Italian Journal of Geosciences
Bollettino della
Società Geologica Italiana
e del Servizio Geologico d'Italia

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Journal:	*Italian Journal of Geosciences*
Manuscript ID:	Draft
Manuscript Type:	Original Article
Date Submitted by the Author:	n/a
Complete List of Authors:	MARRONI, MICHELE; UNIVERSITA' DI PISA, DIPARTIMENTO DI SCIENZE DELLA TERRA PANDELI, ENRICO; UNIVERSITA' DI FIRENZE, DIPARTIMENTO DI SCIENZE DELLA TERRA pandolfi, luca; UNIVERSITA' DI PISA, DIPARTIMENTO DI SCIENZE DELLA TERRA CATANZARITI, RITA; CONSIGLIO NAZIONALE DELLE RICERCHE, ISTITUTO DI GEOSCIENZE E GEORISORSE
Keywords:	Ligurian and Sub-LigurianUnits, tectonics, stratigraphy, Mt.Amiata, Southern Tuscany-Italy

UPDATED PICTURE OF THE LIGURIAN AND SUB-LIGURIAN UNITS IN THE AMIATA AREA (TUSCANY, ITALY): ELEMENTS FOR THEIR CORRELATION IN THE FRAMEWORK OF THE NORTHERN APENNINES

Marroni Michele°,*, Pandeli Enrico°°, **, Pandolfi Luca°,* & Catanzariti Rita*

° Dipartimento di Scienze della Terra, Università di Pisa
°° Dipartimento di Scienze della Terra, Università di Firenze
* Istituto di Geoscienze e Georisorse, CNR, Pisa
** Istituto di Geoscienze e Georisorse, CNR, Florence Section

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CORRESPONDING AUTHOR:
PROF. MICHELE MARRONI,
DIPARTIMENTO DI SCIENZE DELLA TERRA,
UNIVERSITÀ DI PISA, VIA S. MARIA, 53
56126 PISA, ITALY.
E-MAIL: marroni@dst.unipi.it

ABSTRACT

The Monte Amiata region, (SE Tuscany, Italy) represents the southernmost area of the Northern Apennines where the different lithologies belonging to the Ligurian and Sub-Ligurian Units widely crop out. This paper aims to provide an update of the stratigraphic, paleontological and structural features of the Ligurian and Sub-Ligurian from the Amiata area achieved by an integration of the new data derived from the Regional Geological Map project with those available from the existing literature.

In the study area, the Sub-Ligurian units are represented only by Canetolo Unit whose succession includes the middle Eocene (NP15 Zone) Argille e Calcari and Vico Fms showing eteropic relationships. The Ligurian Units are instead represented by the Ophiolitic and Santa Fiora Units. The Ophiolitic Unit is represented mainly by Early Cretaceous Palombini Shale associated with scattered Middle-Late Jurassic ophiolites. The age of the Palombini Shale spans from late Hauterivian-Barremian Zone CC5 to the Aptian Zone CC7 of Sissingh (1977). The Ophiolite Unit overlains the Santa Fiora Unit that consist of Pietraforte Fm and Varicoloured Shales topped by the Santa Fiora Fm. The Pietraforte Fm show eteropic relationships with the Varicoloured Shales and both formations can be referred to ?Aptian to middle Coniacian whereas the age of the Santa Fiora Fm seems to span from late Coniacian-early Santonian (CC14 Zone) to middle-late Campanian (CC21-CC22 Zones).

The results of the structural analysis indicates that all the Ligurian and Sub-Ligurian Units are affected by a polyphase, complex deformation history consisting of several folding phases regarded as achieved during the closure of the Ligure-Piemontese oceanic basin and the following continental collision developed from the middle Eocene onward. However, the present day relationshisp between the Ligurian and Sub-Ligurian Units occur by low-angle shear zones that can be interpreted as achieved during the last deformation phase recognized in these units can, i.e. the middle Miocene extensional tectonics. This tectonics is responsible of a strong delamination by development of low-angle faults with staircase geometry that produced the omission not only of several stratigraphic levels, but probably also of entire tectonic units.

Despite the extensional tectonics, the collected stratigraphical and structural data allow to propose a correlation of the Ligurian and Sub-Ligurian Units from Mt. Amiata area with the units cropping out in the Southern Tuscany and Ligurian Apennines.

KEY-WORDS: Ligurian and Sub-Ligurian Units, tectonics, stratigraphy, Mt Amiata area, Southern Tuscany-Italy.

1. INTRODUCTION

The Monte Amiata region (SE Tuscany, Italy) represents the southernmost area of the Northern Apennines where the different lithologies belonging to the Ligurian and Sub-Ligurian Units widely crop out (Fig.1a). These units provide important insights for the reconstruction of pre-collisional geodynamic evolution of the Northern Apennines, mainly because they represent fragments of the Ligurian-Piemontese oceanic domain, from whose closure the collisional belt originated.

Even if the outcrops of the Monte Amiata are of bad quality and not so continuous as those of the Ligurian and Emilian Apennines, this sector can be the same regarded as one of the best areas in the Northern Apennines to study the stratigraphic, paleontological and structural features of the Ligurian and Sub-Ligurian Units.

Several studies on the Ligurian and Sub-Ligurian Units of this area are available, generally devoted to outline their stratigraphic features (Pandeli et alii, 2005 and references therein). Recent geological mapping of the Amiata area in the framework of the project for the Regional Geological Map funded by Regione Toscana has provided not only a new 1:10.000 geological map of the Amiata area but has also allowed a collection of new and complete dataset about the Ligurian and Sub-Ligurian Units.

The goal of this paper is to provide a summary of the stratigraphic, paleontological and structural features of the Ligurian and Sub-Ligurian from the Amiata area achieved by an integration of the new data derived from the Regional Geological Map project (Regione Toscana, 2014) with those available from the existing literature. This integration offers the chance for a comparison between the Ligurian and Sub-Ligurian cropping out in the Amiata area with those cropping out to the west and to the north, i.e. in Southern Tuscany as well as in the Ligurian-Emilian Apennines.

2. GEOLOGICAL SETTING OF THE AMIATA MT. AREA

The Amiata area is located in the inner part of the Northern Apennines belt (Fig.1a), just 100 km northwest of the Olevano-Antrodoco line, i.e. the geological boundary between Northern and

Central Apennines. This area is characterized by a 300-190 Ka old volcano (Ferrari et alii, 1996) built up over an uplifted substratum belonging to the so-called "Montalcino-Monte Amiata-Monte Razzano Ridge" (Fig.1b). This ridge corresponds to a north-south trending horst bounded by two main grabens filled by late Miocene to Quaternary continental to marine deposits, known, from west to east, as Cinigiano-Baccinello and Siena-Radicofani basins. The ridge consists of a stack of tectonic units whose relationships are unconformably sealed by late Miocene to Quaternary sedimentary deposits.

This tectonic setting can be regarded as the result of a long-lived geodynamic history resulting in the building of the Northern Apennines collisional belt. This history started with the opening of the Jurassic Ligure-Piemontese oceanic basin, located between the continental margins of Eurasian and Adria plates. The Ligure-Piemontese basin was affected by a Late Cretaceous-middle Eocene intraoceanic subduction (Bortolotti et al., 1970; Elter, 1975; Principi & Treves, 1984; Abbate et alii, 1986; Bortolotti et alii, 1990; Carmignani & Kligfield, 1990; Carmignani et alii, 1995; Barchi et alii, 2001; Carmignani et alii, 2001; Molli, 2008; Marroni et alii, 2010). The remnants of the accretionary wedge developed during the intraoceanic subduction is today represented by the Ligurian Units, that have are subdivided in Internal and External ones, representative, respectively, of the oceanic basin and the ocean-continent transition at the Adria plate margin (Elter, 1975; Treves, 1984, Marroni et alii, 2001). Also the Sub-Ligurian Units can be regarded as representative of the thinned continental margin of the Adria plate close to the ocean-continent transition (Treves, 1984, Marroni et alii, 2001). The intraoceanic subduction was followed in the middle Eocene by the inception of the continental collision. The continental collision was characterized by the progressive migration of the deformation front toward the eastern domains of the Adria plate, resulting in the building of a fold-and-thrust belt composed of structural units (Tuscan, Umbrian and Romagnan Units) deriving from the Adria domains and deformed with an E to NE vergence (e.g. Costa et alii, 1998; Barchi et alii, 2001). This evolution, from the Oligocene to present day, was combined with the development of foreland basins (foredeep and piggy-back basins of Ori and Friend, 1984) that were successively incorporated into the collisional belt (Ricci Lucchi, 1986; Aruta et alii, 1998; Barchi et alii, 2001). During middle Miocene the uppermost structural levels of the Apennines were affected by low-angle extensional faults regarded as the consequence of the overthickening of the collisional belt (Carmignani & Kligfield, 1990; Decandia et alii, 1993). From late Miocene onward, the migration of the deformation front was followed in space and time by an extensional tectonic characterized by development by high-angle normal faults and coeval marine to continental basins (e.g. Elter et alii, 1975; Ambrosetti et alii, 1978; Lavecchia et alii, 1987; Bertini et alii, 1991; Martini & Sagri, 1993; Martini et alii, 2001).

In the framework of the Northern Apennines, the Amiata area (Fig.1b) is the southernmost area where the uppemost structural levels of the collisional belt are well preserved (Calamai et alii, 1970; Bettelli et alii, 1980; Brunacci et alii, 2003; Batini et alii, 2003; Pandeli et alii, 2005). These levels are represented by the Ligurian and Sub-Ligurian Units (Fig.2). Whereas the Ligurian Units consist of Jurassic ophiolites and Cretaceous-Early Tertiary sedimentary successions, the Sub-Ligurian Units are represented only by Eocene deposits (Calamai et alii, 1970; Pandeli et alii, 2005). These units were affected by a complex structural evolution associated to a very low-grade metamorphism or without any metamorphic imprint (Franceschelli et alii, 1994 and references therein). The Ligurian and Sub-Ligurian Units overlain the Tuscan Nappe (Calamai et alii, 1970; Batini et alii, 2003; Brogi et alii, 2004c), that is well exposed in some tectonic windows (Fig.1b) located west (M.Aquilaia-M.Labbro) and east of the Monte Amiata (Poggio Zoccolino, M.Civitella-Castell'Azzara-M.Elmo). This unit is made up of Mesozoic to Tertiary passive margin-type sedimentary succession (Fazzuoli et alii, 1994 and references therein) that includes Late Triassic-Early Jurassic, continental and shallow water deposits showing a transition to Middle Jurassic to late Oligocene, pelagic deposits topped by late Oligocene-early Miocene foredeep siliciclastic turbidites (Macigno Fm). Most of the shear zones at the top or inside the Tuscan Nappe can be regarded as low-angle thursts developed during the contractional tectonics, as suggested by local tectonic doublings of the successions (e.g. M.Aquilaia, Poggio Zoccolino and subsurface of Bagnore in Brogi & Lazzarotto, 2002; Pandeli et alii, 2005). At depth, the logs of the deep boreholes indicated that the Tuscan Nappe tectonically lies onto the Tuscan Metamorphic Units that consists of ?Devonian to Upper Permian formations capped by Triassic Verrucano sediments (Pandeli et alii, 1988; Elter & Pandeli, 1991).

However, outcrops and subsurface data throughout the entire Southern Tuscany show that the Tuscan Nappe, as well as the overlying Ligurian and Sub-Ligurian Units, are often affected by tectonic delamination ("Serie ridotta" in Decandia et alii, 1993, 2001; Bertini et alii, 1991 and many others). This delamination is the result of the development of low-angle faults with staircase geometry that produced the omission of several stratigraphic levels. As result of the tectonic delamination, the Internal Ligurian Units of the Amiata area directly overlies the lowermost structural levels of the Tuscan nappe represented by the Late Triassic evaporites (e.g. Calamai et alii, 1970; Pandeli et alii, 2005; Brogi 2004a). Some authors suggested that this peculiar tectonic setting can be related to extensional tectonics affecting the uppermost structural levels of an overthickened nappe stack during the middle Miocene compressive processes (Carmignani & Kligfield, 1990; Decandia et alii, 1993, 2001; Bertini et alii, 1991).

Since late Tortonian, a further regional extensional, post-contractional tectonics produced high angle faulting with a main NW-SE and N-S strike, with development of horst (e.g. the Montalcino-Monte Amiata-Monte Razzano Ridge) and graben (e.g. Cinigiano-Baccinello and Siena-Radicofani basins) structures (Elter et alii, 1975; Pasquarè et al., 1983; Martini & Sagri, 1993; Martini et alii, 2001). As result of the progressive eastward migration of the regional extensional tectonics, the base of the sedimentary deposits that seal the relationshisp among the Ligurian, Sub-Ligurian and Tuscan Units is assigned to late Tortonian and to early Pliocene in, respectively, the Baccinello-Cinigiano and the Siena-Radicofani basins. In addition the horst and grabens structures were dissected by SW-NE striking sub-vertical faults, characterized by strike- and oblique-slip kinematics with a predominantly left-lateral movement (Liotta, 1991; Brogi and Fabbrini, 2009). The strike-slip faults can be associated to the fissural eruptions and domes as that originating the Quaternary Monte Amiata volcano (Mazzuoli and Pratesi, 1983; Gianelli et alii, 1988; Ferrari et alii 1996). Possible minor compressive pulses affected the Mt. Amiata region in the middle-late Pliocene (Boccaletti & Sani, 1998; Bonini & Sani, 2002), but they did not produce significant rearrangement of the tectonic pile (e.g. doublings or detachments).

3. THE SUB-LIGURIAN UNITS

In the Amiata area, the Sub-Ligurian Units are represented only by the Canetolo Unit, that crops out in the surrounding of the Monte Aquilaia – Monte Labbro tectonic window located SW of Monte Amiata (Fig.2). This units is everywhere sandwiched between the Tuscan Nappe at the base and the Ligurian Units at the top. In any case, due to Miocene extensional tectonics, the Canetolo

Unit can be overlain by Santa Fiora Unit as well as the Ophiolitic Unit (Fig.2). In particular, two main outcrops of the Canetolo Unit occur also along the ENE-SSW strike-slip fault located south of Monticello Amiata. The Canetolo Unit shows a polyphase deformation history, developed under medium to high diagenetic conditions (Franceschelli et alii, 1994).

3.1. THE CANETOLO UNIT

The Canetolo Unit shows a succession consisting of Argille e Calcari Fm and Vico Fm (Cf. Calcari di Groppo del Vescovo, Perilli et alii, 2009 and references therein). The formations show eteropic relationships. The strong deformations as thrust and folds that affect the whole Canetolo Unit hamper a correct appraisal of the true thickness of its succession. The apparent thickness is about 200-300 m.

3.1.1. STRATIGRAPHY

The Argille e Calcari Fm is represented by prevailing hemipelagic carbonate-free shales and subordinate carbonate turbidites. The carbonate turbidites are generally represented by thin to thick beds of fine-grained limestones, generally without sedimentary structures, whose thickness range from 30 cm to 1 m (Fig.3a). However, very thick beds of carbonate turbidites, decimetric to metric (up to 4-5 m) in thickness, also occur. These very thick turbidites, showing by Tb-e and Tc-e Bouma intervals, includes beds of limestones and marly-limestones characterized by the occurrence of sedimentary structures such as plane lamina ad ripples. These turbidites sometimes show a hybrid medium- to coarse-grained arenitic base showing a mixing of benthic (*Orbitoides, Nummulites and Discocyclina*) and planctonic (*Globorotalia and Globigerina*) foraminifera bioclasts. These turbidites derived from low-density turbidity currents.

Subordinate siliciclastic turbidites occur as 5-30 cm thick beds of quartz-rich arenites and siltstones, that display Tb-e or Tc-e Bouma incomplete sequences. The arenitic beds occur locally (e.g. SW of Bagnore) as corse-grained amalgamated bodies characterized by Ta, Ta/c-e and Ta/d-e Bouma intervals.

The silicilastic and carbonate turbidites are intercalated in very thick beds of hemipelagic, carbonate-free black shales.

The Vico Fm (Fig.3b) is represented by medium- to very-thick beds of carbonate turbidites with Ta-e, Tb-e and minor Ta/c-e Bouma sequences. These turbidites are represented by continuous beds of bioclastic-rich calcarenites or calcirudites, limestones and marlstones, whose thickness range from 1 to 5 m. In the calcarenites bioclast fragments can be recognized even using the lens. Amalgamations surfaces and erosional bases are locally present in the coarser beds. The carbonate turbidites are alternating with thin to thick beds of black, hemipelagic carbonate-free shales.

In thin section the arenites from Vico Fm are sublitharenites characterized by a hybrid and mixed siliciclastic-carbonate framework composition (Fig.3c,d). The carbonate intabasinal fragments are mainly bioclasts as includes the same benthic (*Orbitoides, Nummulites, Discocyclina*) and planctonic (e.g. *Globoratalia and Globigerina*) foraminifera as found in the fragments of lamellibranc, red algae and sponge can be also recognized. Few intabasinal mudstone soft clast are sometimes recognizable. Extrabasinal carbonatic fragments are mainly represented by mudstone, radiolaria-bearing wackestones and dolostones. It is possible includes in this group silicified and partly silicified fragments of radiolaria-bearing wackestones, probably derived by cherty limestones. The extrabasinal siliciclastic arenite framework is characterized by mono- and polycrystalline quartz, minor plagioclase and K-feldspar monocrystals. Coarse-grained lithic fragments of granitoids and porphyritic rhyolites as well low grade metamorphic rock fragments can be also recognized. Ophiolite derived rock fragments are lacking at all.

3.1.2. PALEONTOLOGICAL DATINGS

Last datings of the Argille e Calcari Fm produced by Pandeli et alii (2005) for the Amiata area were based on foraminifera and calcareous nannofossils assemblages referable to early-middle Eocene. Foraminifera are represented by *Acarinina bullbrooki*, *Morozovella aragonesi*, *Morozovella crassata*, *Turborotalia cerroazulensis*; the nannofossils assemblages contain *Coccolithus pelagicus, Discoaster kuepperi, Reticulofenestra dictyoda, Reticulofenestra samodurovii, Sphenolithus radians and Zygrhablithus bijugatus.* The Cretaceous nannofossil assemblages found in samples coming from limestones of the were considered reworked as contain species referable to late Campanian CC22-CC23 Zones of Sissingh (1977) *Aspidolithus parcus constrictus*, *Calculites obscurus*, *Ceratolithoides aculeus*, *Cribrosphaerella erhenbergii*, *Manivitella pemmatoidea*, *Prediscosphaera cretacea*, *Prediscosphaera intercisa*, *Quadrum sissinghii*, *Quadrum trifidum*, *Reinhardtites levis* and *Watznaueria barnesae*.

In order to analyze the calcareous nannofossils content and to better define the age of the Canetolo Unit, we sampled the Argille e Calcari Fm south of Monticello Amiata and the Vico Fm in the area southeast of Montegiovi. The samples, prepared as smear slides (Bown and Young, 1998), were studied under cross polarized light at 1250X.

Calcareous nannofossils were found to be abundant and their preservation moderately good (Fig.4). The easily identified species are *Chiasmolithus gigas, Chiasmolithus grandis, Chiasmolitus nitidus, Chiasmolithus titus, Clausicoccus fenestratus, Coccolithus eopelagicus, Coccolithus pelagicus, Cyclicargolithus floridanus, Ericsonia formosa, Discoaster barbadiensis,Discoaster binodosus, Discoaster deflandrei, Discoaster kuepperi, Discoaster nodifer, Discoaster saipanensis, Discoaster tanii, Girgisia gammation, Dictyococcites scrippsae, Nannotetrina alata, Nannotetrina cristata, Nannotetrina pappii, Neococcolithes dubius, Pseudotriquetrorhabdulus inversus, Reticulofenestra dictyoda, Sphenolithus cuniculus, Sphenolithus furcatolithoides, Sphenolithus radians, Sphenolithus spiniger, Sphenolithus richterii, Zygrhablithus bijugatus* (Fig.5). The concomitant presence of *C. gigas, N. cristata, S. cuniculus and S. furcatolithoides* assigns the sampled Argille e Calcari Fm to the upper part of Lutetian (middle Eocene) NP15 Zone of Martini (1971) (Fig.6). The samples collected in the uppermost and finer parte of the turbidites from Vico Fm contain only Cretaceous calcareous nannofossil assemblages referable to Aptian-Albian (*Eprolithus floralis*, *Brarudosphaera* spp., *Prediscosphaera columnata*, *Nannoconus* spp., *Assipetra terebrodentarius*, *Biscutum* spp., and *Watznaueria* spp.), to Coniacian (*Micula staurophora*, *Eiffellithus eximius* and *Watznaueria* spp.) and to Campanian (*Aspidolithus parcus*, *Calculites obscurus*, *Micula* spp. and *Watznaueria* spp.). The presence of *Nummulites* sp. in the calcarenites associated to the limestones and marlstone sampled for the calcareous nannofossil study, induce us to consider the Cretaceous species reworked.

3.1.3. DEFORMATION HISTORY

The deformation history of the Canetolo Unit has been reconstructed mainly in the Argille e Calcari Fm, where the multilayer represented by beds of shales and limestones allow a better record of the structural evolution.

Before any folding phase, parallel-bedding veins with mm thickness developed. These veins show a mosaic texture with a calcite infilling.

The D1 phase is mainly represented by a S1 scaly foliation parellel to bedding (Fig.7a). This foliation is associated to rare F1 isoclinal folds with similar geometry. The limbs of the F1 folds are generally affected by a brittle boudinage with recrystallization of calcite fibers in the space opened among the boudins.

The D2 phase is pervasive and recognized in all the outcrops of this unit. The D2 phase mainly consists of by asymmetric and overturned F2 folds (Fig.7b) with approximately parallel geometry (classes 1b, 1c and 2 of Ramsay, 1967). The A2 axes show a NNE-SSW trend, as suggested by the measured axes as well as the dispersion of the bedding poles (Fig.7c). The hinges of F2 folds are rounded, whereas the interlimb angles range from 40° to 100°. These folds are characterized by low-angle PA2 axial plane parallel to a well developed S2 foliation that can be classified as disjunctive cleavage. The S0/S2 intersection lineations originate a typical pensil cleavage (Fig.7d). The F2 folds are associated to low-angle thrust marked by cataclasites showing top-to-E sense of shear.

The D3 phase is characterized by gentle F3 folds showing a clear N-S trend. The F3 folds show an approximately parallel geometry (classes 1b, 1c and 2 of Ramsay 1967) and subvertical PA3 axial plane. These structures are responsible of the further dispersione of the bedding, as show by the stereonet of the Fig.7e. The interlimb angles range from 90° to 160°, whereas the A3 axes show a trend ranging from NNE/SSW to NNW/SSE (Fig.7e). F3 folds are characterized by a well-spaced fracture cleavage, everywhere recognized as a subvertical surface.

4. THE LIGURIAN UNITS

In the Amiata area, the Ligurian Units are represented by two units, the Ophiolitic Unit (cf. Ligurian-Maremma Group of Brunacci et alii, 1983; Upper Ophiolitic Unit of Bertini et alii, 2000; Ophiolitiferous Unit of Pandeli et alii, 2005) and the Santa Fiora Unit (cf. Formazione argilloso-calcarea of Bettelli, 1980; 1985). The relationships between these two units occur by subhorizontal, low-dipping shear zones that can be interpreted as low-angle normal faults developed during the middle Miocene extensional tectonics (Bertini et alii, 1991; Brogi, 2004a and b). Both the Ligurian Units are characterized by a complex structural setting derived from a polyphase deformation history, generally developed under medium to high diagenetic conditions in the Santa Fiora Unit and under very low-grade metamorphism (anchizone) in the Ophiolitic Unit (Franceschelli et alii, 1994).

4.1. THE SANTA FIORA UNIT

The succession of Santa Fiora Unit includes the Varicoloured Shales, the Pietraforte Fm and the Santa Fiora Fm. Whereas the Varicoloured Shales and the Pietraforte Fm are characterized by stratigraphic, probably heteropic relationships, the Santa Fiora Fm represents the youngest deposit of this unit. The Santa Fiora is affected by a map-scale structure that displays a core of Santa Fiora Fm with Varicoloured Shales and the Pietraforte Fm at its base as well as at its top, as recognized in the Seggiano area. This structure can be depicted as a recumbent synform with a core represented by the Santa Fiora Fm bounded by well developed overturned and normal limbs. Along both the limbs the detachment of the Santa Fiora Fm from the Varicoloured Shales/Pietraforte Fms couple (tectonic “Pietraforte sub-Unit” in Pandeli et alii, 2005) can be locally observed. This detachment can be regarded as achieved during the fold development but it was subsequently reworked by low-angle normal faults. Despite the strong deformations, the original stratigraphic relationships among Santa Fiora Fm and the Varicoloured Shales/Pietraforte Fms couple are clearly identified in some places (e.g. Costantini et alii, 1977; Pandeli et alii, 2005). The folding and the scattered distribution of the outcrops hampers a correct appraisal of the true thickness of the original whole succession, that can be estimated as not less of 1000 m.

4.1.1. STRATIGRAPHY

The Varicoloured Shales are characterized by massive beds of manganesiferous shales with typical grey, grey-greenish and black and reddish colours. Thin-bedded silicified limestones, are present as intercalations within the shales.

The Pietraforte Fm is represented by turbidite deposits that in Amiata area occur in three different lithofacies.

The first, most widespread lithofacies (Arenaceous and arenaceous-pelitic lithofacies in Pandeli et alii, 2005) is represented by massive to graded turbidites consisting of medium- to thick-bedded (locally more than 10 m) arenites and siltites with a/p ratio generally > 4 (Fig.8a). The fine- to medium-grained rudites (“Cicerchina” Auctt.) as well as clay chips are quite common at the base of the thickest arenite beds. The turbidite beds, that are generally lenticular and amalgamated, are characterized by Ta, Ta-c, Ta/c-e, Tab/de and Ta-d Bouma sequence. Rarely, thin-bedded shales are preserved. The coarse beds are generally lenticular and amalgamated and they can be recognized by high-density turbidity current-derived deposits (cfr. F5 and F8 facies of Mutti, 1992). According to Mutti 1992 these deposits are characterized by scarce sorting, erosive bottom structures such us small scours and widespread clay chips.

The second lithofacies (Arenaceous-conglomeratic lithofacies in Pandeli et alii, 2005) consists of thick to very thick amalgamated beds of coarse- to fine-grained conglomerates passing abruptly upwards into coarse-grained sandstones. The clasts are made up of carbonates, radiolarites, acidic plutonic and metamorhic rocks (e.g. schists and gneisses). Clay chips of pelites are also frequent especially at the base of the beds.

The upper part of the Pietraforte Fm is characterized by a third lithofacies (pelitic-arenaceous lithofacies in Pandeli et alii, 2005) consisting of medium- to thin-bedded coarse- to fine-grained arenites, siltites and shales with a/p ratio □ 1. These deposits mainly derived from low-density turbidity currents and the incomplete Bouma sequence Tb-e, Tc-e, and Tde are the widespread structures. Subordinate thin to medium thick beds of fine-grained limestons also occur. In the uppermost part of the Pietraforte Fm, levels of Varicoloured Shales are intercalated.

The arenites from Pietraforte Fm (Fig.8b) are sublitharenites characterized by a mixed siliciclastic-carbonate framework composition. The extrabasinal siliciclastic framework part is characterized by mono- and polycrystalline quartz, plagioclase and K-feldspar clasts. Coarse-grained lithic fragments of granitoids are also common while minor porphyritic rhyolites can be recognized. Metamorphic rock fragments include low- to medium-grade schists, micaschists and minor fragments of quartzites, mylonitic quartzites and subordinate gneisses. The quartzite fragments are often characterized by stripped quartz (Fig.8c). Ophiolite derived rock fragments have not been observed.

The Santa Fiora Fm (cf. Formazione argilloso-calcarea" of Bettelli, 1985) is in turn represented by carbonate turbidites and minor hemipelagic shales. The carbonate turbidites are represented by medium to very thick beds of limestones and marlstones grading upward to shaly-marlstones and marly-shales. The Tc-e and Td-e Bouma sequences characterize these turbidites The base of the carbonate turbidites are often characterized by fine to very-fine carbonatic arenites, but the main body of these carbonate turbidites are composed of calcilutites and marls without sedimentary structures (Fig.8d). In thin section these deposits are foraminifera- and radiolaria-bearing wackestones (Fig.8e) where the matrix is dominated by nannofossils. In the Poggio Nibbio area (SE of the Monte Amiata), lenticular bodies (max 15–20 m thick) of arenaceous beds mixed siliciclastic-carbonate framework composition occur as intercalations in the carbonate turbidites. These bodies can be correlated to the Mt. Rufeno Sandstone Member recognized in the Santa Fiora Fm in the areas south of Mt. Cetona (Costantini et alii, 1977). According to Pandeli et alii (2005), these arenites show a composition similar to that of arenites of Pietraforte Fm. This occurrence can be regarded as the result of heteropic relationships between the Santa Fiora and Pietraforte Fms.

The uppermost stratigraphic level of the Santa Fiora Fm is represented by thin-bedded turbidites consisting of thin to medium beds (10-60 cm) of fine- to medium-grained arenites and coarse-grained siltites alternating with 10 to 100 cm thick beds of shales and shaly marls. These strata are generally well graded only in their uppermost part where current ripples and sinusoidal lamina can be present.

The arenites have been sampled for the arenite petrography. In thin section (Fig.8f) they are siliciclastic extrabasinal to mixed (carbonatic/siliciclastic) extrabasinal arenites. The framework composition is dominate by mono-crystalline quartz, feldspar and extrabasinal carbonate fragments (mudstone made of calcite or dolomites micro crystals). Minor low grade metamorphic rock fragments and white mica mono-crystals are also present. No ophiolite fragments are detected.

The hemipelagic deposits are represented by carbonate free, black-shales ranging in thickness from 2-3 cm to 2 m.

4.1.2. PALEONTOLOGICAL DATINGS

In Pandeli et alii (2005), the generic Aptian to to Maastrichtian ages suggested by rich foraminifera microfaunas investigated in the Santa Fiora Fm, were specified through calcareous nannofossil assemblages referable to the Aptian Zone CC7 (occurrence *of Rhagodiscus angustus+Hayesites irregularis*, the Albian Zone CC9 (occurrence of *Eiffellithus turriseiffelii*), the late Coniacian-early Santonian Zone CC14 (occurrence of *Micula decussata*) and the Campanian Zones CC18-CC23 (appearance of *Aspidolithus parcus constrictus*, *Ceratolithoides aculeus*, *Quadrum gothicum* and *Quadrum trifidum*). New datings performed for the recent geological mapping of the Mt. Amiata area partially agree with these data, the reported assemblages (Fig.9) are referable to late Albian Zone CC9 (occurrences of *E. turriseiffelii* and *Corollithion kennedyi*) and to middle-late Campanian Zones CC21-CC22 (occurrence of *Q. gothicum*, *Eiffellithus eximius* and *Reinhardtites levis*). Further data of the Santa Fiora Flysch comes from poorly preserved assemblages (Fig.10a) present in samples collected in the area of Seggiano and Montegiovi, in the northern side of the Mt. Amiata. The impoverished assemblages are mainly referable to Albian, Turonian and post Coniacian ages. The late Albian assemblages, probably referable to Zone CC9, are represented by *E. turriseiffelii*, *Eiffellithus monechiae*, *Tranolithus orionatus*, *Eiffellithus* sp., *Cylindralithus nudus*, *Brarudosphaera africana*, *Eprolithus floralis*, *Biscutum constans*, *Chiastozygus platyrhethus*, *Helenea chiastia*, *Assipetra terebrodentarius*, *Helicolithus trabeculatus*, *Rhagodiscus asper*, *Retecapsa crenulata*, *Zeughrabdotus embergeri*, *Brarudosphaera* sp., *Cyclagelosphaera* sp., *Nannoconus* spp., *Watznaueria* spp. The Turonian is represented by the species *Lithraphidites pseudoquadratus* and *Quadrum gartneri* that are in assemblage with *E. floralis*, *R. crenulata*, *T. orionatus* and *Watznaueria* spp. The late Coniacian-Santonian ages are represented by assemblages containing *Micula decussata*, *Reinhardtites anthophorus*, *Eiffellithus gorkae*, *E. turriseiffelii* and *Watznaueria* spp.

The Pietraforte Fm investigated by Pandeli et alii (2005) exhibits fossils referable to a generic Late Cretaceous (small Globigerinidae and Globotruncanidae). The assemblages recovered during the recent geological mapping contain poorly preserved taxa that allow the identification of late Albian on the presence of *E. turriseiffelii* and *E. floralis*. Few samples collected for this study turned out to be barren or nearly sub barren with only very rare specimens of *Micula* sp., *Eprolithus eptapetalus* and *Watznaueria* spp. (Fig.10a), that suggest a possible middle Coniacian age.

The Varicoloured Shale was referred to Aptian-Albian ages by Pandeli et alii (2005) on the presence of varied nannofossil assemblages (i.e. *E. turriseiffelii*, *Prediscosphaera cretacea*, *Braarudosphaera bigelowii*, *H. irregularis*, *R. angustus*, *R. asper*, *Nannoconus* sp.) coming from the carbonate beds. The presence of *P. cretacea* and *B. bigelowii* in the early Cenomanian (Burnett 1998), refers the formation to ages not older than Cenomanian.

On the whole, the paleontological and stratigraphic data provide a picture where the Pietraforte Fm and the Varicoloured Shale can be regarded as ?Aptian to middle Coniacian in age whereas the age of the Santa Fiora Fm seems to span late Coniacian-early Santonian Zone CC14 to middle-late Campanian Zones CC21-CC22.

4.1.3. DEFORMATION HISTORY

The D1 phase is presented by isoclinal to subisoclinal F1 folds with rounded hinges found only in the arenaceous-pelitic facies of the Pietraforte Fm. The F1 folds (Fig.11a) are characterized by with approximately parallel geometry (classes 1b, 1c and 2 of Ramsay, 1967). These folds are not observed in the Santa Fiora Fm where the D1 phase is represented by cataclastic shear zones parallel to the bedding that are deformed by the subsequent F2 folds. The foliation associated to the F1 folds is represented by disjunctive cleavage.

The structures of the D2 phase are the most widespread and the best developed in the Santa Fiora Unit. This phase is characterized by asymmetric and overturned F2 folds (Fig.11b) with approximately parallel geometry (classes 1b, 1c and 2 of Ramsay, 1967). The hinges of F2 folds range from rounded to subacute, whereas the interlimb angles range from 70° to 140°. The PA2 axial planes are generally low dipping. On the stereonet, the A2 fold axes show a ranging from NW/SE to NE/SW trend (Fig.11c). The trend of the bedding seems to be mainly acquired during the D2 phase, according to the steronet shown in Figure 11c. The S2 axial-plane foliation developed in both shales and sandstones can be recognised as a convergent fanning disjunctive cleavage. During the D2 phase the sandstones and arenites of the Pietraforte Fm behaved as a competent layer whereas the Santa Fiora Fm is intensely folded. The most important thrusts developed during the D2 phase are represented by the floor thrusts of the Santa Fiora Unit that appears reworked as low-angle normal fault.

The D2 phase was followed by the D3 phase is characterized by asymmetric F3 folds with approximately parallel geometry (classes 1b, 1c and 2 of Ramsay 1967). These folds generally display a N/S trend (Fig.11 c) and a subvertical axial planes. The interlimb angles range from 145° to 80°.

4.2. THE OPHIOLITIC UNIT

The Ophiolitic Unit, whose best outcrops occur at the western edge of the Siena-Radicofani basins, south of the Orcia River and around the Mt. Amiata volcano, is mostly made up of Palombini Shale and rare bodies of ophiolites and ophiolitic breccias, sometimes found at the core of isoclinal folds and/or as slices along the main shear zones. In the Piancastagnaio and Torrente Senna area, small dykes and sills of basic magmatic bodies ("Selagiti" Auctt.) of Cretaceous age are intruded in the Palombini Shale (Brunacci et alii, 1983). The complex polyphased deformation that affected the Palombini Shale hampers a correct appraisal of the true thickness of the Ophiolitic Unit. The apparent thickness is about 600-700 m.

4.2.1. STRATIGRAPHY

The ophiolites are represented by serpentinites (e.g. south and east of Rocca d' Orcia, north-east of Campiglia d'Orcia, south of Abbadia S.S., south of S.Fiora and west of Bagno Vignoni) as well as by ophicalcites or by polymictic ophiolitic breccias, particularly in the southern side of the Monte Amiata.

The Palombini Shale are characterized by carbonate and siliciclastic thin bedded turbidites alternating with thick bedded hemipelagic deposits. The carbonate turbidites (Fig.12a) consist of fine grained silicified limestones (calcilutites and rare fine calcsiltites) whose thickness ranges from 10 cm to about 1,5 m. The limestone beds, characterized by a thickness ranging from 10 cm up to 1.5 m, show a good lateral continuity. Rare centimetric to decimetric calcarenite bases can be found at the base of the thickest beds of calcilutites. Sometimes the calcilutites show the presence of structures like plane laminae, convolute laminae and ripples (cfr. Bouma missing beds, Tb-e, Tc-e or F9a facies of Mutti, 1992) which allow us to refer these deposits to the product of low density turbidity currents. The thickest beds show Te Bouma interval consisting of marlstones and marly shales, that have been sampled for nannoplancton analyses. South of Santa Fiora, the Palombini Shale are represented by a thick level where the carbonates turbidites are represented by m-thick beds of marlstones and marly shales (Brunacci et alii, 1983).

At places (e.g. south of Saragiolo, SE side on the Monte Amiata), thin bedded siliciclastic turbidite beds are intercalated within the shales and consist of quartz-rich arenites ranging in grain size from medium-fine sand to siltstone.

Both the carbonate and siliciclastic thin-bedded turbidites (Fig.12b) are alternating with thick bedded carbonate-free shales, whose thickness reaches up to 3-4 m. These deposists represent the hemipelagic background sedimentation.

The Palombini Shale can be subdivided in two different members; the lowermost one is characterized by prevailing carbonate turbidites whereas in the uppermost one the siliciclastic turbidites and the hemipelagic shales are predominant.

In, addition basaltic dykes and sills ("Selagiti" Auctt.), up to 2 m in thickness and of Early to Late Cretaceous age (86.3±1.7 Ma and 97.1±2.3 Ma radiometric age in Brunacci et alii, 1983), occur within the Palombini Shale in the area south of Piancastagnaio in the Senna Valley and Bagnolo-Saragiolo along the southern flank of Monte Amiata. In the latter area, the widest outcrop of such basic magmatic close to Case Lorentano shows structure typical of pillow lavas. The dykes and sills, are characterized by coarse-grained central parts and very fine-grained at the contacts with the sedimentary rocks ("chilled margins"). Brunacci et alii (1983) defined these magmatic rocks as oceanic, intra-plate alkaline olivine-basalts. According to Stoppa et alii (2014), these rocks are derived from the melting of a two component, metasomatised mantle, which can be tied into plume-related magmatism. The emplacement of these magmatic rocks was probably driven by transform faults that segmented the Ligure-Piemontese oceanic basin in the Cretaceous time.

4.2.2. PALEONTOLOGICAL DATINGS

The ages recorded for the Palombini Shale in the Southern Tuscany are referable to a generic uppermost Early Cretaceous (Marcucci & Passerini 1980, 1982). Recent samplings for the realization of the 1:50.000 "Castel del Piano" geological map, provided assemblages of rare and poor preserved calcareous nannofossils that can be referred to the late Hauterivian-Barremian

Zones CC5-CC6 of Sissingh (1977), on account of the presence of *Assipetra terebrodentarius* and *Nannoconus steinmannii* together with *Watznaueria* spp., *Nannoconus colomii*, *Zeugrhabdotus embergeri* and *Lithraphidites carniolensis* (Fig.13). The occurrence of *Eprolithus floralis* extends the age of the Palombini Shale, cropping out in this area, to the Aptian Zone CC7 (Fig.14).

4.2.3. DEFORMATION HISTORY

A complex structural history, consisting of four distinct deformation phases (hereafter referred as D1, D2, D3 and D4), has been recognized within the Palombini Shale.

Before any deformation phase, the Palombini Shale are characterized by bedding-parallel calcite veins, whose thickness range from 1-2 mm to 5-6 cm. These veins are characterized by a mosaic texture where the calcite grains enclose fragments of the vein walls.

The D1 phase is mainly represented by a well-developed, continous S1 foliation, generally parallel to or at low angle to the bedding surfaces. The S1 foliation is associated to non-cylindrical, tight to isoclinal folds showing subrounded and thickened hinge zones. The F1 folds are characterized by an approximately similar geometry. The stereographic distribution of fold A1 axes (Fig.15c) is scattered as result of the presence of non-cylindrical folds. Brittle boudinage of the fold limbs and associated necking are very common features producing a fabric where isolated fragments of beds are scattered in the shaly matrix.

In thin section of the shales, the S1 axial-plane foliation can be classified as poorly developed slaty cleavage (Fig.15a) showing aligned, preferred-dimension phyllosilicates and elongate quartz-albite-mica aggregates showing the effects of the deformation, mainly consisting of pressure-solution parallel to the slaty cleavage domains. The S1 foliation is characterized by quartz + calcite + albite + chlorite + white mica + Fe-oxides recrystallization. During the D1 phase, extension veins showing infillings of calcite fibres perpendicular to the vein walls developed. In thin section, the antitaxial calcite fibres are characterized by the presence of a widespread median line and inclusion bands of wall rock fragments related to crack-seal deformation (Ramsay 1980). According to the classification of twins in thin section (Burkhard 1993), calcite from antitaxial veins belong to type I and II. The type of calcite twins (Fig.15b) and the data about the illite crystallinity (Franceschelli et alii, 1994) suggest a T between 150° and 200°C and P lower than 3 Kbars.

The D2 phase are characterized by asymmetric and overturned folds with approximately parallel geometry (classes 1b, 1c and 2 of Ramsay, 1967). The hinges of F2 folds range from rounded to acute, whereas the interlimb angles range from 70° to 140°. The axial planes are low-angle dipping. On the stereonet, the A2 fold axes shows a trend ranging from NNW/SSE to NNE/SSW (Fig.15c) as suggested also by the dispersion of the bedding (Fig.15c). The S2 axial-plane foliation developed in the shales can be recognized as a convergent fanning crenulation cleavage of zonal type, with parallel domains showing discrete transition. The crenulation cleavage can be recognized in the shales, whereas it is absent or poorly developed in limestones and sandstones. The F2 folds are strictly associated to low-angle shear zones marked by foliated cataclasites with well widespread S-C structures.

The D3 phase is mainly represented by thrusts marked by foliated cataclasites with well widespread S-C structures. Kinematic criteria inferred from these foliated cataclasites indicate a top-to-the east sense of shear. The thickness of the cataclasites attains several meters producing a block-in-matrix fabric, that characterizes large volumes of the Palombini Shale.

The D4 phase is characterized by gentle folds with approximately parallel geometry (classes 1b, 1c and 2 of Ramsay 1967). The interlimb angles range from 90° to 160°, whereas the axial planes occur everywhere as subvertical surface. On the stereonet, the A4 fold axes show a N-S trend that produces a dispersion clearly detected in the stereonets of Fig 15c. The F4 folds are characterized by a well-spaced fracture cleavage, everywhere recognized as a subvertical surface.

5. CORRELATION WITH THE SUB-LIGURIAN AND LIGURIAN UNITS OF THE NORTHERN APENNINES

The collected stratigraphic and paleontogical data allow a correlation of the Ligurian and Sub-Ligurian Units of Amiata area with those cropping out in the Southern Tuscany as well as those from the Ligurian-Emilian Apennines.

A correlation of the succession of Canetolo unit cropping out in the Amiata area with the same unit of Emilian Apennines is confirmed by stratigraphic and paleontological data. The review of paleontological data for the Canetolo Unit of Emilian Apennines (Perilli et alii, 2009) based on semiquantitative analysis of the nannofossils assemblages, indicates for the Calcari di Groppo del Vescovo Fm (= Vico Fm) an age ranging from aarly Eocene (NP11) to middle Eocene (NP14), whereas for the Argille e Calcari Fm an age spanning from late Paleocene (NP5) to middle Eocene (NP14 to NP15) has been assessed. These data fit very well with the middle Eocene age (NP15) of the Argille e Calcari Fm from Amiata area. In addition, the eteropic relationships between the Argille e Calcari Fm with the Vico Fm corresponds to the stratigraphic setting assessed in the Emilian Apennines (Perilli et alii, 2009 and references therein). However, the lacking of the deposits referable to late Paleocene-early Eocene time span as well as the reduced thickness of the succession in the Amiata area indicates for the Canetolo Unit a strong tectonic delamination.

The picture arising from the analyses of the data about the Ophiolitic Unit indicates the occurrence of a succession consisting of Palombini Shale with rare outcrops of ophiolites, found at the core of the isoclinal folds and/or along the main shear zones. The ophiolitic unit can be correlated with the Bracco-Val Graveglia Unit from Ligurian Apennines (e.g. Cortesogno et alii, 1987) and the Upper Ophiolitic Unit (e.g. Bertini et alii, 2000) of Southern Tuscany. The available age for the Palombini Shale cropping out in Southern Tuscany ranges from early Valanginian to late Hauterivian/early Barremian (Perilli, 1997). Bertini et al. (2000) indicate for the top of the Palombini Shale an Aptian age, whereas in the Ligurian-Emilian Apennines the uppermost levels of this formation have been referred to Santonian (Marroni and Perilli, 1990). These data are coherent with the data achieved for the Palombini Shale in the Amiata area that indicates an age of late Hauterivian-early Barremian. Consequently, also for the ophiolitic unit of Amiata area the related succession seems to be more delaminated than observed in the other areas of Northern Apennines.

More problematic is the correlation of the Santa Fiora Unit with the Ligurian Units of Southern Tuscany and Ligurian-Emilian Apennines.

This unit can be regarded as belonging to the External Ligurian Units, as suggested by the occurrence of carbonate turbidites of Late Cretaceous age (“Helminthoid Flysch”). In the geological framewotk of Southern Tuscany, the lacking of ophiolite-bearing clastic deposits and the Late Cretaceous age of the carbonate turbidites allow to propose a correlation of the Santa Fiora Unit with the Monteverdi Marittimo Unit (e.g. Lazzarotto et alii, 2002 and references therein). This unit, that crops out in the areas north of Mt Amiata area, is represented by the Argilliti e Calcari di Poggio Rocchino Fm that consists of varicoloured shales with scattered intercalations of few beds of limestones and marls showing a nannofossils assemblage of late Albian-early Turonian age (Marino and Monechi, 1994; Lazzarotto et alii, 2002). This formation, that can be correlated with the Varicoloured Shales from Santa Fiora Unit, shows gradual stratigraphic relationships with the Monteverdi Marittimo Fm, an Helminthoid Flysch of Santonian-Maastrichtian age (Marino and Monechi, 1994). As detected in the Santa Fiora Unit, the whole succession of the Monteverdi Marittimo Unit is devoided of ophiolite-bearing clastic deposits.

Concerning the Emilian Apennines, the occurrence of Pietraforte Fm, i.e. a thick succession of arenites and conglomerates characterized by a mixed siliciclastic-carbonate framework composition (Fontana et alii, 1987; Fontana, 1991), seems to indicate a strict correlation of the Santa Fiora Unit with the succession of Monte Cassio Unit, belonging to Eastern External Ligurian Units (Marroni et alii, 2001 and references therein). The succession of Monte Cassio Unit consists of Palombini Shale (Early Cretaceous), Ostia Sandstone and Varicoloured Shales (Cenomanian-late Campanian) showing a transition to Campanian-Maastrichtian carbonate turbidites (Helminthoid Flysch of Monte Cassio). The varicoloured, hemipelagic shales are characterized by intercalations of conglomerates, known as Salti del Diavolo Conglomerate. Both the arenites and the conglomerates are characterized by a mixed siliciclastic-carbonate framework composition (Bracciali et al. 2007 and references therein).

The framework composition of the Pietraforte arenites characterized by siliciclastic extrabasinal to mixed (carbonatic/siliciclastic) extrabasinal arenites can be compared with the composition of the lowermost part of the Cassio Unit sequence (cfr. Ostia Sandstone, Scabiazza Sandstone, Salti del Diavolo Conglomerate and Case Baruzzo Sandstone, Bracciali et al. 2007, Vescovi et al. 1999, Daniele and Bianchi, 1995) and seem to indicate an anologue source area.

On the whole, the entire succession from the Cassio unit is characterized by deposits supplied by a continental margin, where ophiolites are lacking (Valloni and Zuffa, 1984). The correlation of the Cassio Flysch with the Santa Fiora Fm suggest that the base of the latter formation can be regarded as middle-late Campanian Zones (CC21-CC22), whereas the old nannofossils assemblages can be regarded as reworked. However, this suggestion needs more data to be assessed because an age of the base of the Santa Fiora Fm older than that of the Cassio Flysch cannot be excluded a priori. It is noteworthy that the Santa Fiora Unit is deformed at map scale in a synform with Santa Fiora Fm at the core, as recognized for several External Ligurian units in the Northern Apennines (e.g. Marroni et al., 2002).

When the pile of the tectonic units recognized in the Amiata area is compared with that reconstructed in southern Tuscany and Ligurian-Emilian Apennine, the most striking difference is represented by the lacking of several tectonic units and by the strong reduction of the thickness of the outcropping units. For instance, the Montaione Unit that crops out in the Southern Tuscany is lacking at all in the Amiata area. This unit consists of a carbonate turbidites of Campanian-Maastrichtian age (Helminthoid Flysch) whose base is represented by an ophiolite-bearing deposits like pebbly mudstones, pebbly sandstones and coarse-grained arenites. In addition, the Canetolo Unit and the Ophiolitic Unitis are both represented by a very thin succession. This setting can be regarded as the result of the low-angle normal faults developed during the middle Miocene extensional tectonics, that produced a strong delamination of the tectonic pile of units originated during the previous compressive evolution of the Apennine belt. This picture is coherent with the occurrences of the Palombini Shale or Santa Fiora Fm directly over the lowermost levels of the Tuscan Nappe (e.g. Palombini Shale over the Triassic Fms of the Tuscan Nappe; Brogi et alii, 2004b).

The results of the structural analysis indicates that the Ligurian and Sub-Ligurian Units are affected by a polyphase, complex deformation history consisting of several folding phases. The correlation among these phases in the different units is hampered because their boundaries are represented by low-angle normal faults developed during the middle Miocene extensional tectonics. These shear zones are deformed by open folds with subvertical axial plane and a km-long wavelenght that were developed during the D3 phase in Santa Fiora and Canetolo Units and D4 phase in Ophiolitic Unit. These folds can be probably related to the Tuscan Nappe megaboudinage developed during the extensional tectonics (Brogi, 2004a). A couple of low-angle normal faults with the same dip but with staircase trajectory resulted in the development of a megaboudin delimited at the top and bottom by two extensional shear zones. One side of the megaboudin is thus forced to rotate passively leading to a shape with two side with steep opposite dip. The overlying Ligurian and Sub-Ligurian were thus folded to adapt themselves to the shape of the underlying megaboundins.

The pre-D4 and pre-D3 phase deformations identified, respectively in the Ophiolitic Unit and in Santa Fiora and Canetolo Units can be referred to pre-middle Miocene time.

The more complex deformation history detected in the Ophiolitic Unit can be interpreted as achieved in the intraoceanic convergence and the subsequent continental collision in the Late Cretaceous-middle Eocene time span (Marroni et alii, 2010). Analogously to the Internal Ligurian Units of the Ligurian Apennines (Marroni, 1991; Marroni et alii, 2004; Meneghini et alii, 2007), the deformations related to the D1 and D2 phases recognized in the Ophiolitic Unit can be regarded as the record of the process developed in the accretionary wedge originated in the Ligure-Piemontese basin. This is suggested by the anchizone metamorphism (Franceschelli et alii, 1994) associated to D1 phase, developed before the thrusting of the Ophiolitic Unit over the External Ligurian and Sub-Ligurian Units.

About the D1 and D2 phases recognized in the Canetolo and Santa Fiora Units, the related deformations can be regarded as achieved during the closure of the Ligure-Piemontese basin and the subsequent inception of the continental collision.

6. CONCLUSIONS

The collected data indicate that the stratigraphic setting of the Ligurian and Sub-Ligurian Units in the Mt. Amiata has been strongly reworked by the extensional tectonics of middle Miocene age. Even if this tectonics has produced a strong delamination of all the successions, a detailed structural and stratigraphical analyses performed during the Regional Geological Map project integrated with those available from the existing literature allow to recognize the main features of these units.

The Sub-Ligurian units are represented by the Canetolo Unit whose succession consists of Argille e Calcari and Vico Fms of middle Eocene (NP15 Zone) age. The Santa Fiora Unit consists of Pietraforte Fm and Varicoloured Shales topped by the Santa Fiora Fm. The Pietraforte Fm show eteropic relationships with the Varicoloured Shales and both formations can be referred to ?Aptian to middle Coniacian whereas the age of the Santa Fiora Fm seems to span from late Coniacian-early Santonian (CC14 Zone) to middle-late Campanian (CC21-CC22 Zones). In turn, the Ophiolitic Unit is represented by scattered Middle-Late Jurassic ophiolites associated to Palombini

Shale spanning from late Hauterivian-early Barremian Zone CC5 to the early Aptian Zone CC7 of Sissingh (1977).

The results of the structural analysis indicates that all the Ligurian and Sub-Ligurian Units are affected by a polyphase, complex deformation history developed without metamorphic imprint (medium to high diagenetic conditions for the Canetolo and Santa Fiora Units) or under very low-grade metamorphism (anchizone for the Ophiolite Unit). This deformation history is regarded as achieved during the closure of the Ligure-Piemontese oceanic basin and the following continental collision that predate the middle Miocene extensional tectonics.

These features can be compared with the data available for the Ligurian and Sub-Ligurian Units cropping out in the Southern Tuscany and Ligurian Apennine. Particularly, the Santa Fiora and Ophiolitic Units can be correlated, respectively, with the Monteverdi Marittimo and Upper Ophiolitic Units cropping out in the Southern Tuscany. Concerning the Ligurian-Emilian Apennine, the same units can be correlated, respectively, with the Cassio and Bracco-Val Graveglia Units. These comparisons allow to state that the Ligurian and Sub-Ligurian Units are continuos with quite homogenous features across the whole Apennine belt.

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CAPTIONS

FIG.1 Tectonic sketch map of Tuscany (a) and tectonic sketch map of Monte Amiata area (b). The location of Monte Amiata area is shown in the tectonic sketch map of Tuscany.

FIG.2 Chronostratigraphic sketch of the Sub-Ligurian and Ligurian Units from Monte Amiata area.

FIG.3 Stratigraphic features of the succession from Canetolo Unit a) outcrop of Argille e Calcari Fm; b) outcrop of Vico Flysch; c) Photomicrograph of the fossil-bearing arenites from Vico Flysch; d) Photomicrograph of the arenites from Vico Flysch.

FIG.4. Photomicrographs of selected calcareous nannofossils recognized in the Argille e Calcari Fm. All specimens X 1200. 1) *Chiasmolithus gigas*, crossed nicols. Sample CDP50. 2) *Reticulofenestra dictyoda*, crossed nicols. Sample CDP46. 3) *Pseudotriquetrorhabdulus inversus*, crossed nicols. Sample CDP50. 4) *Sphenolithus furcatolithoides*, crossed nicols. Sample CDP50. 5) *Sphenolithus spiniger*, crossed nicols. Sample CDP48. 6) *Neococcolithes dubius*, crossed nicols. Sample CDP48. 7) *Discoaster barbadiensis*, parallel light. Sample CDP48. 8) *Discoaster saipanensis*, parallel light. Sample CDP48. 9) *Chiasmolithus grandis*, parallel light. Sample CDP51. 10) *Nannotetrina cristata*, parallel light. Sample CDP48. 11) *Nannotetrina alata*, parallel light. Sample CDP46. 12) *Nannotetrina pappii*, parallel light. Sample CDP48.

FIG.5. Stratigraphic distribution of calcareous nannofossil taxa recognized in the Argille e Calcari Fm.

FIG.6. Calcareous nannofossils zonal system with the main biohorizons, adopted to date the Argille e Calcari Fm, the Santa Fiora Fm, the Pietraforte Fm and Varicoloured Shale, and the Palombini Shale. The NP Zones are after Martini (1971), the CC Zones are after Sissingh (1977), the chronostratigraphic scheme is after Gradstein et al. (2012).

FIG.7. Structural features of Canetolo Unit a) F1 fold in the Argille e calcari Fm, b) F2 fold; c) stereonets of S0, A2 and A3 data from Canetolo Unit.

FIG.8. Stratigraphic features of the succession from Santa Fiora Unit: a) Pietraforte Fm. from Arenaceous and arenaceous-pelitic lithofacies of Pandeli et alii, (2005); b) outcrop of Santa Fiora Fm; c) Photomicrograph of arenites from Pietraforte Fm; d) Photomicrograph of marly limestone from Santa Fiora Fm.

FIG.9. Stratigraphic distribution of calcareous nannofossil taxa recognized in the Santa Fiora Fm.

FIG.10. Photomicrographs of selected calcareous nannofossils recognized in the Santa Fiora Fm. All specimens X 1200. 1) *Eprolithus floralis*, crossed nicols. Sample CDP80. 2) *Eiffellithus turriseiffelii*, crossed nicols. Sample CDP78. 3) *Helenea chiastia*, crossed nicols. Sample CDP80. 4) *Micula* sp., crossed nicols. Sample CDP80. 5) *Quadrum gartneri*, crossed nicols. Sample CDP68. 6) *Nannoconus* sp., crossed nicols. Sample CDP78. 7) *Retecapsa crenulata*, crossed nicols. Sample CDP67. 8) *Zeughrabdotus embergeri*, crossed nicols. Sample CDP77. 9) *Cylindralithus nudus* crossed nicols. Sample CDP68.

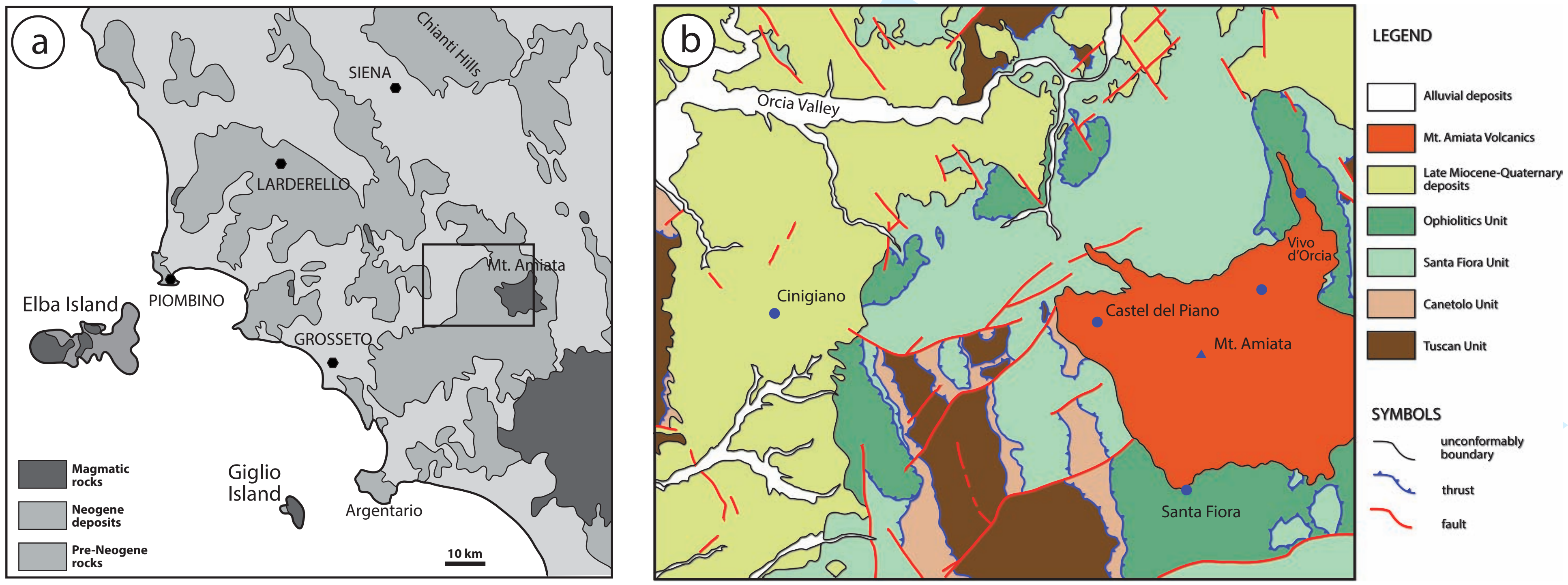
FIG.11. Structural features of the Santa Fiora Unit: a) F1 folds in the Santa Fiora Fm.; b) F2 meso folds in the Santa Fiora Fm (the boxed area corresponds to a; c) stereonets of S0, A2 and A3 data from Santa Fiora Unit;

FIG.12. Stratigraphic features of the succession from the Ophiolitc Unit: a) Carbonate turbidites from Palombini Shale; b) Siliciclastic turbidites from Palombini Shale.

FIG.13. Stratigraphic distribution of calcareous nannofossil taxa recognized in the Palombini Shale.

FIG.14. Photomicrographs of selected calcareous nannofossils recognized in the Palombini Shale. All specimens X 1200. 1) *Eprolithus floralis*, crossed nicols. Sample CDP93. 2) *Nannoconus colomii*, crossed nicols. Sample CDP94. 3) *Nannoconus steinmannii*, crossed nicols. Sample CDP94. 4) *Michrantolithus obtusus*, crossed nicols. Sample CDP92. 5) *Lithraphidites carniolensis*, parallel light. Sample CDP92. 6) *Assipetra terebrodentarius*, crossed nicols. Sample CDP91.

FIG.15. Structural features of the Ophiolitic Unit a) Photomicrograph of the relationshisp between S0, S1 and S3; b) Photomicrograph of antitaxial calcite vein; c) stereonets of S0, A2 and A4 data from Ophiolitic Unit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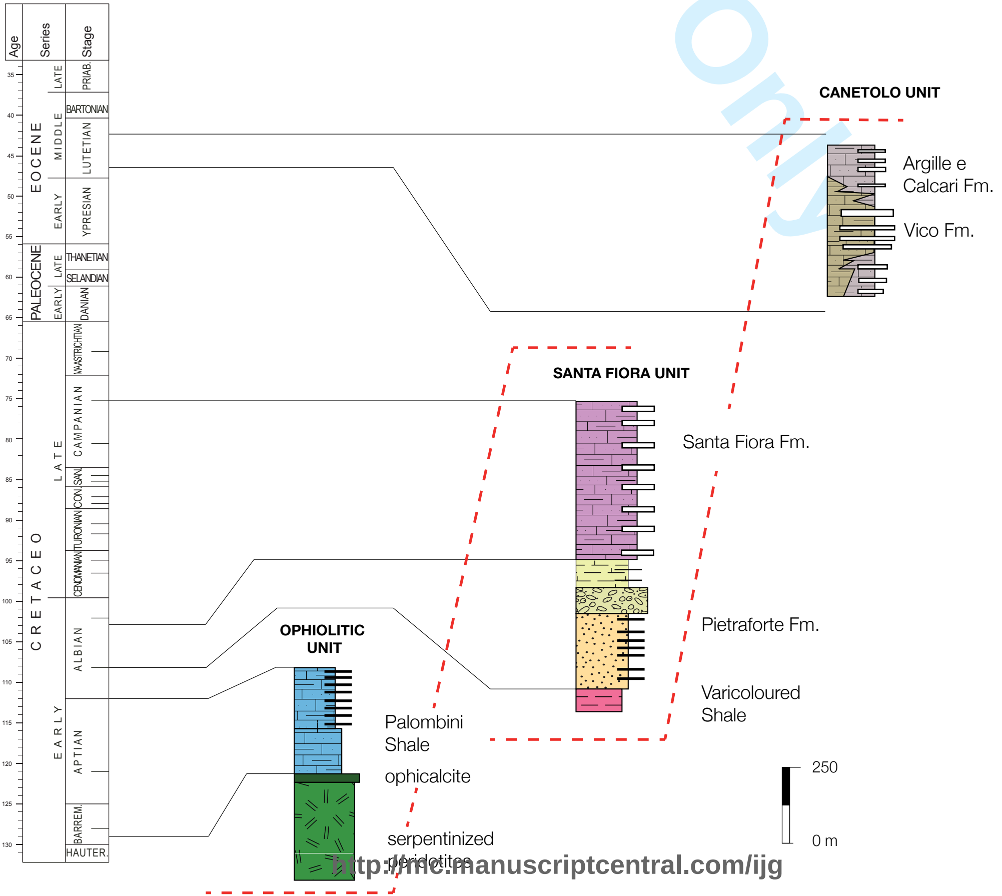
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CANETOLO UNIT
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Vico Fm.
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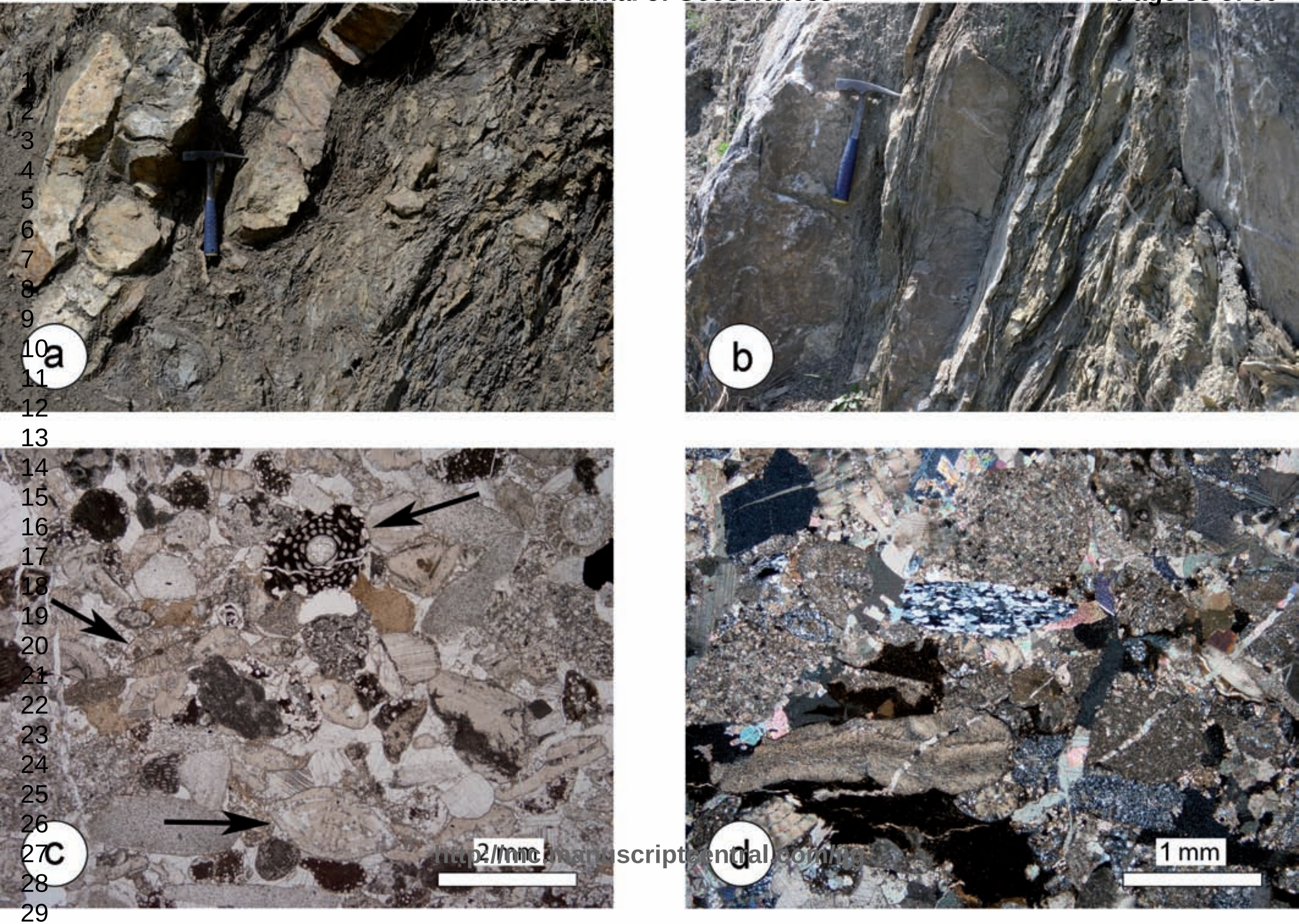
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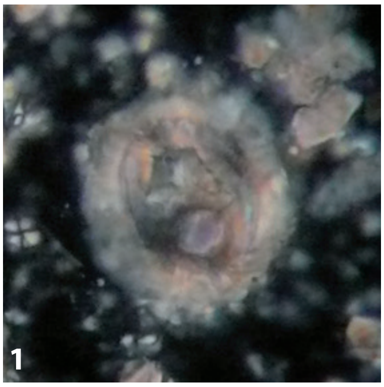
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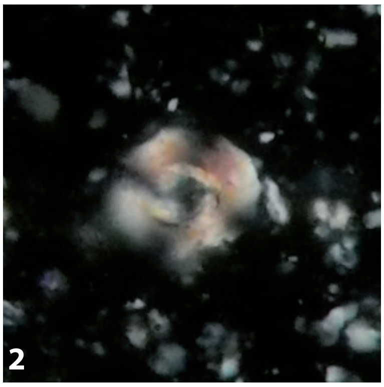
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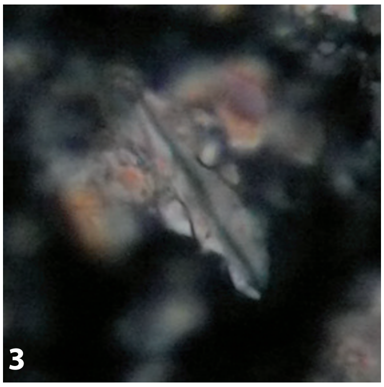
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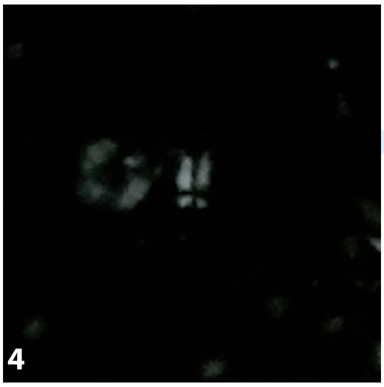
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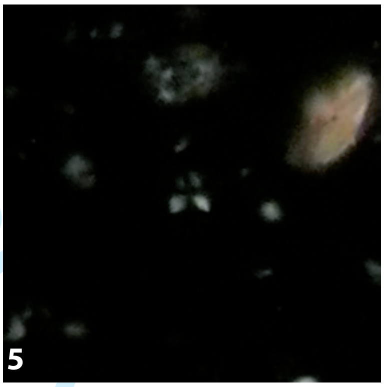
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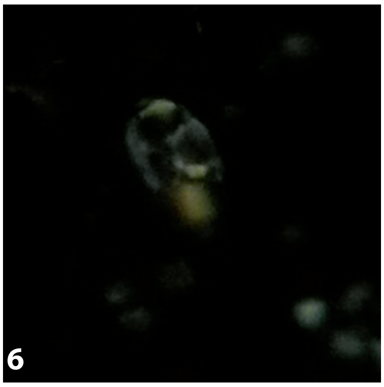
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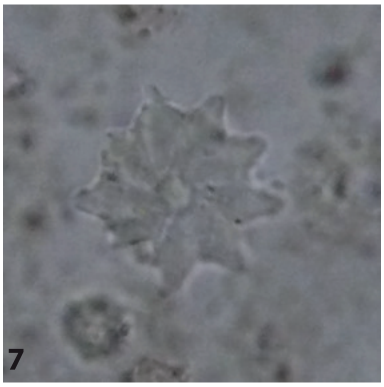
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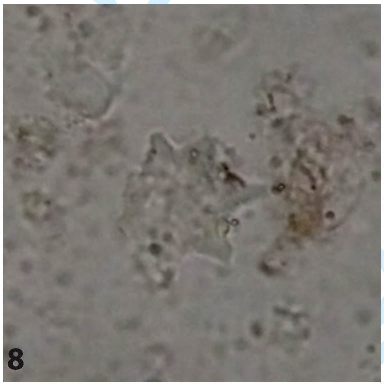
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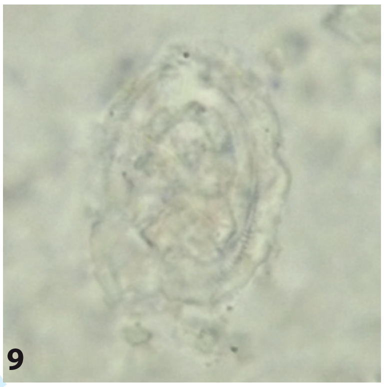
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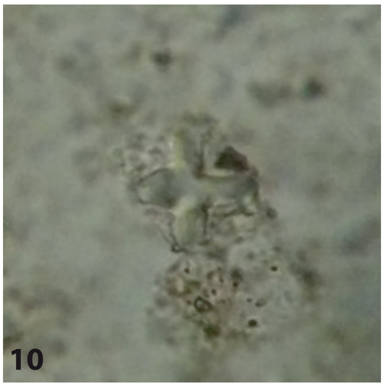
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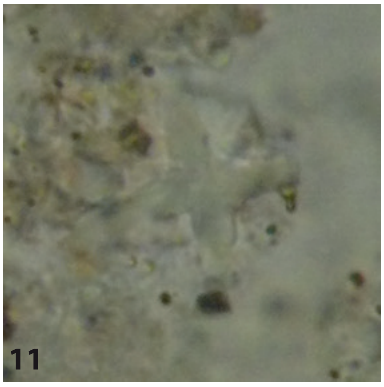
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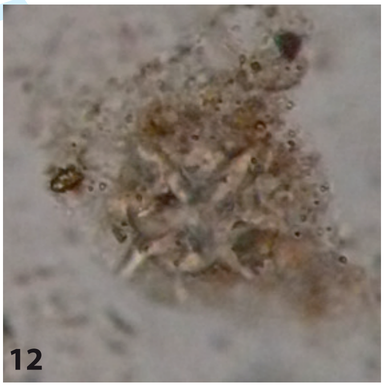
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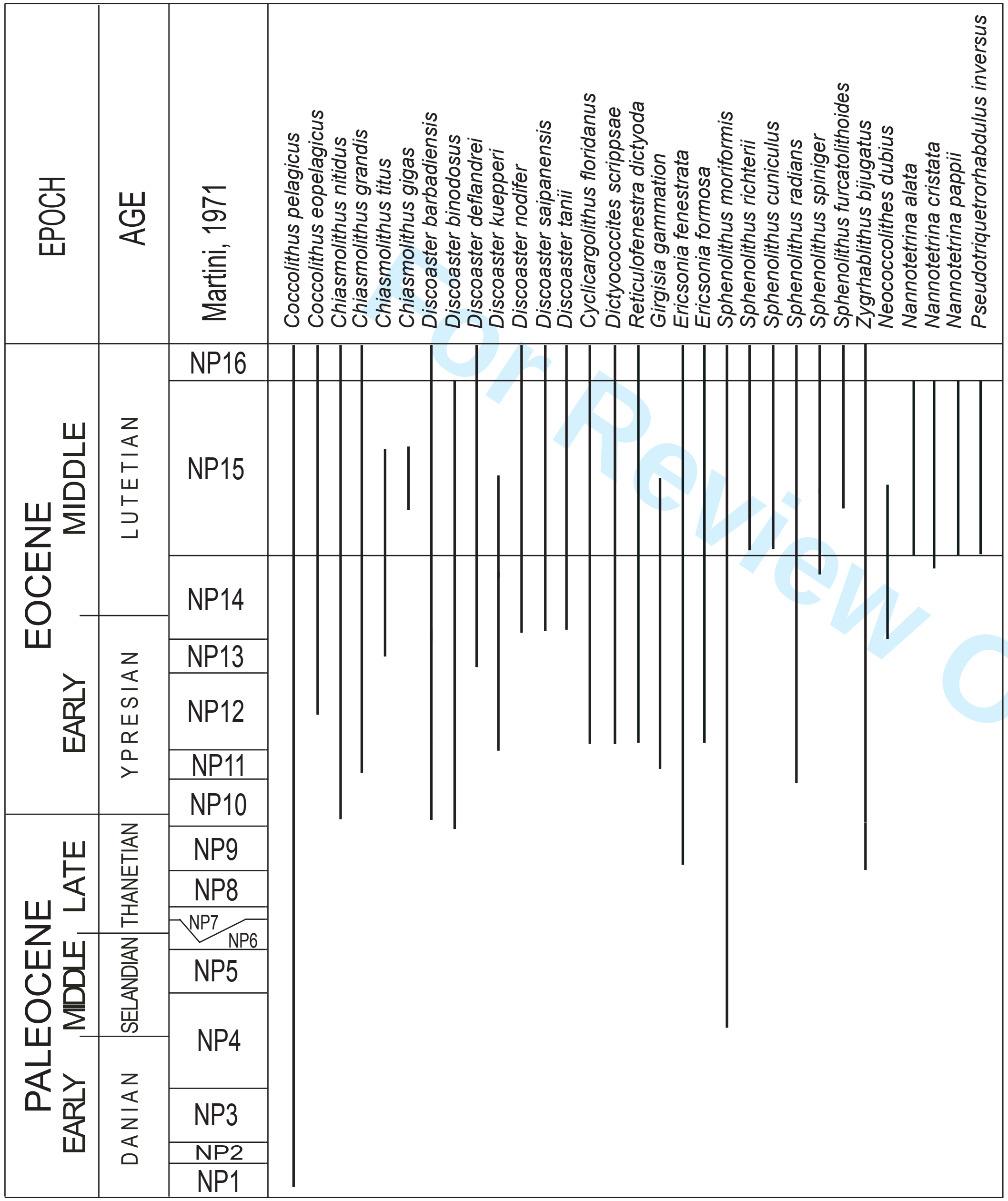
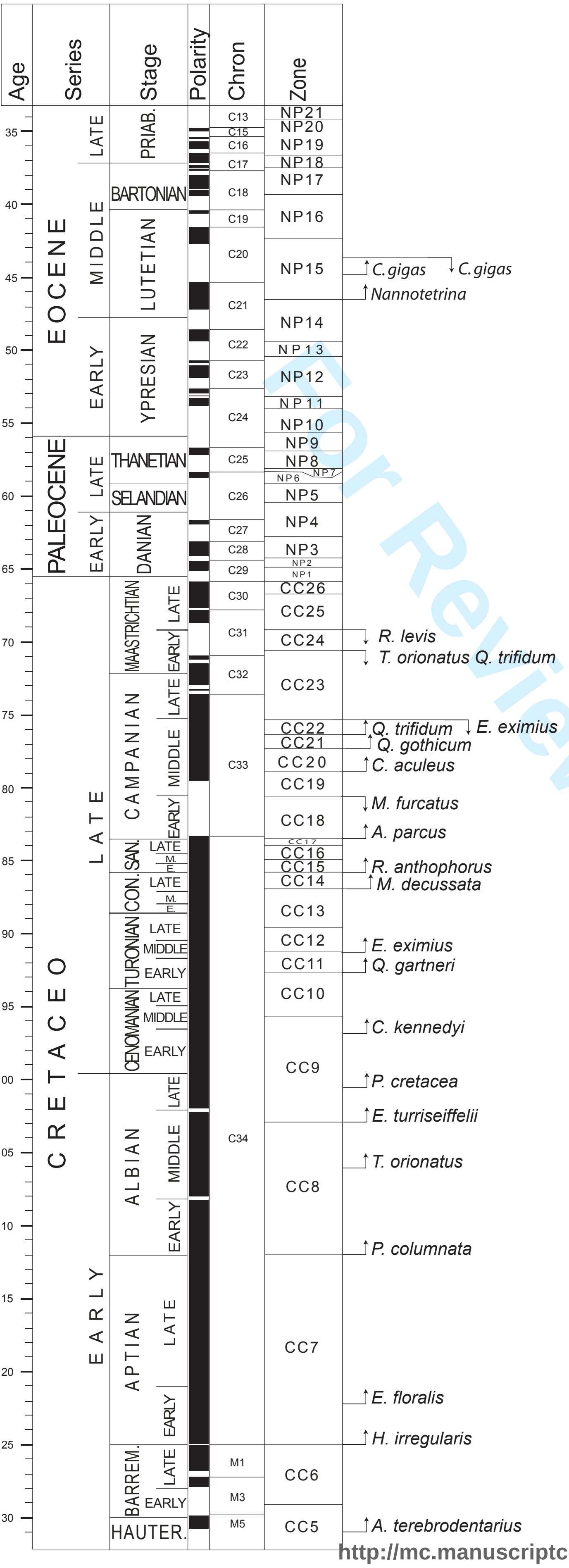
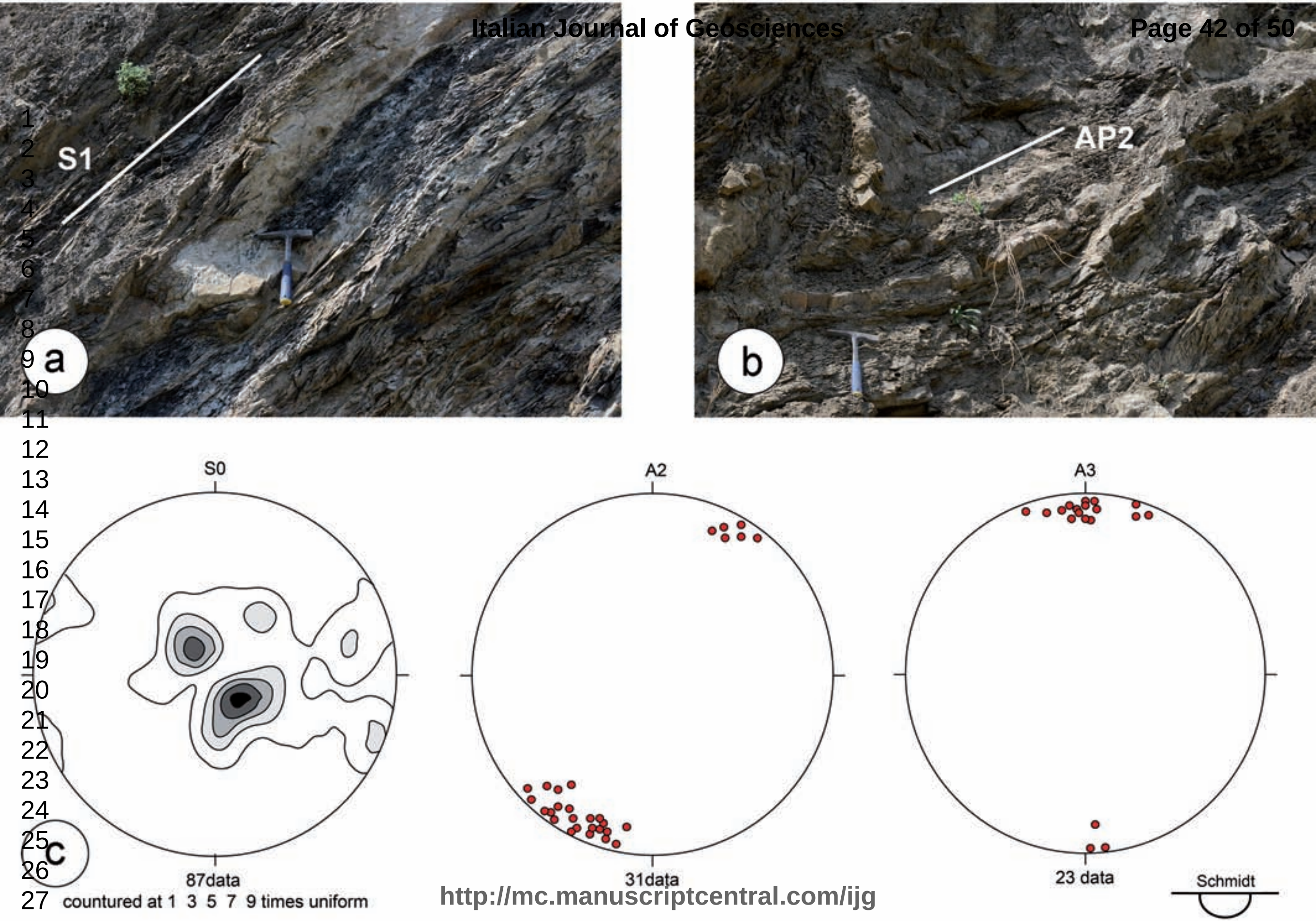
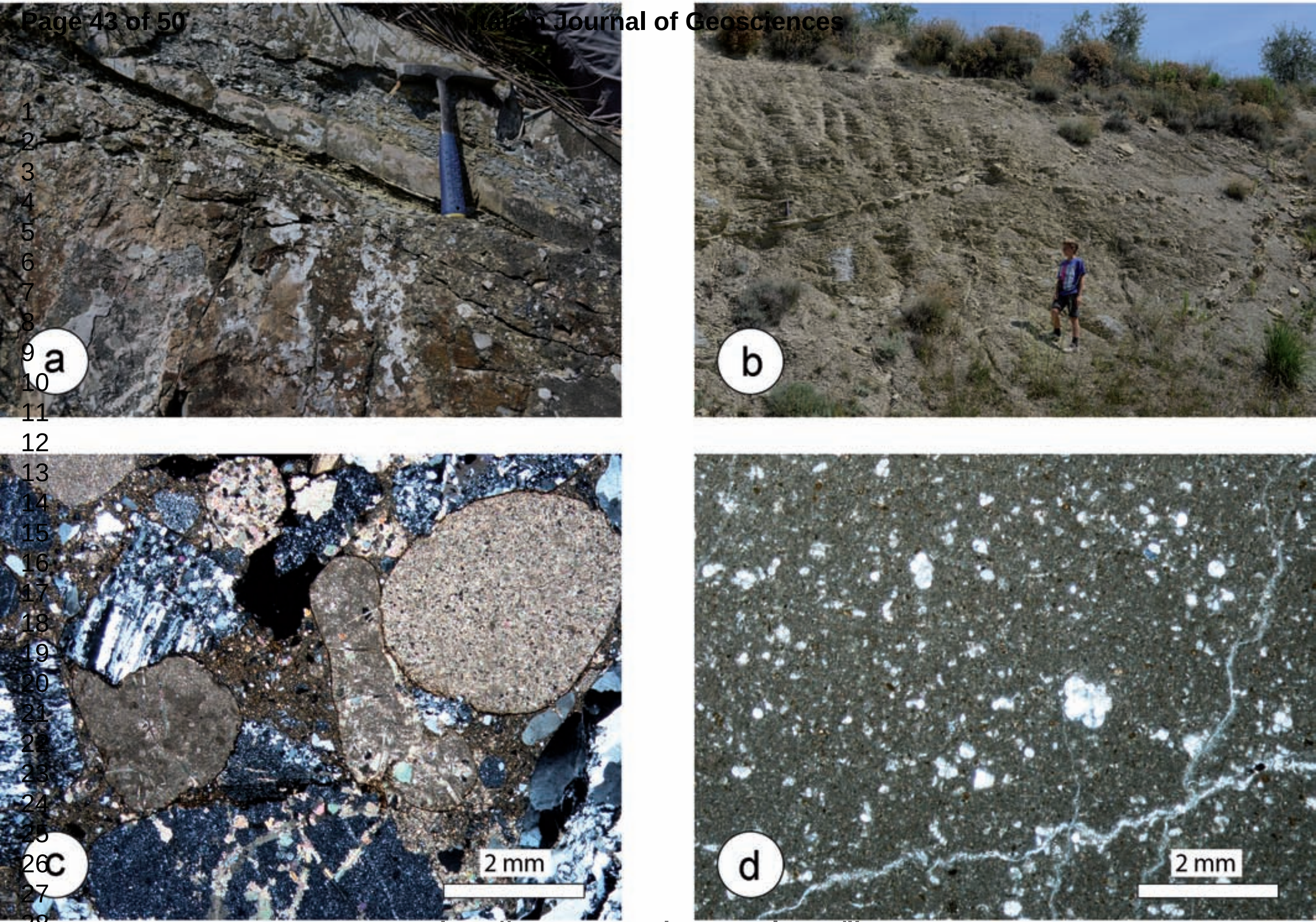
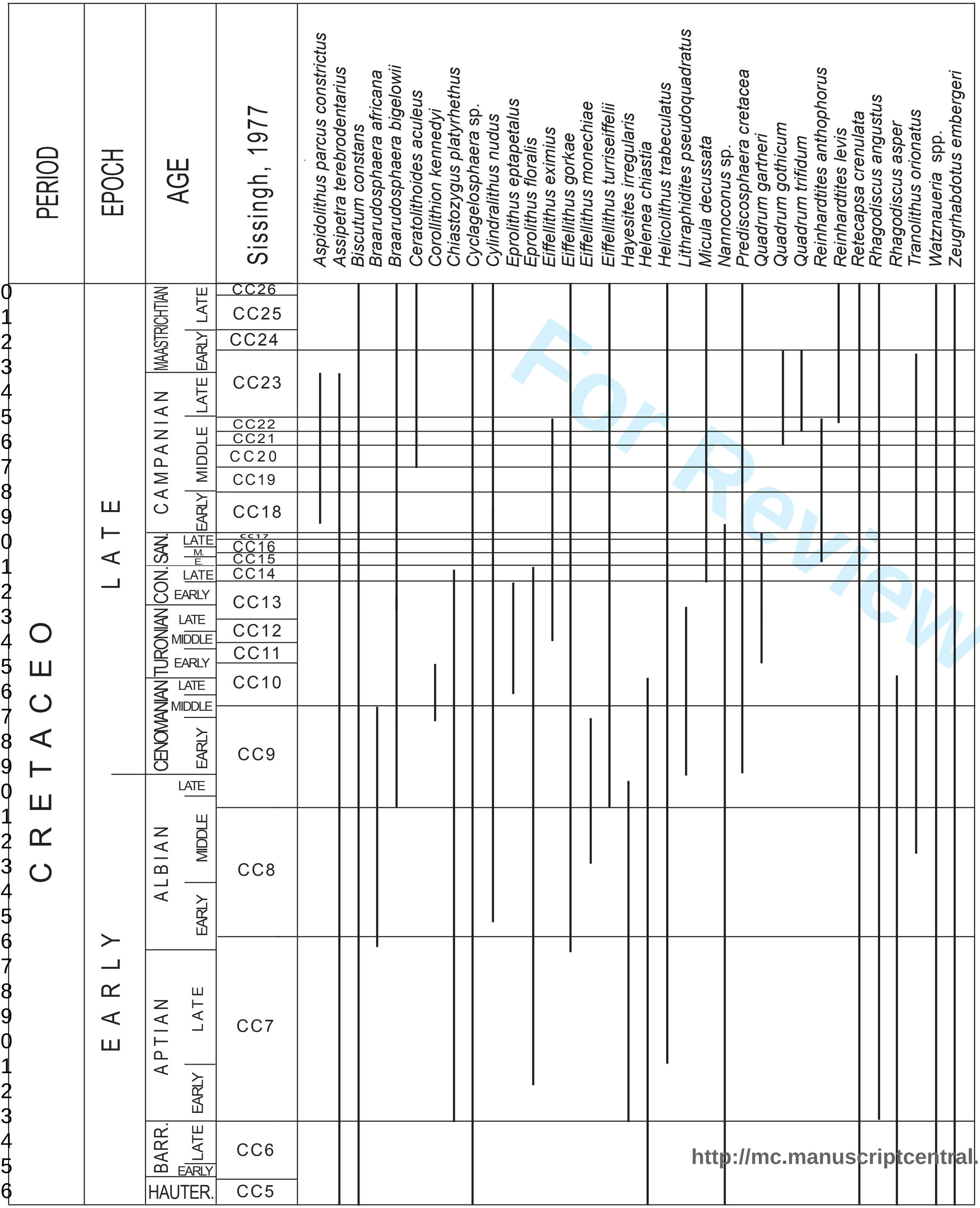

EPOCH
AGE
Martini, 1971
Coccolithus pelagicus
Coccolithus eopelagicus
Chiasmolithus nitidus
Chiasmolithus grandis
Chiasmolithus titus
Chiasmolithus gigas
Discoaster barbadiensis
Discoaster binodosus
Discoaster deflandrei
Discoaster kuepperi
Discoaster nodifer
Discoaster saipanensis
Discoaster tanii
Cyclicargolithus floridanus
Dictyococcites scrippsae
Reticulofenestra dictyoda
Girgisia gammation
Ericsonia fenestrata
Ericsonia formosa
Sphenolithus moriformis
Sphenolithus richterii
Sphenolithus cuniculus
Sphenolithus radians
Sphenolithus spiniger
Sphenolithus furcatolithoides
Zygrhablithus bijugatus
Neococcolithes dubius
Nannotetrina alata
Nannotetrina cristata
Nannotetrina pappii
Pseudotriquetrorhabdulus inversus
EOCENE
MIDDLE
EARLY
LUTETIAN
YPRESIAN
PALEOCENE
LATE
MIDDLE
EARLY
THANETIAN
SELANDIAN
DANIAN
NP16
NP15
NP14
NP13
NP12
NP11
NP10
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1


Age
Series
Stage
Polarity
Chron
Zone
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
EOCENE
LATE
MIDDLE
EARLY
PALEOCENE
LATE
EARLY
CRETACEO
LATE
EARLY
PRIAB.
BARTONIAN
LUTETIAN
YPRESIAN
THANETIAN
SELANDIAN
DANIAN
MAASTRICHTIAN
LATE
EARLY
CAMPANIAN
LATE
MIDDLE
EARLY
SAN.
LATE
M.
E.
CON.
LATE
M.
E.
TURONIAN
LATE
MIDDLE
EARLY
CENOMANIAN
LATE
MIDDLE
EARLY
ALBIAN
LATE
MIDDLE
EARLY
APTIAN
LATE
EARLY
BARREM.
LATE
EARLY
HAUTER.
C13
C15
C16
C17
C18
C19
C20
C21
C22
C23
C24
C25
C26
C27
C28
C29
C30
C31
C32
C33
C34
M1
M3
M5
NP21
NP20
NP19
NP18
NP17
NP16
NP15
NP14
NP13
NP12
NP11
NP10
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
CC26
CC25
CC24
CC23
CC22
CC21
CC20
CC19
CC18
CC17
CC16
CC15
CC14
CC13
CC12
CC11
CC10
CC9
CC8
CC7
CC6
CC5
C. gigas
C. gigas
Nannotetrina
R. levis
T. orionatus Q. trifidum
Q. trifidum
E. eximius
Q. gothicum
C. aculeus
M. furcatus
A. parcus
R. anthophorus
M. decussata
E. eximius
Q. gartneri
C. kennedyi
P. cretacea
E. turriseiffelii
T. orionatus
P. columnata
E. floralis
H. irregularis
A. terebrodentarius


S1
a
AP2
b
S0
87data
countured at 1 3 5 7 9 times uniform
A2
31data
A3
23 data
Schmidt
c


a
b
c
2 mm
d
2 mm


PERIOD
EPOCH
AGE
Sissingh, 1977
Aspidolithus parcus constrictus
Assipetra terebrodentarius
Biscutum constans
Braarudosphaera africana
Braarudosphaera bigelowii
Ceratolithoides aculeus
Corollithion kennedyi
Chiastozygus platyrhethus
Cyclagelosphaera sp.
Cylindralithus nudus
Eprolithus eptapetalus
Eprolithus floralis
Eiffellithus eximius
Eiffellithus gorkae
Eiffellithus monechiae
Eiffellithus turriseiffelii
Hayesites irregularis
Helenea chiastia
Helicolithus trabeculatus
Lithraphidites pseudoquadratus
Micula decussata
Nannoconus sp.
Prediscosphaera cretacea
Quadrum gartneri
Quadrum gothicum
Quadrum trifidum
Reinhardtites anthophorus
Reinhardtites levis
Retecapsa crenulata
Rhagodiscus angustus
Rhagodiscus asper
Tranolithus orionatus
Watznaueria spp.
Zeugrhabdotus embergeri
CRETACEO
LATE
EARLY
MAASTRICHTIAN
CAMPANIAN
SAN.
CON.
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARR.
HAUTER.
LATE
EARLY
MIDDLE
M.
E.
CC26
CC25
CC24
CC23
CC22
CC21
CC20
CC19
CC18
CC17
CC16
CC15
CC14
CC13
CC12
CC11
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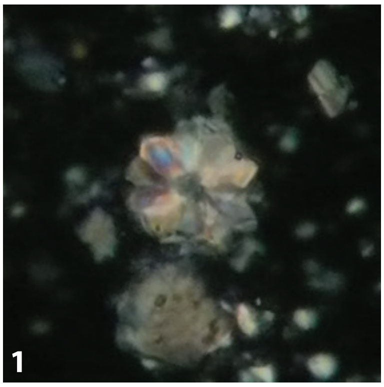
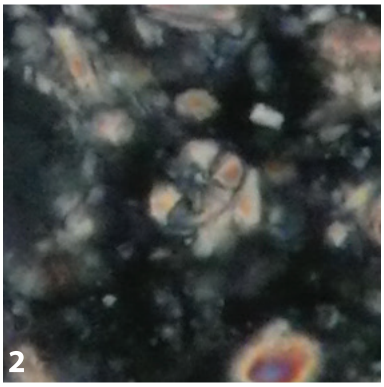
CC9
CC8
CC7
CC6
CC5


1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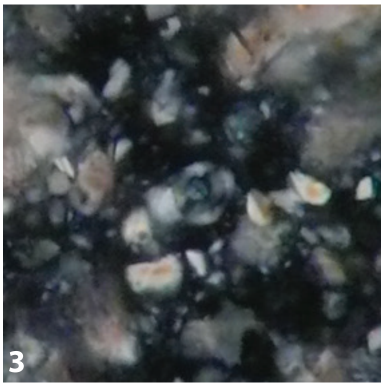
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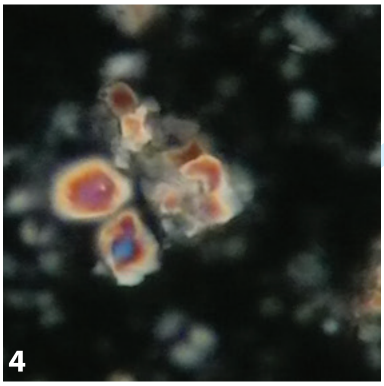
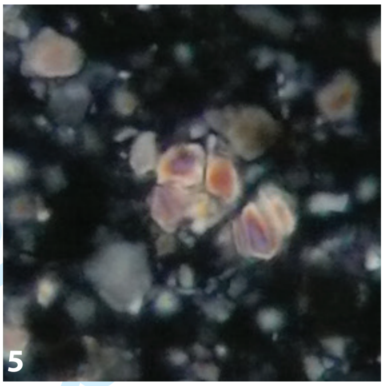

4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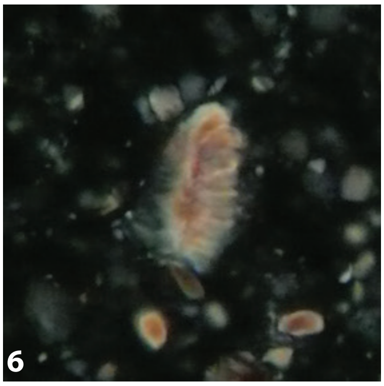
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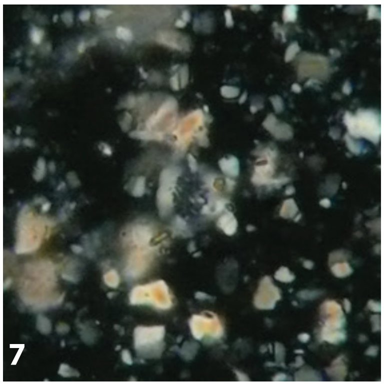
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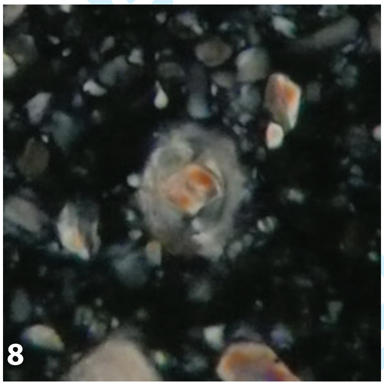
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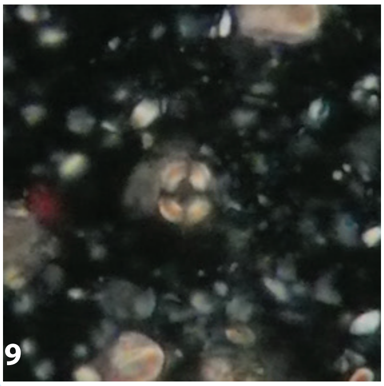
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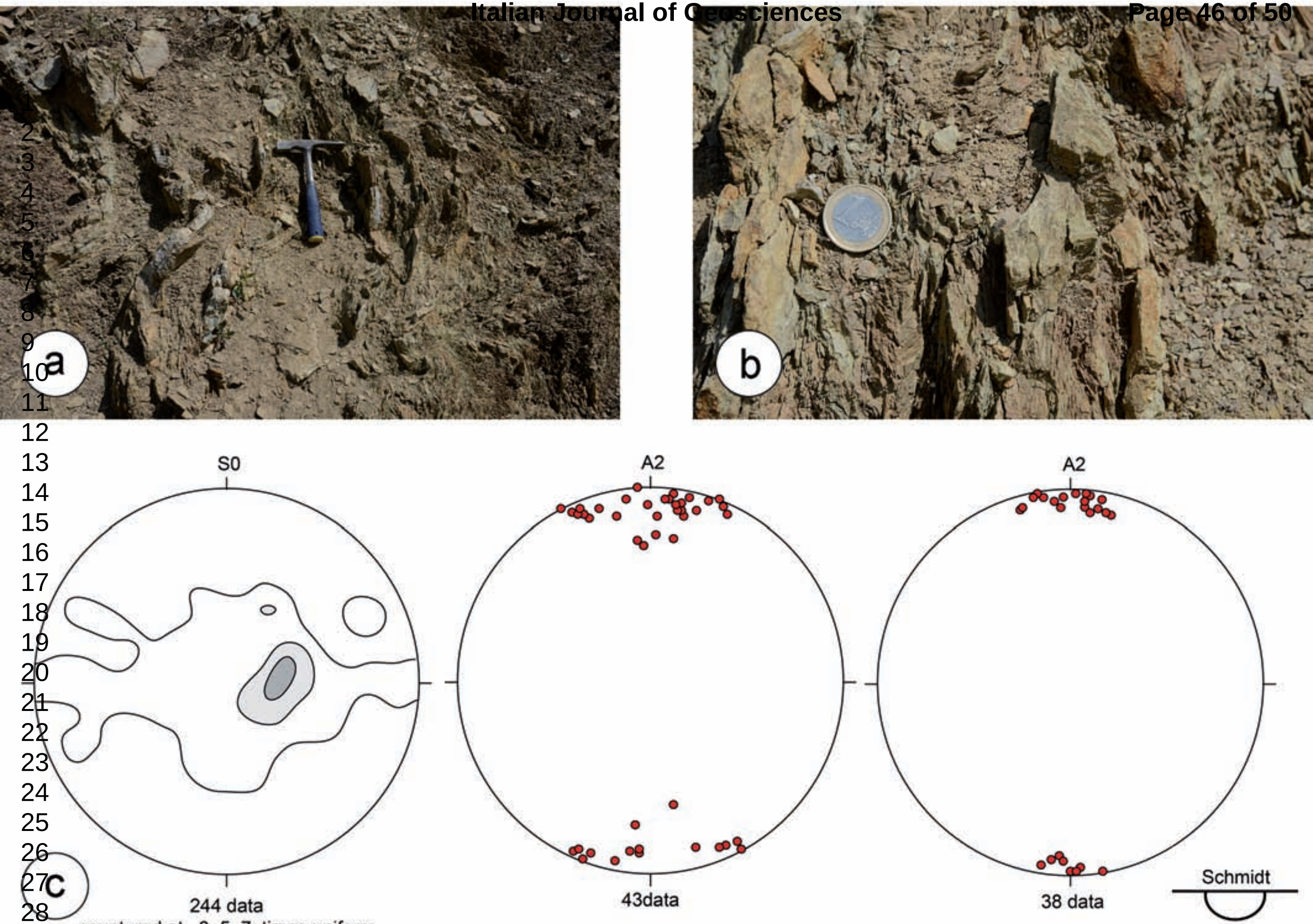
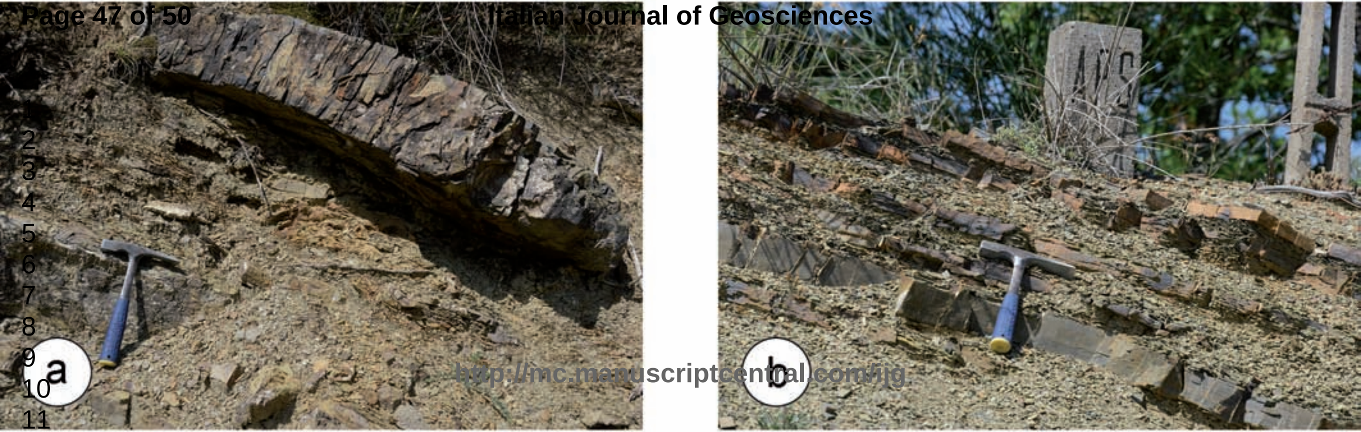
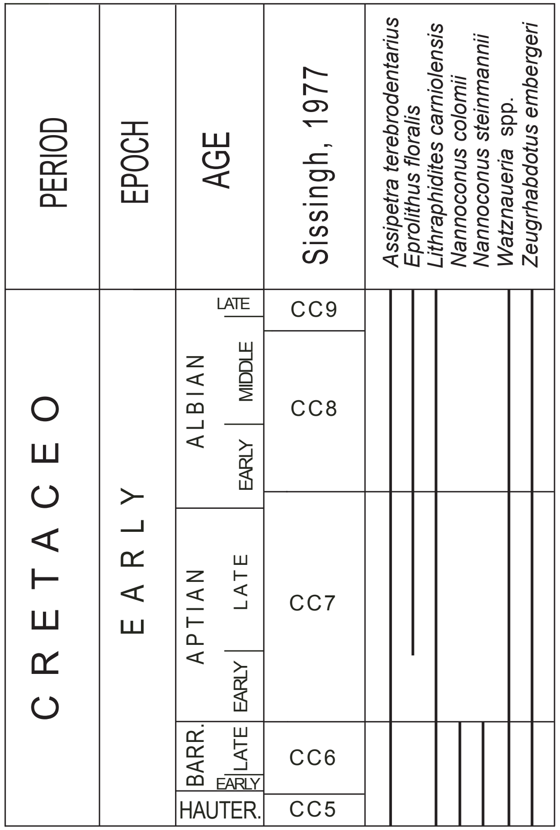
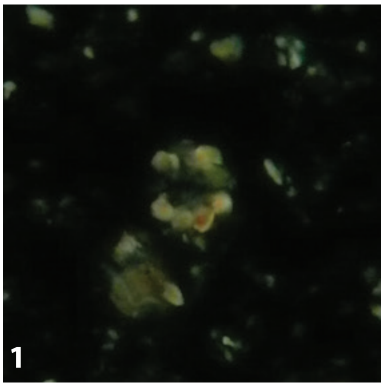

a
b
S0
A2
A2
244 data
countured at 3 5 7 times uniform
43data
38 data
Schmidt
c


a
b


PERIOD
EPOCH
AGE
Sissingh, 1977
Assipetra terebrodentarius
Eprolithus floralis
Lithraphidites carniolensis
Nannoconus colomii
Nannoconus steinmannii
Watznaueria spp.
Zeugrhabdotus embergeri
C R E T A C E O
E A R L Y
A L B I A N
LATE
MIDDLE
EARLY
A P T I A N
L A T E
EARLY
BARR.
LATE
EARLY
HAUTER.
CC9
CC8
CC7
CC6
CC5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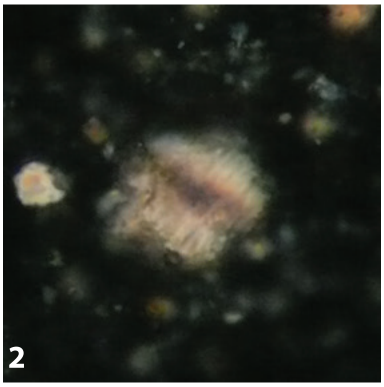
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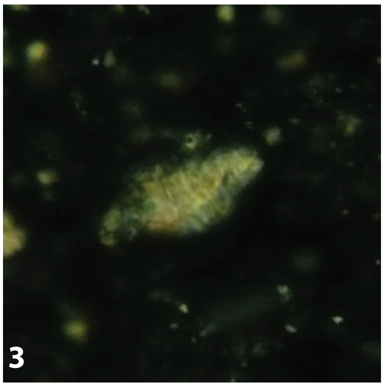
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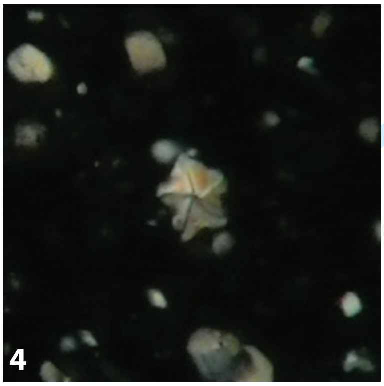
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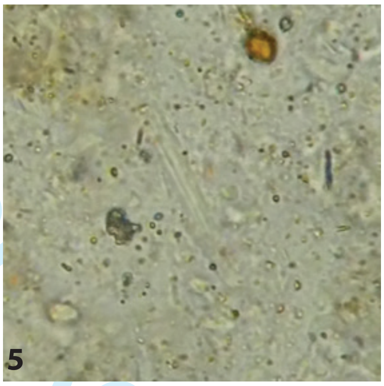
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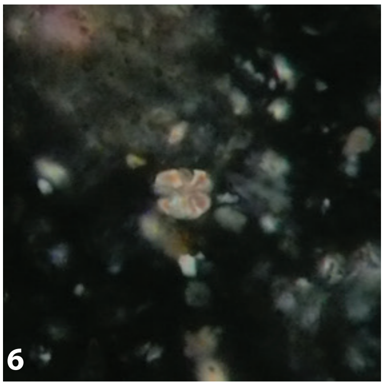
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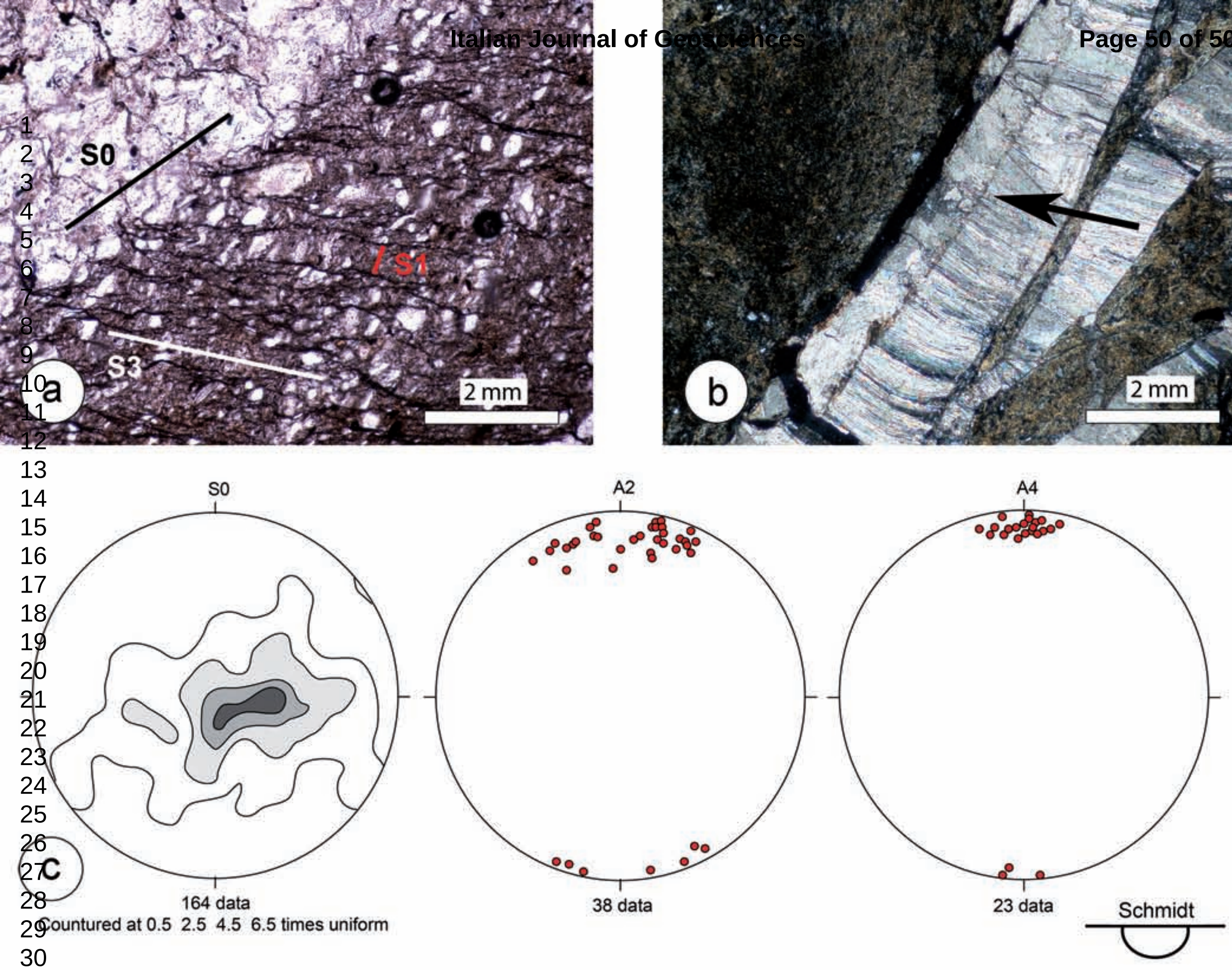
S0
S1
S3
a
2 mm
b
2 mm
c
S0
A2
A4
164 data
Countured at 0.5 2.5 4.5 6.5 times uniform
38 data
23 data
Schmidt