mt. Modino succession is formed by Ligurian-derived slices and clasts (Bettelli *et alii*, 1987; Abbate & Bruni, 1987; Chicchi & Plesi, 1991a; Perilli, 1994; Puccinelli *et alii*, 2009b; Marchi *et alii*, 2017), indicating the adjacency of a deformed Ligurian unit stack.
4. The age of the Mt. Modino Sandstone, which is referable to the MNP25b-MNN1c-d interval (late Chattian to Aquitanian) (Plesi *et alii*, 2000; Plesi, 2002; Catanzariti *et alii*, 2002; Botti *et alii*, 2009; Catanzariti & Perilli, 2009; Marchi *et alii*, 2017), corresponds with that of the Macigno Fm.
5. The petrographic features of the Mt. Modino Sandstone (mainly Petrofacies A') show some differences with the sandstone of the Macigno Fm. (mainly Petrofacies A) and the Mt. Cervarola Sandstone type-area (mainly Petrofacies A"), as also emphasized in the literature data (BRUNI *et alii*, 1994a).

The Macigno and the Mt. Modino Sandstone fms should therefore represent two different, but very similar turbidite systems, as the lithological, sedimentological and architectural data seem to show (Abbate & Bruni, 1987; Bruni *et alii*, 1994a). The petrographical data indicate a similar provenance (Figs. 3, 8; Online Supplementary Material 1), changing only in minor components such as carbonate grains, albeit in small quantities for the Mt. Modino Sandstone (Bruni *et alii*, 1994b; Valloni & Zuffa, 1984). As the two turbidite successions are almost coeval, with the only age discrepancy concerning an older base for the Macigno Fm., the two turbidite systems should settle adjacently. This is also strengthened by the strong lithological affinities between the Paleogene marly-shaly successions lying below each of the two turbidite formations. Furthermore, the evidence suggests that the Cenozoic Mt. Modino succession lies on a chaotic Ligurian-derived complex, whereas the Macigno-Scaglia Toscana succession lies on a Triassic-Cretaceous series belonging to the Adria continental margin (see in Ielpi & Cornamusini, 2013 with references therein). This implies that the Mt. Modino succession, although deposited close to the Macigno Fm., was settled in a more internal basin or portion of basin located on the advancing orogenic wedge. During the sedimentation of the Mt. Modino Sandstone and Macigno Fm., more external minor sub-basins developed, with the sedimentation of the Torre degli Amorotti-Gazzano turbidite system, adjacent to the more external sub-basin of the Gova system.

The turbidite deposits of the Torre degli Amorotti-Gazzano system have few lithostratigraphic differences from the Mt. Modino system. The sedimentological and petrographical features are indeed very similar (mainly petrofacies A' for both), which does not enable an easy distinction to be made between them in the field (Andreozzi, 1991; Mezzadri & Valloni, 1981; Andreozzi & Di Giulio, 1994; Valloni *et alii*, 2002). Differently, the Gova turbidite system shows more marked differences, both sedimentological and petrographical. In particular, the Gova succession with respect to the other more internal successions shows a lower sandstone/mudstone ratio, is richer in marlstone, and has thinner bedding and carbonate-rich sandstone (mainly petrofacies A"); the beds are also more intensely bioturbated, with abundant horizontal and vertical trace fossils.

The more external turbidite system of the Mt. Cervarola area has been defined as the Fellicarolo-Dardagna turbidite system, belonging to the major and wider Cervarola turbidite complex (Günther & Reutter, 1985; Andreozzi, 1991; Andreozzi *et alii*, 1995; Botti *et alii*, 2002; Piazza, 2016). The sandstone has sedimentological and petrographical features that are similar to those of the Gova system (mainly Petrofacies A") and are rich in carbonate content and marly beds. It started its deposition during the latest Chattian-Aquitanian (Fig. 9), which is later than the other systems, meaning a later activation of a more external sub-basin. The Fellicarolo-Dardagna system fully developed during the late Aquitanian, contemporaneously with the closure of the innermost Mt. Modino system (Fig. 9), due to the advancing orogenic wedge. This development continued during the Burdigalian. At this time, due to the increase in the deformation and shortening rate, the inner sub-basins closed and the respective turbidite sedimentation deactivated, with external migration of the basin system and the development of other sub-basins belonging to the outer Mt. Cervarola complex (Fellicarolo-Dardagna, Castiglione dei Pepoli, Granaglione systems) (ANDREOZZI, 1991; ANDREOZZI *et alii*, 1995; BOTTI *et alii*, 2002; PLESI, 2002; VALLONI *et alii*, 2002).

The basin model development presented here fits well in the migration basin concept of RICCI LUCCHI (1986) and ARGNANI & RICCI LUCCHI (2001). It also explains well the complex field relationships between the different turbidite successions and marly successions that represented: the hemipelagic sedimentation anticipating the turbidite systems; and the sedimentation in structural highs separating the sub-basins. The structuration of the foredeep of the NA in migrating sub-basins could also explain some differences in composition and, consequently, in provenance, as testified by the different petrofacies (from A to A' to A").

The marlstones approached in this research belongs to two main lithostratigraphic units, as the Marmoreto Marl those of Oligocene age and the so-called Civago Marl those of Early Miocene age. They revealed two main different geological settings for both: at the base of turbidite deposits, the Mt. Modino Sandstone and the Mt. Cervarola Sandstone respectively; as tectonic slices both on top of the turbidite successions, and particularly englobed within the Sestola-Vidiciatico Unit, often assuming a highly deformed appearance. In our opinion, these marlstones deposited either: before the turbidite sedimentation lying below the sandstone successions; and laterally of the respective turbidite systems, on structural/morphological highs separating the turbidite sub-basins. These two types of depositional setting well explain the positions of the marlstone successions, either stratigraphically below or tectonically on top of the sandstone units, or their occurrence in the form of tectonic slices within shear zones close to thrust fronts (Fig. 11). Specifically, the results of the analyses highlight that the marlstone depositional unit of the Torre degli Amorotti-Civago log (MOL in Log 1 of Fig. 4), which lies below the sandstone depositional units (AMS-AMG in Fig. 4), is time-equivalent to the Marmoreto Marl, as well as the marlstones tectonically overlying the Gova Sandstone and the Pracchiola Sandstone in the Pracchiola window (Marra Marl of ZANZUCCHI, 1963). Differently, the younger marlstone units deposited in structural highs (MMI in Fig. 4), and occurring in the Ligonchio area (Log4 of Fig. 6) and tectonically on top of the Gazzano Sandstone (figs 2 and 4), are time-equivalent with the Civago Marl of the literature.

EVOLUTION OF THE BASIN SYSTEM

The presented data allow us to draw the evolution of the different stages of the NA foredeep basin system during the Late Oligocene and Early Miocene.

Stage 1 - Late Oligocene (early Chattian, MNP24 Zone, Fig. 11a): the Tuscan Domain foredeep was developing, with the deposition in the forming depocentre of: marly-mudstone deposits such as the Rovaggio Marl; the shales and marls of the Scaglia Toscana Fm.; the Marmoreto Marl in an internal position close to the Ligurian and Subligurian tectonic wedge; and more external marls in the depocentre and on a growing structural high (MOL in Fig. 11).

Stage 2 - Late Oligocene (Chattian, MNP25a subzone, Fig. 11b): the main depocentre continued to be filled by the Macigno turbidite system, whereas the marly sedimentation (Marmoreto Marl) continued in the more internal part of the foredeep basin onto the front of the Ligurian orogenic wedge. Externally, two more minor depocentres developed, linked with active thrusts, forming basins and structural highs. The more internal basin was infilled by the Torre degli Amorotti - Gazzano turbidite system and the more external basin by the more carbonatic Pracchiola Sandstone, with the latter, as well as the foreland ramp, covered by marly deposits.

Stage 3 - latest Oligocene (late Chattian, MNP25b-MNN1a-b zone interval, Fig. 11c): a minor, most internal depocentre developed on the growing frontal thrusts of the Ligurian/Subligurian wedge, was filled by the Mt. Modino turbidite system that could also be partially heteropic with the similar and adjacent more external Macigno system. This latter fully developed, as the Torre degli Amorotti/Gazzano turbidite system and the more external and more carbonatic Gova turbidite system; this latter system could be correlated with the Pracchiola system. Marly deposition continued onto the structural highs separating the sub-basins and at the margins of the foredeep.

Stage 4 - earliest Miocene (early Aquitanian, MNN1c subzone, Fig. 11d): at this stage, we have the continuous infilling of the basins that developed in the previous stages, and the development of new and more external basins that received a siliciclastic-carbonate filling: the Fellicarolo-Dardagna turbidite system belonging to the more external Mt. Cervarola complex.

Stage 5 - early Miocene (Aquitanian, MNN1d subzone, Fig. 11e): the tectonic shortening phase that developed several sub-basins led to the closure of the Mt. Modino sub-basin that was incorporated in the accretionary thrust system. Within the other sub-basins, the hemipelagic sedimentation continued and led to the full development of the more external Fellicarolo-Dardagna turbidite system.

Stage 6 - early Miocene (latest Aquitanian-early Burdigalian, MNN2 Zone, Fig. 11f): at this time, ongoing tectonic activity (Tuscan phase or Burdigalian phase) led to further emplacement of the orogenic wedge, with the development of km-scale thrusting, closing the sedimentation in the internal sub-basins such as those of the Macigno, Torre degli Amorotti-Gazzano and Gova turbidite systems that were involved in the deformation. The more external sub-basin of the Fellicarolo-Dardagna turbidite system continued to develop (Fig. 11h).

Stage 7 - early Miocene (Burdigalian, MNN3 Zone, Fig. 11g): the shortening phase continued with the consequent migration of the basin depocentre and the development of the entire Mt. Cervarola succession, with sedimentation in the Fellicarolo-Dardagna sub-basin and the development of another more external sub-basin filled by the Castiglion dei Pepoli turbidite system, probably at least partially interfingered with the former.

This evolution continued until the late Burdigalian, with the closure of the Mt. Cervarola system and the inception of a new, even more external, basin system: the Marnoso-arenacea Fm. (ARGNANI & RICCI LUCCHI, 2001; TINTERRI & TAGLIAFERRI, 2015; CORNAMUSINI *et alii*, 2017).

CONCLUSIONS

This study highlights how some of the discussed and poorly constrained Oligo-Miocene marly-arenaceous successions of the Northern Apennines are part of the

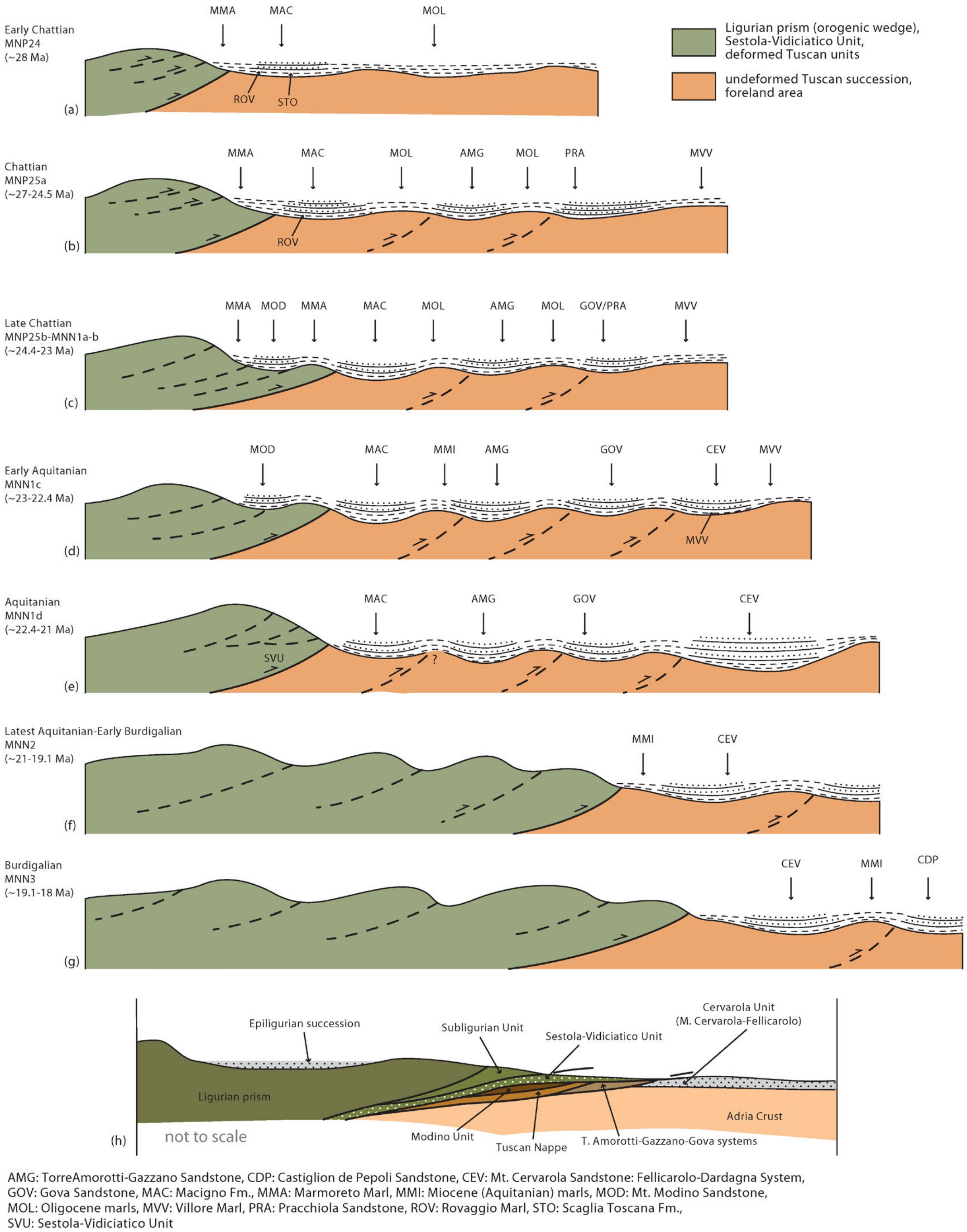

Fig. 11 - Evolution of the foredeep basin system in the studied sector of the Northern Apennines during Chattian-Burdigalian time span (a to g). Ma are from biozone distribution (see fig. 9). (h) Cartoon not to scale showing the deformational plate setting at the Aquitanian-Burdigalian transition.

foredeep-thrust wedge complex. The main conclusions derived from the joint analysis of both new and previous literature data are as follows.

First, field investigations allow us to define a geological setting structured in some stacked tectonic units and assign a precise position to each marly-arenaceous succession. The main result is the attribution of the Torre degli Amorotti-Gazzano and Gova sandstones, as well as the Miocene marlstones, to the lowest Cervarola Unit. Differently, the Mt. Modino marly-arenaceous successions belong to the Modino Unit, or outcrop as tectonic slices in the overlying Sestola-Vidiciatico Unit.

In more detail, the Gazzano and Torre degli Amorotti successions are part of the same turbidite system, referred to as the internal Mt. Cervarola Sandstone system, which is Chattian to Aquitanian (MNP25a to MNN1d interval) in age and tectonically overlain by the Sestola-Vidiciatico Unit. Their sandstone petrography, as well as the stratigraphic architecture, are quite similar to the Mt. Modino Sandstone, rather than to the more external Mt. Cervarola Sandstone, emphasizing an articulated basin physiography.

The age of the Gova turbidite succession, is late Chattian-Aquitanian (MNP25b to MNN1d interval) that is much older than the attribution in the literature and is tectonically overlain by Oligocene marlstone (MOL) and by the Sestola-Vidiciatico Unit. Unlike the Gazzano and Torre degli Amorotti successions, the coeval Gova turbidite succession shows lithostratigraphic and petrographic features that are more similar to the younger and more external Mt. Cervarola Sandstone of the Fellicarolo-Dardagna system (Aquitanian to late Burdigalian in age, MNN1c to MNN3 interval).

The marlstone deposits (MOL and MMI, respectively Marmoreto Marl and Civago Marl of the authors) sedimented during late Oligocene and early Miocene, both within the basins preceding the turbidites and accompanying them along the structural highs at the margin of the basins. This results in the involvement of marlstones within slices and tectonic units (Modino, Cervarola units) or shear zone (Libro Aperto Shear Zone), and as part of the uppermost Sestola-Vidiciatico Unit.

Taking all these elements into account, an articulated setting for the turbidite successions of the Emilia-Tuscan Apennines can be proposed, drawing a complex foredeep setting for the Oligo-Miocene period. This is formed by several migrating sub-basins that followed the movement towards the foreland of the Ligurian orogenic wedge. Different stages of deposition and deformation have been recognized, culminating in the Burdigalian deformation phase that led to the closure of the inner Tuscan Domain sub-basins. Thereafter, wider, less articulated and more external foredeep basins developed (Mt. Cervarola Sandstone s.s., Marnoso-arenacea Fm.).

ELECTRONIC SUPPLEMENTARY MATERIAL

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

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