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Ligurian-derived olistostrome in the Pseudomacigno Formation of the Stazzema Zone (Alpi Apuane, Italy). Geological implications at regional scale

ETTA PATACCA (*), PAOLO SCANDONE (*), PAOLO CONTI (**), (***), SERGIO MANCINI (***) & GIOVANNI MASSA (***)

ABSTRACT

In the Stazzema Zone (southern part of the Alpi Apuane tectonic window) an olistostrome of kilometric extent (here informally called Ricavo olistostrome) incorporating blocks and slides of Lower Cretaceous limestones referable to the "Argille a Palombini" Formation of the Internal Ligurian Units forms a well-defined lens-shaped body in the upper portion of the Pseudomacigno Formation. The Pseudomacigno Formation is an Oligo-Miocene siliciclastic foredeep deposit making up the upper portion the Alpi Apuane metamorphic sequence. In spite of the greenschist metamorphic imprint of the sequence, the exotic limestones included in the olistostrome have locally escaped recrystallization so that their primary depositional texture and microfossil content are still recognizable. The microfacies of these limestones are represented by mudstones/wackestones with abundant calcitized radiolarians and sponge spicules associated with rare calpionellids and some planktonic forams indicative of the Valanginian. The occurrence of exotic materials derived from the Internal Ligurian Units in the Pseudomacigno Formation is consistent with the current model of forward migration of the thrust belt-foredeep system in the Northern Apennines according to which the tectonic transport of the Ligurian/Subligurian Nappes was accompanied by the emplacement of olistostromes in the flysch deposits. The presence of an olistostrome derived from the Ligurian Nappes in the Pseudomacigno Formation contributes in a roundabout way to highlight some contradictions existing between the 27 Ma age of metamorphism of the Alpi Apuane Unit obtained from radiometric measurements, widely accepted in the literature, and the regional paleogeographic model currently adopted by the Apennine geologists. The mere presence of Ligurian-derived materials in the Pseudomacigno Formation, in fact, establishes new constraints that make a 27 Ma age of the metamorphic peak incompatible with the paleogeographic reconstruction of the Northern Apennines that relocates the domain of the metamorphic Tuscan Units east of the original domain of the Tuscan Nappe. Following this restoration, ages of metamorphism not older than 13-14 Ma would be expected.

KEY WORDS: *Olistostrome, "Argille a Palombini", Pseudomacigno, Stazzema Zone, Alpi Apuane Unit.*

INTRODUCTION

Mass-transport-related chaotic bodies including exotic blocks older than the host deposit (olistostromes and olistoliths *sensu* FLORES, 1955) have been recognized in the Oligo-Miocene foredeep deposits of the Northern Apennines since more than fifty years (e.g. ELTER & SCHWAB, 1959). A quite exhaustive review is available in ABBATE *et alii* (1970). In the Northern Apennines, olistostromes form discrete sedimentary units embedded in the Oligo-Miocene siliciclastic flysch deposits of the Tuscan Nappe (see among many others ABBATE & SAGRI, 1970; CASTELLUCCI & CORNAGGIA, 1980; BRUNI *et alii*, 1994; PANDELI *et alii*, 1994; LUCENTE & PINI, 2008), as well as in more external, younger terrigenous deposits (e.g. Monte Falterona and Marnoso-Arenacea Formations). The chaotic emplacement of allochthonous materials in the Tertiary foredeep deposits of the Northern Apennines has been usually considered an herald of the arrival of the Ligurian and Subligurian Nappes in the external depositional domains (precursory olistostromes *sensu* ELTER & TREVISAN, 1973). The importance of these mass-wasting complexes has been stressed by PINI *et alii* (2004), LUCENTE & PINI (2008), CAMERLENGHI & PINI (2009) and FESTA *et alii* (2010) who have evidenced their significance for the reconstruction of the time-space migration of the thrust belt-foredeep system at a regional scale.

Aim of this paper is to document the recovery of Lower Cretaceous exotic materials included as olistostrome in the metamorphic flysch deposits of the Alpi Apuane Unit cropping out in the Stazzema region, one of the most complex areas of the Alpi Apuane in terms of structural features (see ZACCAGNA, 1894, 1932; NARDI, 1963; GIGLIA, 1967; TREVISAN *et alii*, 1968, 1971; CARMIGNANI & GIGLIA, 1983; CONTI *et alii*, 2010). The olistostrome, here informally called Ricavo olistostrome, is made up of slides and blocks of slightly recrystallized Lower Cretaceous calcilutites dispersed in a dark-grey metapelite/metasiltite matrix and forms a well-defined lens-shaped sedimentary body in the Oligo-Miocene metasediments of the Pseudomacigno Formation. The Pseudomacigno (the name was coined by SAVI, 1832) is the youngest lithostratigraphic unit of the Alpi Apuane sequence and is considered the metamorphic equivalent of the Oligo-Miocene Macigno Formation, a siliciclastic flysch deposit making up the upper portion of the non-metamorphic (or anchimetamorphic, see CERRINA FERONI *et alii*, 1983; CAROSI *et alii*, 2003) Tuscan Nappe. In spite of the greenschist metamorphic imprint characterizing the Alpi Apuane Unit (BONATTI, 1938; MOLLI *et alii*, 2002 and references therein), the exotic micritic limestones included in the olistostrome have locally escaped pervasive recrystallization, so that their original depositional texture and microfossil content are still recognizable. In this paper we shall describe the position of the

(*) Dipartimento di Scienze della Terra dell'Università di Pisa, Via Santa Maria, 53 - 56100 Pisa. Corresponding author: Paolo Scandone scandone@dst.unipi.it; Tele-phone +39 050 2215850.

(**) Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente dell'Università di Siena, Via Laterina, 8 - 53100 Siena.

(***) Centro di Geotecnologie dell'Università di Siena, Via Vetri Vecchi, 34 - 52027 San Giovanni Valdarno (Arezzo).

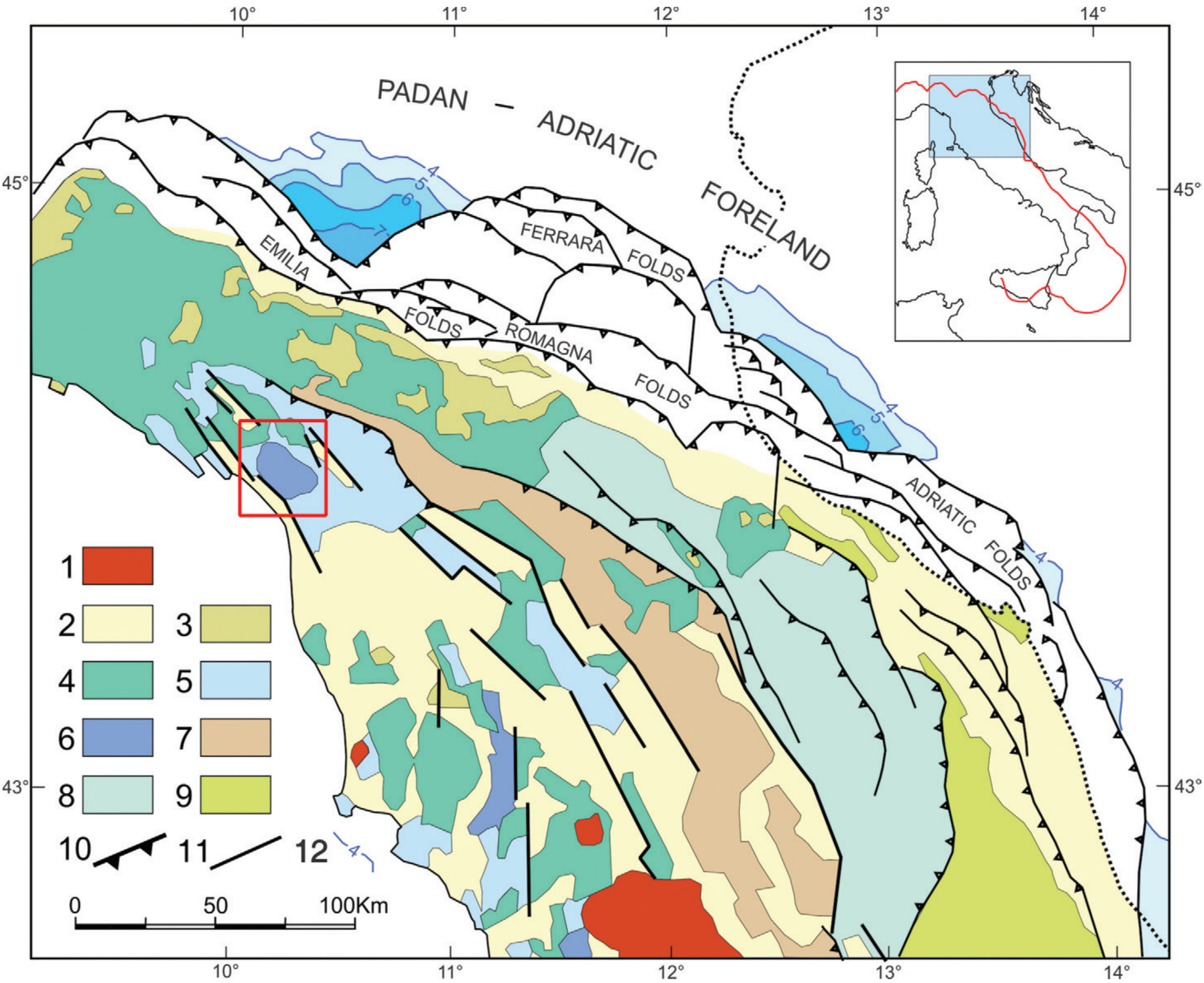

Fig. 1 - Structural map of the Northern Apennines (simplified from CNR-Progetto Finalizzato Geodinamica, 1990). The red box indicates the area represented in fig. 2: 1) Neogene-Quaternary volcanites and plutonites; 2) Uppermost Miocene (Messinian) to Quaternary deposits unconformably overlying the outer margin of the Apennines and filling intermontane basins; 3) Oligocene to Upper Miocene deposits unconformably overlying the Ligurian Units (Epiligurian Auct.); 4) Ligurian and Sub-Ligurian Units; 5) Tuscan Nappe; 6) Metamorphic Tuscan Units; 7) Falterona-Trasimeno Unit; 8) Romagna-Umbria-Marche Units; 9) External Marche Units; 10) Major thrust ramps on the surface and in subsurface; 11) Normal faults and subordinate strike-slip faults; 12) Isobaths of the base-of-Pliocene in the Padan-Adriatic Foreland.

olistostrome and the microfacies of the exotic blocks, interpreted as derived from the Internal Ligurian Units. Finally, we shall discuss the implications on the age of metamorphism of the Alpi Apuane Unit arising from the occurrence of Ligurian-derived materials in the Pseudomacigno Formation.

GEOLOGICAL OUTLINES OF THE NORTHERN APENNINES

The Northern Apennines are a segment of mountain chain around 500 kilometres long and 200 kilometres wide composed of a stack of thrust sheets off-scraped from oceanic and continental lithosphere. As a whole, they form an arc-shaped structure convex towards the Padan-Adriatic Foreland (fig. 1). The highest nappes of the tectonic edifice are represented by the Ligurian Units (Abbate & Sagri, 1970), which are divided into Internal and External Ligurian Units (Elter, 1975). Apennine geologists usually separate two units or two groups of units having the same name with the adjectives "internal" and "external" referring to the position of the original depositional domains with respect to the present-day foreland region. In this sense, the Internal Ligurian Units are classically considered to have been derived from an oceanic domain located westward of the External Liguride Domain. The Internal Ligurian Units are constituted of Middle-Upper Jurassic ophiolites overlain by Upper Jurassic-Lower Paleocene deep-marine deposits. The External Ligurian Units consist of well-bedded thick sequences of calcareous turbidites of Late Cretaceous-Middle Eocene age (Helmintoid Flysch *Auct*.) partly overlying a chaotic basal complex containing blocks and slides of ophiolitic rocks. These units have possibly derived from an ocean-continent transitional domain bordering Adria, i.e. the African Promontory of ARGAND (1924). Both Ligurian Units, unconformably covered by Eocene-Miocene thrust-top deposits (Epiligurian Units of the geological literature), tectonically overlie the so-called Sub-Ligurian or Canetolo Unit (CERRINA FERONI *et alii*, 2002, and references therein). The latter consists of a succession of calcareous-shaly basinal resediments and siliciclastic to volcaniclastic turbidites ranging in age from the Late Cretaceous to the Oligocene/Lower Miocene. Several uncertainties exist on the age (Oligocene?; Lower Miocene?) and the depositional setting of the upper portion of this sequence (foredeep flysch deposits?; unconformable thrust-top deposits?). The Ligurian and Sub-Ligurian Units tectonically overlie the Tuscan Nappe, which in turn covers the metamorphic Tuscan Units represented by the Massa and Alpi Apuane Units (see regional distribution of these units in CNR-PROGETTO FINALIZZATO GEODINAMICA, 1990). According to the paleogeographic model currently adopted by the Apennine geologists, the Tuscan Nappe has derived from a depositional domain (Internal Tuscan Domain) located west of the original domains of the Massa and Alpi Apuane Units (External Tuscan Domains). The same model relocates the External Tuscan Domain west of the Romagna-Umbria-Marche Domains (see among many others ELTER *et alii*, 1960; DALLAN NARDI & NARDI, 1972; CARMIGNANI *et alii*, 2001; ELTER *et alii*, 2003). Apart from the Massa Unit, where no terms younger than the Late Triassic (Carnian) have been preserved, the Tuscan Nappe, the Alpi Apuane Unit and the Romagna-Umbria-Marche Units have comparable Meso-Cenozoic sedimentary sequences. These sequences are represented by Upper Triassic-lowermost Jurassic shallow-marine carbonates followed by carbonate and siliceous basinal deposits, ending with siliciclastic flysch sequences. The onset of the siliciclastic sedimentation becoming younger when we move from the Internal Tuscan Domain (Upper Oligocene Macigno Formation) towards the easternmost foredeep basin (Upper Pliocene Porto Garibaldi Formation along the Adriatic coast) marks the progressive incorporation of foreland realms in the Apennine foredeep basin. Intermediate steps of this foredeep migration, which follows the flexure-hinge retreat of the lower plate, are represented by the Upper Oligocene-Lower Miocene Pseudomacigno Formation in the External Tuscan Domain, the Lower Miocene Falterona-Trasimeno Sandstones in the homonymous domain, the Middle-Upper Miocene Marnoso-Arenacea Formation in the Romagna-Umbria and Internal Marche Domains, the Messinian Laga Formation in the External Marche Domain and finally by the Upper Messinian-Lower Pliocene Fusignano Formation and the Lower Pliocene Porto Garibaldi Formation in the Ferrara-Adriatic Domains (PATACCA *et alii*, 1990, 1993 and references therein). In turn, the progressive incorporation of the foredeep/foreland domains into the Apennine mountain chain is temporally constrained, for every tectonic unit, by the age of the flysch deposits involved in the orogenic transport and by the age of the older thrust-top deposits unconformably overlying the tectonic units.

The deep structure of the Northern Apennines is badly known with the exception of the external areas (Padan margin and Emilia, Romagna, Ferrara and Adriatic fold belts), which has been extensively investigated by hydrocarbon exploration. In correspondence to the Apennine foothills, the base thrust of the orogenic system has been recognized at depths exceeding 10 kilometres (see CNR-PROGETTO FINALIZZATO GEODINAMICA, 1990). In the northern part of the mountain chain the Romagna-Umbria thrust-and-fold belt disappears beneath the Ligurian-Subligurian nappes, but its cylindrical continuation towards the NW is quite probable, as suggested by commercial reflection seismic profiles. Moving towards the south, the Romagna-Umbria belt is tectonically overlain by the Falterona-Trasimeno Unit, with a well-exposed contact roughly following the Apennine watershed. The Falterona-Trasimeno Unit, in turn, is overlain by the Tuscan Nappe. Along the Tyrrhenian slope of the Apennines, the Tuscan Nappe tectonically covers the Tuscan metamorphic units (Massa and Alpi Apuane Units). The geometric/kinematic relationships between the Tuscan metamorphic units and the Falterona-Trasimeno Unit are unknown. We do not know whether the metamorphic Tuscan Units represent allochthonous sheets underlain by more external non-metamorphic imbricates, possibly including elements of the Falterona-Trasimeno Unit, or they represent a core complex (Carmignani & Kligfield, 1990) floored by a crystalline basement moderately involved in the Neogene compression, as recently suggested by MOLLI (2008). In the first case, the external units would form a convex-up, buried duplex system in correspondence to the Alpi Apuane window. This is our preferred hypothesis. At the state of the art, anyway, every model of the deep structure of the Northern Apennines will represent a mere opinion until reliable NVR seismic profiles across the whole mountain chain will be available.

THE STAZZEMA ZONE

The study area is located in the southern part of the Alpi Apuane tectonic window (fig. 2) and belongs to the so-called Stazzema Zone. The structural architecture of the Stazzema Zone is characterized (see CONTI *et alii*, 2010) by a complex stack of tectonic slices mainly made up of upper Oligocene-lower Miocene metapsammites and metapelites of the Pseudomacigno Formation (fig. 3). Subordinate lithotypes are represented by Paleozoic phyllites (referable to the Variscan basement), Upper Triassic sparry dolomites (Grezzoni Formation) associated with thin veneers of Lower Jurassic marbles (Apuane Marble) and cherty metalimestones (Metacalcari con Selce Formation), and finally by Cretaceous-lower Oligocene metalimestones and metapelites (Scisti Sericitici Formation). Specific deformational features of this area are the occurrence of repeated stacks of tectonic slices, the overall severe thinning of the slices themselves and the almost systematic absence of the Middle-Upper Jurassic and Lower Cretaceous portions of the Alpi Apuane stratigraphic sequence only locally preserved as small and stretched lenticular bodies in correspondence to ductile shear zones. This peculiar tectonic architecture has been considered by some authors representative of a Schuppenzone originated by compressional processes (e.g. TREVISAN, 1962; NARDI, 1963; GÜNTHER & WALLBRECHER, 1979). Other authors (CARMIGNANI *et alii*, 1999; MASSA, 2005 and references therein), on the contrary, have related the described tectonic structures to kilometric isoclinal folds generated in an extensional regime during

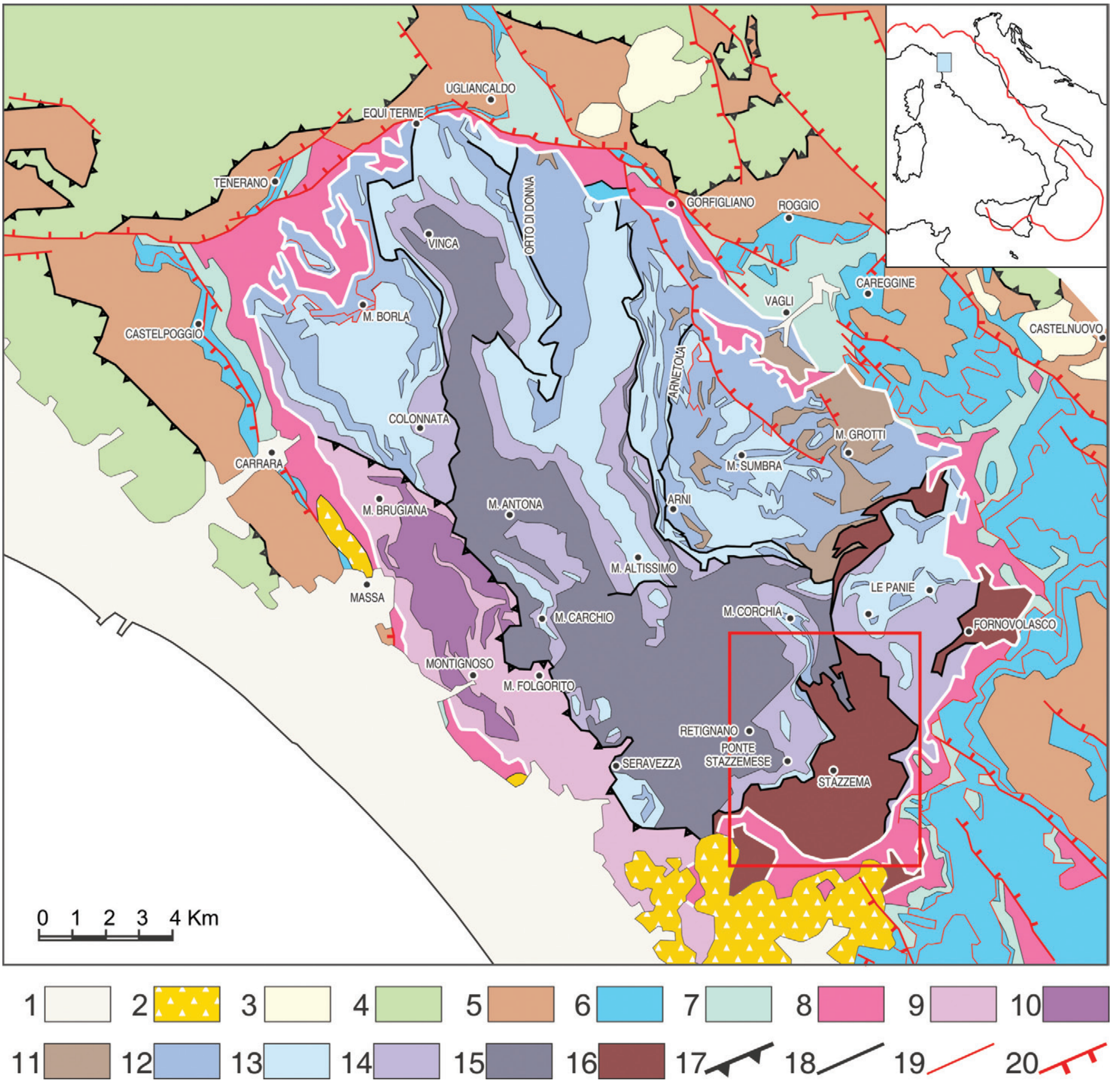

Fig. 2 - Simplified geological-structural map of the Alpi Apuane region showing the geometrical relationships between the metamorphic Tuscan Units (Alpi Apuane and Massa Units), the Tuscan Nappe and the Ligurian plus Subligurian Nappes (modified after Carmignani *et alii*, 2000). The red box indicates the area represented in fig. 3: 1) Upper Pleistocene-Holocene continental and coastal deposits; 2) Lower Pleistocene (Santernian) subaerial talus breccias (Pietrasanta Megabreccia); 3) Villafranchian (upper Pliocene-lower Pleistocene) deposits of intramontane basins; 4) Ligurian and Subligurian Nappes. 5-8 Tuscan Nappe: 5) upper Oligocene-lower Miocene siliciclastic flysch deposits (Macigno Fm); 6) Lower Jurassic p.p.-Oligocene p.p. basinal deposits (from the Rosso Ammonitico Fm to the Scisti Policromi Fm); 7) Lower Jurassic p.p. shallow- to deeper-shelf carbonates (Dolomie di Monte Castellana Fm and Calcari ad Angulati Fm along the western, northern and north-eastern margin of the Alpi Apuane window; Calcare Massiccio Fm along the south-eastern margin); 8) Upper Triassic shallow-water carbonates (Calcari a *Rhaetavicula contorta* Fm and Calcare Cavernoso Fm); 9-10 Massa Unit; 9) Permian and Middle-Upper Triassic metasediments with subordinate Middle Triassic volcanites; 10) Paleozoic metamorphites of the Variscan basement. 11-16 Alpi Apuane Unit; 11) upper Oligocene p.p.-lower Miocene p.p. foredeep deposits (Pseudomacigno Fm); 12) Lower Jurassic p.p.-Oligocene p.p. metamorphosed basinal deposits (from the Metacalcari con Selce Fm to the Scisti Sericitici Fm); 13) Lower Jurassic p.p. shallow-water metacarbonates (Apuane Marble Fm and Dolomitic Marble Fm); 14) Upper Triassic shallow-water metacarbonates (Grezzoni Fm, Marmi a Megalodonti Fm and Nero di Colonnata Fm) locally containing at the base quartz-rich terrigenous metasediments (Vinca Fm); 15) Metamorphites of the Variscan Basement; 16) Tectonic slices of the Stazzema Zone; 17) Base thrust of the Ligurian plus Subligurian Nappes and base thrust of the Massa Unit; 18) Minor thrusts and backthrusts within the Apuane Unit and the Tuscan Nappe; 19) Low-angle detachment faults; 20) Normal faults, locally with a strike-slip component. The heavy white line indicates the major tectonic contact between the Tuscan Nappe and the underlying metamorphic Tuscan Units (Alpi Apuane and Massa Units).

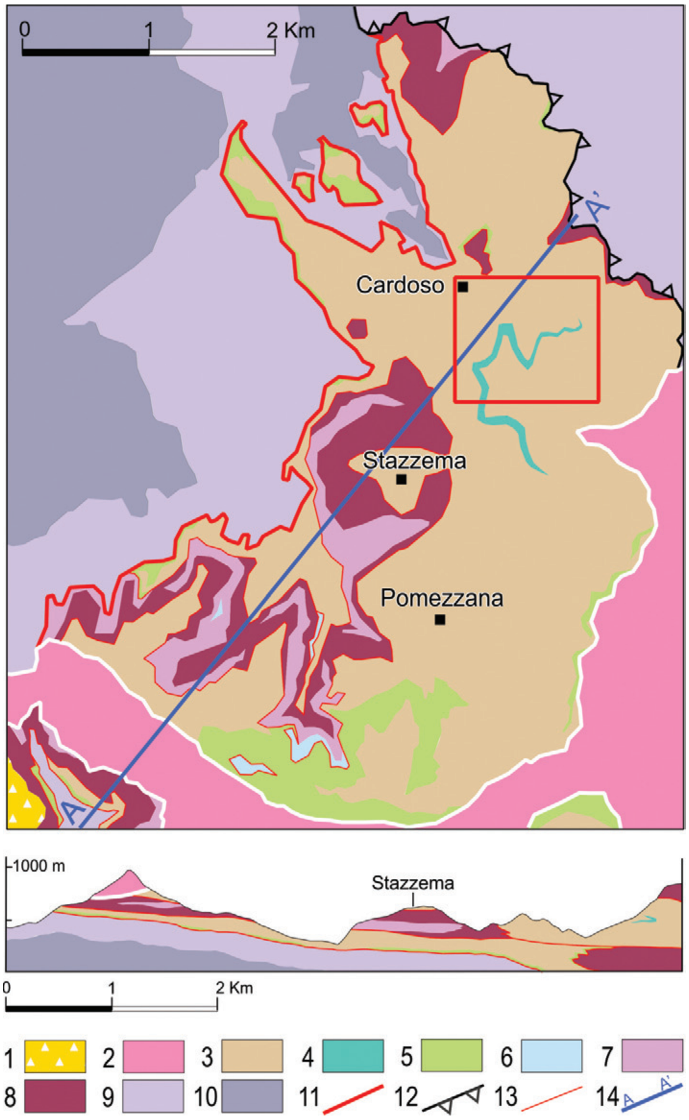

Fig. 3 - Simplified geological map of the Stazzema Zone and schematic cross-section (modified after Conti *et alii*, 2010) with the areal extent of the Ricavo olistostrome. See map location in fig. 2. The red box indicates the area represented in fig. 5. The heavy white line indicates the tectonic contact between the Tuscan Nappe and the Alpi Apuane Unit: 1) Lower Pleistocene (Santernian) subaerial talus breccias (Pietrasanta Megabreccia); 2) Tuscan Nappe. 3-8 Tectonic slices of the Stazzema Zone, including; 3) upper Oligocene p.p.-lower Miocene p.p. basinal metasandstones and metapelites (Pseudomacigno Fm); 4) Ricavo olistostrome; 5) Cretaceous p.p.-Oligocene p.p. basinal metalimestones and metapelites (Scisti Sericitici Fm, mostly "Cipollino"-type metacarbonates); 6) Lower Jurassic basinal cherty metalimestones (Metacalcari con Selce Fm) and subordinate shallow-water metacarbonates (Apuane Marble Fm); 7) Upper Triassic shallow-water dolomites (Grezzoni Fm); 8) Variscan metamorphites; 9) Upper Triassic-Lower Jurassic p.p. metasediments of the Alpi Apuane Unit overlying (NE of Cardoso) and underlying (W of Cardoso) the stack of the Stazzema tectonic slices; 10) Variscan metamorphites of the Alpi Apuane basement; 11) Tectonic contact at the base of the Stazzema slices; 12) Tectonic contacts at the top of the Stazzema slices; 13) Major tectonic contacts within the stack of the Stazzema slices; 14) Trace of the cross-section.

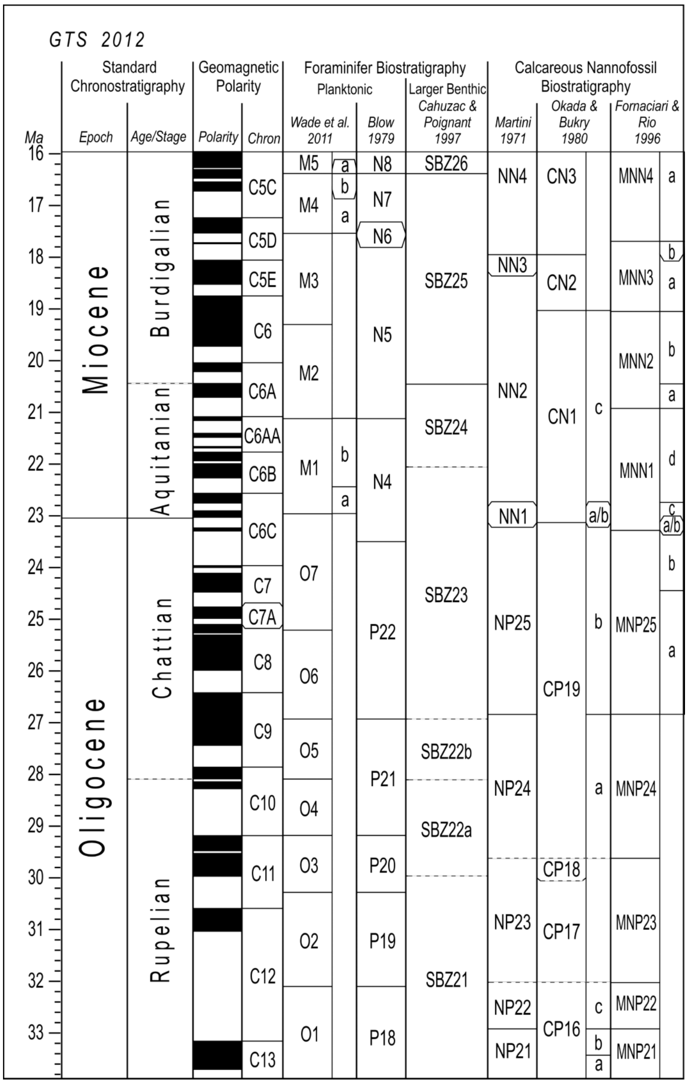

Fig. 4 - Foraminifer and Calcareous Nannofossil Zonation of the Oligocene-early Miocene interval calibrated to the GTS 2012. Source of data: Gradstein *et alii*, 2012; Geologic Time Scale Foundation at http://stratigraphy.science.purdue.edu. and software Time Scale Creator 6.0 at www.tscreator.org.

exhumation processes and have attributed this deformation to the D_2 phase of Carmignani & Kligfield (1990). We do not exclude that deep-seated low-angle detachment faults post-dating the isoclinal folding may have been responsible for tectonic thinning and severe stratigraphic elisions. This mechanism is not unusual in the Alpi Apuane region. Low-angle faults are widespread in the Tuscan Nappe cropping out around the Alpi Apuane tectonic window. They are testified by the direct superposition, with unquestionable mechanical contacts (see fig. 2), of the Cretaceous-Oligocene "Scisti Policromi" Formation and of the underlying Lower Cretaceous Maiolica Formation over different terms of the Lower Jurassic portion of the sequence.

In the Stazzema Zone the thickness of the Pseudomacigno Formation is greater than in other regions of the Alpi Apuane. NE and SE of the Stazzema village, in particular, it seams to exceed 700-800 metres. Obviously this value cannot be assumed as the original thickness of the formation because of the presence of tight isoclinal folds producing telescopic shortening and thickening (see schematic cross-section in fig. 3), and the presence of numerous ductile shear zones producing elisions and thinning. Some of these shear zones are marked by tectonites (mostly mylonites) of calcareous lithotypes referable to different terms of the original stratigraphic sequence. These tectonites are exploited for production of decorative stones called in the area "Bardiglio Fiorito" (MANCINI *et alii*, 2009). Away from the shear zones, the Pseudomacigno Formation consists of interbedded grey to dark-grey metapsammites (feldspatic metawackes) and metapelites locally known as "Pietra del Cardoso" and "Ardesia Apuana", respectively. Detailed petrographic descriptions are available in BONATTI (1938) and in FERRINI & PANDELI (1985). The thickness of the single beds is usually decimetric to pluridecimetric and only subordinately metric. Graded bedding, very useful in such a structural complexity for providing sedimentation polarity, is a quite common depositional feature in the sequence. Due to the strongly penetrative deformation affecting the Pseudomacigno Formation it is impossible to decipher the original stratal stacking pattern, critical for better understanding the overall architecture and the sedimentary evolution of the Alpi Apuane foredeep deposits. The occurrence of *Nephrolepidina morgani* in the lower part of the succession (DALLAN NARDI, 1976; MONTANARI & ROSSI, 1983) indicates that the onset of the foredeep siliciclastic sedimentation in the Alpi Apuane domain is bracketed in a temporal window spanning from the late Oligocene (Chattian) to the early Miocene (fig. 4). This larger benthic foram, in fact, ranges from the SBZ22b/SBZ23 Zone to the SBZ25 Zone (Shallow Benthic Zonation according to WIELANDT, 1996 and CAHUZAC & POIGNANT, 1997) and consequently the base of the Pseudomacigno Formation is not older than 28.1 Ma following the GTS 2012 (GRADSTEIN *et alii*, 2012). Recently, the first occurrence of *N. morgani* has been estimated at approximately 26.7 Ma (FENERO *et alii*, 2012), associated to the major expansion of the Antarctic Ice Sheet and to the paleoenvironmental turnover and sea-level drop following this cooling event, known as the Oi-2b global glacial event. This event falls in the lower part of the planktonic foraminifer O6 Zone, which is tied to the calcareous nannofossil CP19b Zone.

THE RICAVO OLISTOSTROME

Between Ricavo (south-east of Cardoso) and Filucchia (east of Stazzema) a number of aligned olistoliths made up of dark-grey siliceous metalimestones dispersed in dark-grey metapelites/metapsammites allow the identification of a lens-shaped olistostrome embedded in the metapsammites and metapelites of the upper portion of the Pseudomacigno Formation. Fig. 5 is a geological map of the Ricavo area where the olistostrome unit has been traced with a relative lateral continuity due to the quite good exposures in spite of the dense wood covering the region. The olistostrome displays the typical chaotic block-in-matrix fabric, with pebbles, blocks and slides ranging in size from some centimetres to some metres dispersed in a grey to dark-grey shaly/silty matrix (figs. 6.1 and 6.2). The blocks and slides are characterized by an irregular network of closely-spaced calcite/quartz veins (figs. 6.3 and 6.4). The geometrical relationships between the schistosity impressed in the matrix, coincident with the principal schistosity of the Pseudomacigno metasediments, and the network of the veins in the siliceous metalimestones, which do not cross-cut the matrix and the metasediments of the Pseudomacigno Formation, show that the rock was already lithified and tectonically deformed before being included in the olistostrome. Some horizons of debrites (figs. 7.1 and 7.2) and slumped beds (figs. 7.3 and 7.4) have been recognized in the coarse metasandstones just above the olistostrome unit. The debrites are characterized by the occurrence of well-lithified dark-grey to black large shaly clasts.

In spite of the metamorphic processes, shearing and flattening in the limestone blocks are quite weak and the depositional texture of the rock has not been obliterated by recrystallization processes. In addition, some large blocks still preserve a characteristic anvil shape in the weathering profile due to silicification processes developed in proximity of the upper and lower bedding surfaces (fig. 6.4). In thin-section analysis (figs. 8 and 9) the metalimestones appear as mudstones/wackestones containing a relatively rich and diversified assemblage of calcite-replaced radiolarians associated with thin-rayed multi-axoned sponge spicules. In some blocks the radiolarians are also associated with badly preserved specimens of calpionellids and rare *Stomiosphaera*. A few better-preserved radiolarians have been attributed to the genera *Sethocapsa*, *Hiscocapsa*, *Ditrabs*, *Bistarkum* and *Angulobracchia* on the base of the structure and shape of the test observed in thin section. In some limestone blocks the radiolarians, some of which referable to *Ristola* sp. and *Stichomitra* sp., are associated with scattered, recrystallized planktonic forams represented by *"Caucasella" hoterivica* and *Hedbergella sigali*. This planktonic-foram association allows the identification of the *Hedbergella sigali* Zone (*sensu* COCCIONI *et alii*, 2007), which spans through the entire Valanginian. The calpionellid association is quite poor, being represented only by scattered tintinnopselliform specimens. However, it allows the recognition of the *Tintinnopsella* Zone as defined by ANDREINI *et alii* (2007) and supports the Valanginian age indicated by the planktonic forams.

PROVENANCE OF THE RICAVO OLISTOSTROME

In the Northern Apennines basinal limestones of Valanginian age may belong to the "Maiolica" Formation (Tuscan and Umbria-Marche sequences) or to the "Argille a Palombini" Formation (Internal Ligurian sequence). The Maiolica Formation consists of well-bedded off-white to light-grey siliceous cherty limestones with grey shaly interlayers. The lower portion, uppermost Tithonian-Valanginian in age, is characterized by the presence of white-to-cream and pinkish cherty nodules and lenses. The upper portion, Hauterivian-Barremian and possibly lowermost Aptian in age (COCCIONI & PERILLI, 1997), consists of grey to dark-grey hemipelagic limestones with dark-grey cherty nodules and lenses, interbedded with dark-grey to black shales. This portion contains redeposited beds mainly represented by calciturbidites and debrites (BOCCALETTI & SAGRI, 1966; BOCCALETTI *et alii*, 1969; CERRINA FERONI & PATACCA, 1975; FAZZUOLI *et alii*, 1985). The "Argille a Palombini" Formation is a deep-marine shale-limestone lithostratigraphic unit belonging to the sedimentary cover of the ophiolites, which is widespread from the Northern Apennines (ABBATE & SAGRI, 1970; DECANDIA & ELTER, 1972) to Corsica (NARDI *et alii*, 1978; DURAND-DELGA, 1984; MARRONI *et alii*, 2000; PADOA & DURAND DELGA, 2001) and to the Alps (among many others WEISSERT & BERNOULLI, 1985). It has been assigned to the Early Creta-

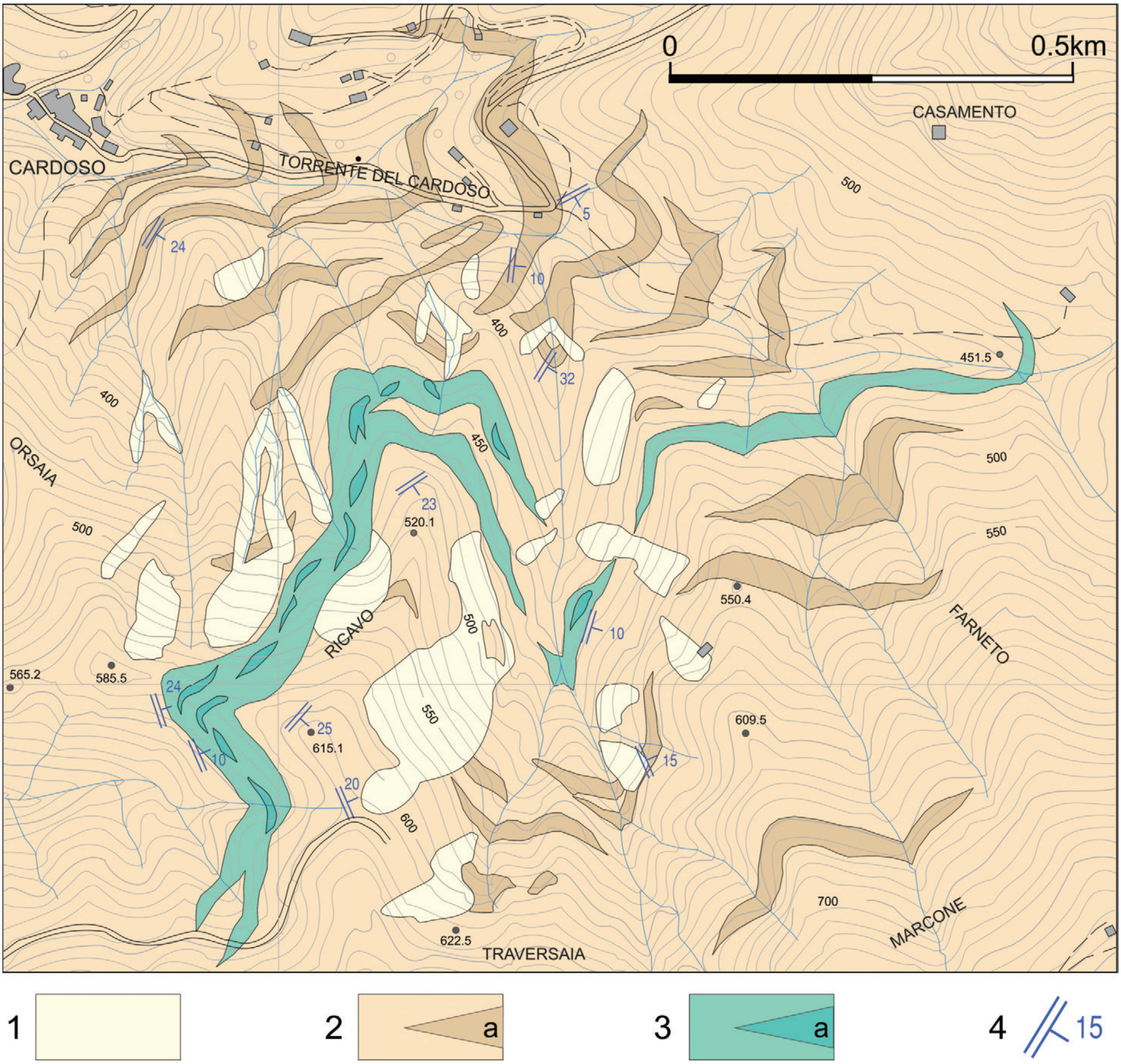

Fig. 5 - Geological map of the Ricavo area showing the olistostrome body included in the Pseudomacigno Formation (2007-2010 field surveys of S. Mancini). Map location in fig. 3: 1) Regolith; 2) Pseudomacigno Formation ("Pietra del Cardoso") with shaly horizons ("Ardesia Apuana" 2a); 3) Olistostrome with several aligned lens-shaped bodies of Ligurian-derived metalimestones (3a); 4) Strike and dip of the principal schistosity surface. Note that the apparent homocline geometry derives from a short-wavelength isoclinal folding. It is possible that the olistostrome marks the axial plane of a major NE-SW trending syncline (see cross-section in fig. 3).

ceous (Cobianchi & Villa, 1992; Cobianchi *et alii*, 1994), and specifically to the early Valanginian-early Barremian (Perilli, 1997; Perilli & Nannini, 1997) on the base of the nannofossil assemblage. Everywhere the "Argille a Palombini" Formation is represented by a well-bedded sequence of dark-grey to black siliceous shales regularly alternating with dark-grey micritic limestones. The limestone beds ("Palombini") show a characteristic anvil-shaped weathering profile due to a diffuse silicification mainly concentrated in proximity of the lower and upper bedding planes. Both age and lithologic features of the exotic limestones included as olistoliths in the Ricavo olistostrome indicate without doubts their derivation from well lithified and highly fractured dismembered portions of the "Argille a Palombini" Formation of the Internal Ligurian Units.

DISCUSSION

Ligurian- and Subligurian-derived materials included as olistostromes in the upper portion of the Macigno Formation are quite common both in northern and southern Tuscany. Their identification has principally derived from

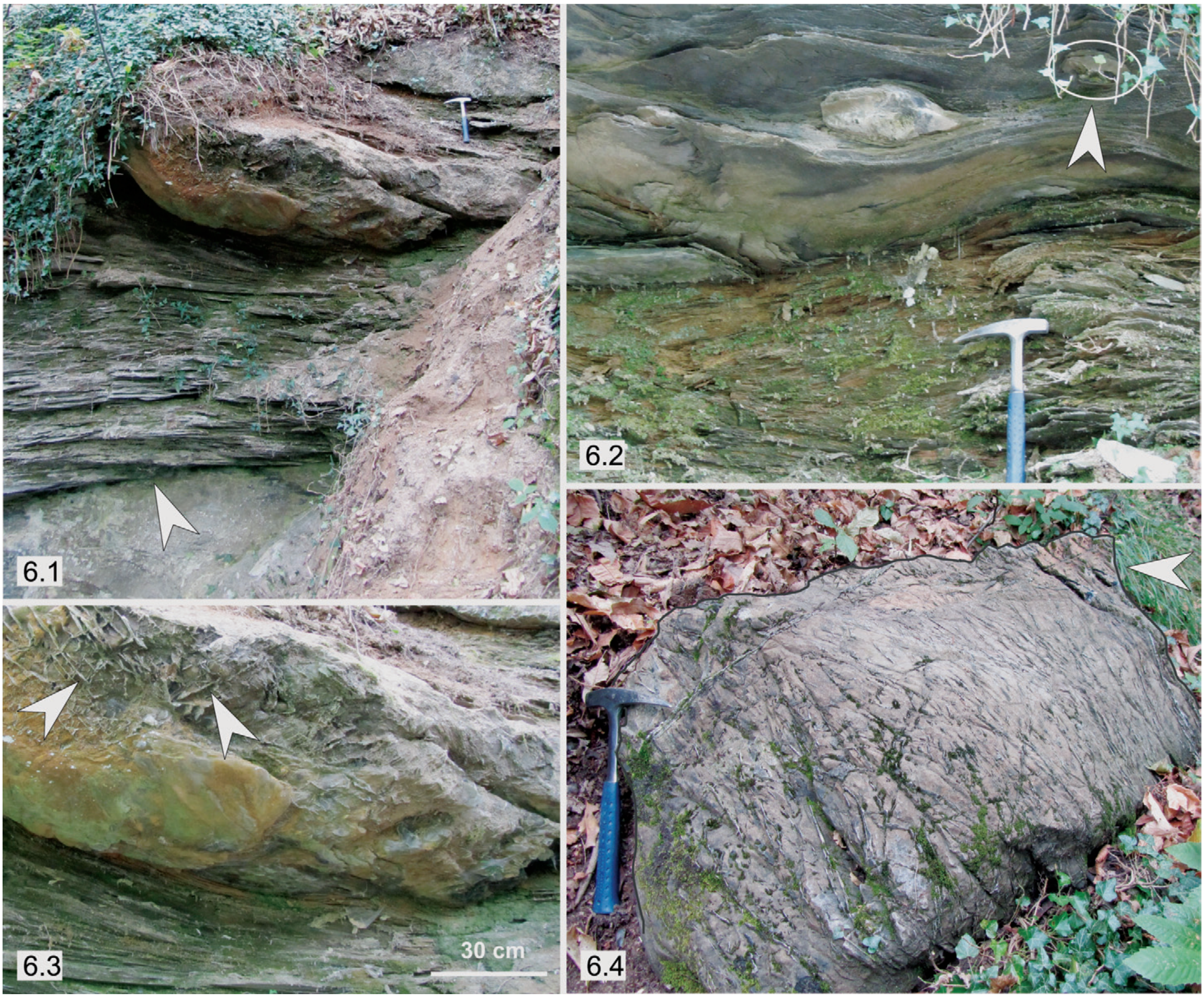

Fig. 6 - Details of the Lower Cretaceous Ligurian-derived olistoliths included in the Pseudomacigno Formation (Ricavo area south of Cardoso, see fig. 5): 6.1) Folded and fractured slide (below the hammer) and isolated lens-shaped block (above the hammer) of slightly recrystallized dark-grey siliceous limestone set in a silty-shaly to shaly matrix. Note the S_0 featured by the contact (white arrow) between the metapsammite thick bed of the Pseudomacigno Fm (below) and the metapelite/metasiltite matrix of the olistostrome (above). The S_0 lies at a very low angle with the principal schistosity well developed in the matrix. The pervasive schistosity in the matrix contrasts with the absence of flattening and shearing of the metalimestone olistoliths; 6.2) Two small olistoliths of Lower Cretaceous metalimestones (note the encircled and arrowed smaller, less evident pebble) included in a dark-grey shaly matrix. These small olistoliths are flattened in the principal foliation plane; 6.3) Detail of the folded slide of metalimestones in fig. 6.1 displaying two sets of intersecting extension veins (white arrows) at high angle with the schistosity of the surrounding metapelite/metasiltite matrix. Only in correspondence to the border of the slide, veins have been transposed in the principal schistosity; 6.4) Olistolith of metalimestone preserving (white arrow) the characteristic anvil-shaped weathering profile. Note also the irregular network of calcite/quarts extension veins.

the detailed surveys carried out in the sixties for the official geological map of Italy 1:100.000 (just referring to Northern Tuscany, see Sheets 84 Pontremoli, 85 Castelnuovo ne' Monti, 96 Massa and 97 S. Marcello Pistoiese (Servizio Geologico d'Italia 1968a, b, c; 1970), as well as to the respective explanatory notes (Dalla Casa & Ghelardoni, 1967; Trevisan *et alii*, 1971; Merla & Abbate, 1969). Some of these olistostromes, consisting of blocks of siliceous calcilutites dispersed in a dark-grey/black shaly matrix referable to the "Argille a Palombini" Formation (e.g. Dalla Casa & Ghelardoni, 1967), display evident analogies with the Ricavo olistostrome of the Stazzema Zone.

In northern Tuscany the olistostromes are included in the uppermost portion of the Macigno sequence. An Aquitanian age of this portion, and thus an Aquitanian age of the olistostrome emplacement, is indicated by nannofossil associations recovered in Val di Lima (MNN1c Zone, Catanzariti & Perilli, 2009) and in the Apennine watershed region (MNN1d Zone, Plesi *et alii*, 2000). In the same region (Monte Le Porraie), the base of the Macigno Formation is not older than the late Chattian, established by the age of the underlying hemipelagic pre-flysch deposits the top of which belongs to the calcareous nannofossil MNP25a Zone of the Mediterranean region (Catanzariti & Perilli, 2009), which corresponds to the lower

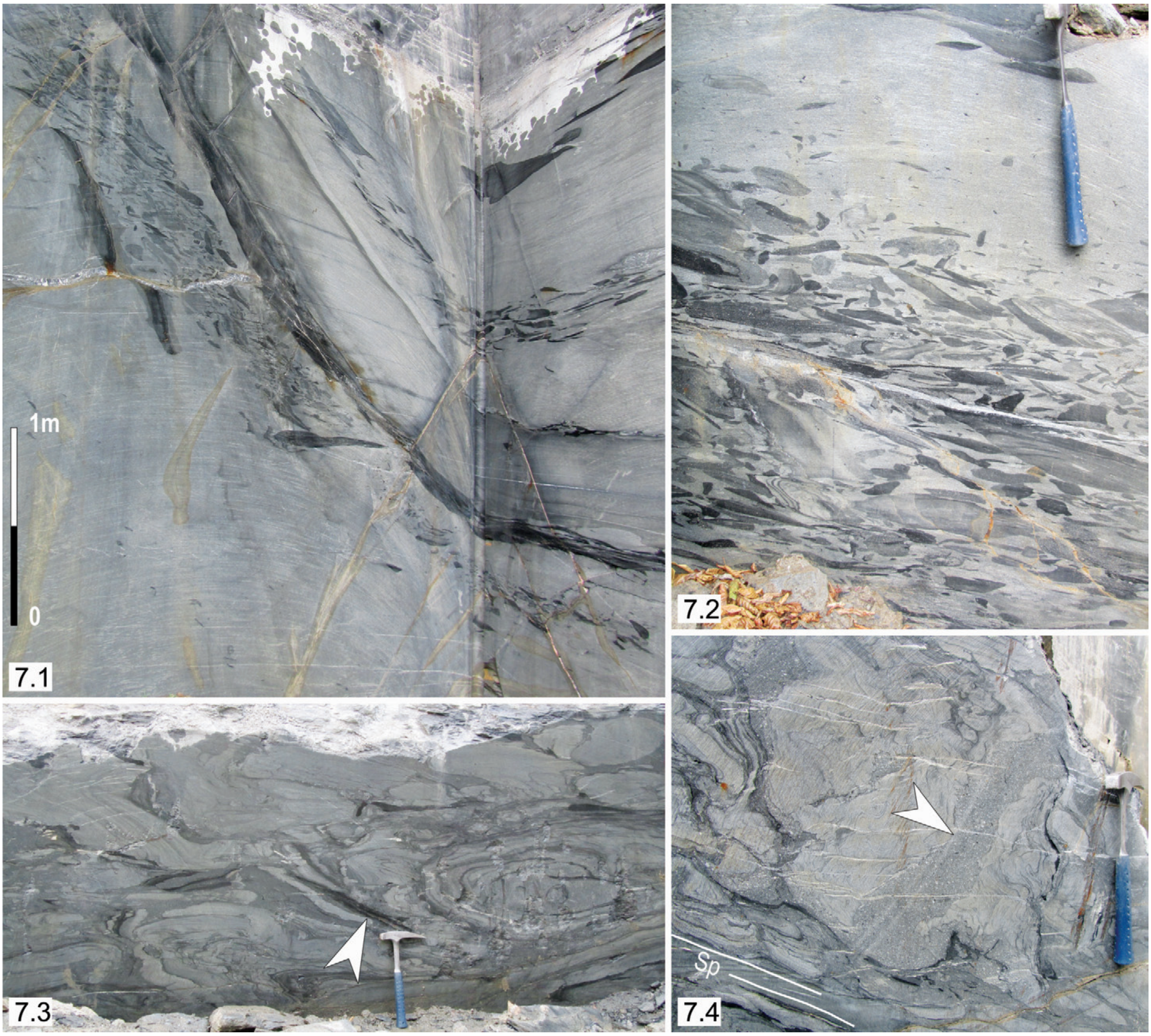

Fig. 7 - Polished walls of a quarry of "Pietra del Cardoso" ENE of Stazzema (Cava Ficaio) showing debrites together with slumped beds in the Pseudomacigno Formation. These syndepositional deformations are associated with the olistostrome event: 7.1 and 7.2) Debrites with clasts composed of light-grey metapsammites/metasiltites and dark-grey to black metapelites. Note the sharp edges of the tabular darker shaly clasts, evident in fig. 7.2, which denote lithification before gravity transport. These clasts have likely derived from well lithified shaly interlayers of the Lower Cretaceous Ligurian "Argille a Palombini" Fm; 7.3) Slumps evidenced by the original alternation of light-grey sandstones and grey to dark-grey clayey interlayers. The white arrow indicates a black tabular shaly clast, probably derived from the "Argille a Palombini" Fm; 7.4) Detail of a slumped bed showing soft-sediment deformation overprint by schistosity. Note the S_0 evidenced by lithology changes (white arrow) lying at high angle with the principal schistosity (Sp in the picture).

part of the CP19b Zone of Okada & Bukri (1980) and can be correlated with the lower part of the Larger Benthic Foraminifer SBZ23 Zone (fig. 4). This indicates that the onset of the siliciclastic supply in the Internal and External Tuscan Domains was roughly coeval (though the age attribution is based on fossils belonging to different taxa) and not older than 26.7 Ma. Consequently, the Macigno and the Pseudomacigno stratigraphic successions had to be deposited in the same foredeep basin.

The sedimentary sequence of the Alpi Apuane Unit has been affected by a greenschist metamorphism (Bonatti, 1938) with maximum temperature values around 400°-500° and pressures not lower than 0.8 GPa (Molli *et alii*, 2002 and references therein). Based on K/Ar measurements, Giglia & Radicati di Brozolo (1970) assigned to this metamorphism an age of 11 Ma (early Tortonian). Subsequently, Kligfield *et alii* (1986) published a very interesting paper documenting an attempt to date the individual deformation episodes accompanying the metamorphism. For this purpose, the authors tried to separate into three groups white micas collected in the S_1, S_2 and S_3 schistosities in order to analyze this mater-

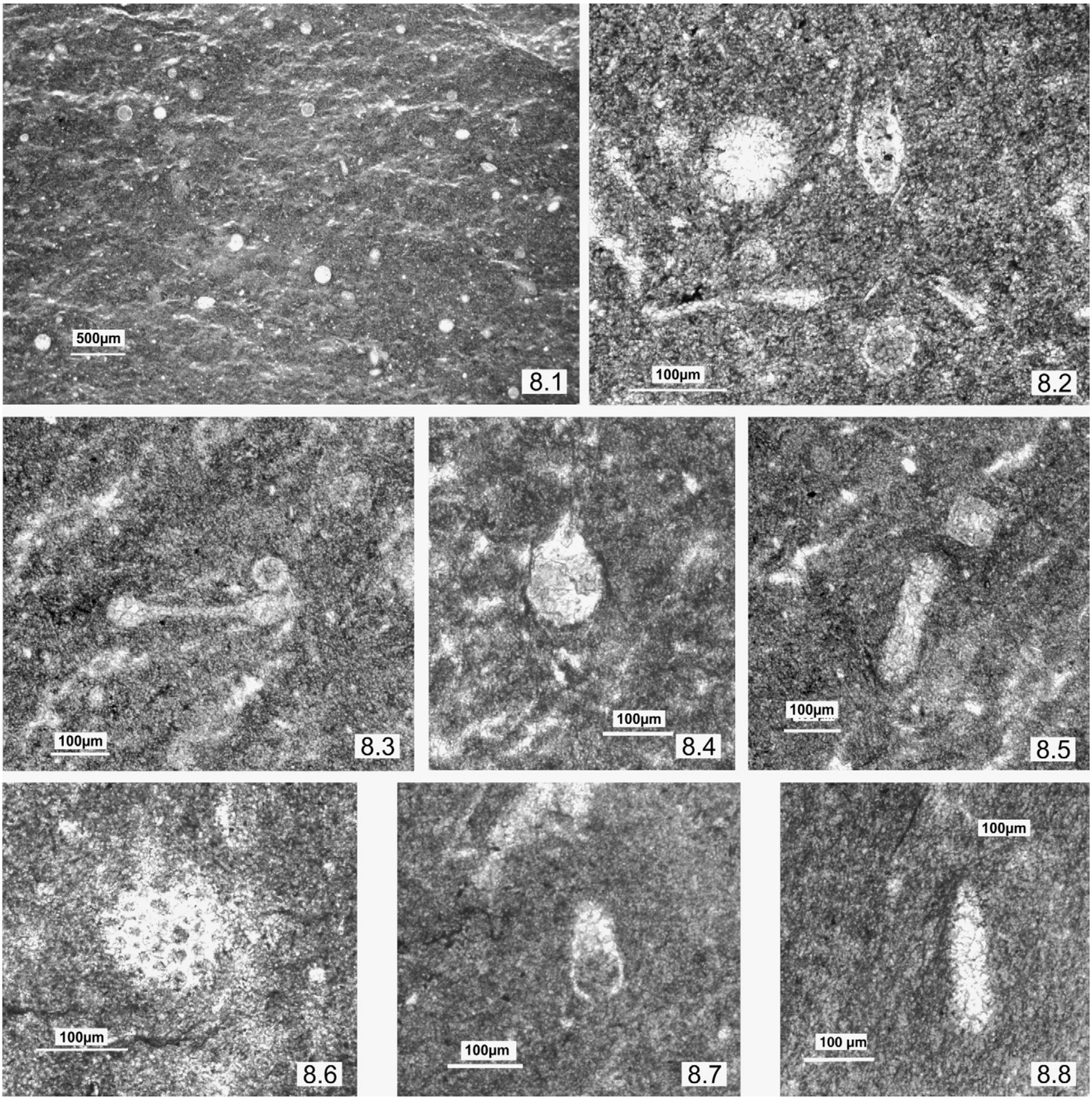

Fig. 8 - Thin-section microphotographs of the planktonic microfossils contained in the calcareous olistoliths of the Ricavo olistostrome. All figures at transmitted light. Sample coordinates: Long. 10°19'20"; Lat. 44°00'12": 8.1) Wackestone with a moderately well preserved assemblage of radiolarians showing calcite-replaced tests (Sample EP 6094, Ricavo); 8.2) Radiolarian-calpionellid association. An oblique section of *Angulobracchia* sp. (lower left) with its distally-diverging rays can be seen below the recrystallized test of a large spherical spumellarian. A calpionellid with a strongly recrystallized tintinnopselliform lorica is present just right of the spumellarian radiolarian (Sample EP 6094, Ricavo); 8.3) *Ditrabs* sp. (Sample EP 6094, Ricavo); 8.4) *Sethocapsa* sp. (Sample EP 6094, Ricavo); 8.5) *Bistarkum* sp. (Sample EP 6094, Ricavo); 8.6) *Hiscocapsa* sp. (Sample EP 6094, Ricavo); 8.7) *Stichomitra* sp. (Sample EP 6098, Ricavo); 8.8) *Rispola* sp. (Sample EP 6099, Ricavo).

ial by conventional K/Ar and $^{40}Ar/^{39}Ar$ incremental gas release measurements. The conclusions of this work are:

– Ages bracketed between 27.0 and 23.8 Ma, obtained from slate samples containing uncrenulated S_1 phengite, may be representative of the major deformation phase D_1, with the metamorphic peak at 27 Ma;

– Ages around 12 Ma, obtained from intensely crenulated phyllites characterized by a penetrative S_2 surface, may be representative of the second deformation phase D_2;

– Ages around 8-10 Ma, finally, have been attributed to the post-tectonic growth of diablastic microporphyroblasts of white mica.

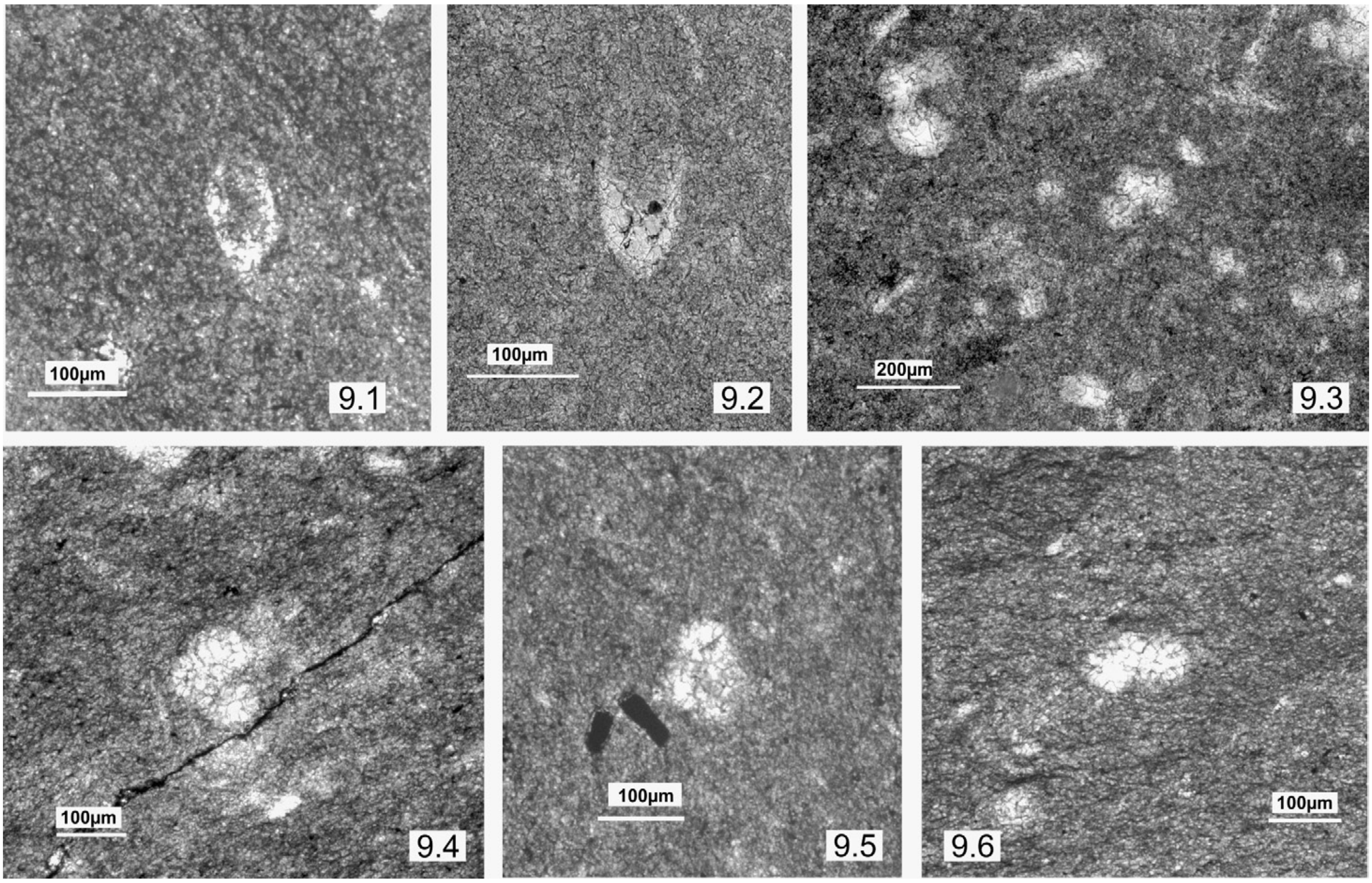

Fig. 9 - Thin-section microphotographs of the microfossil content of the calcareous olistoliths included in the Ricavo olistostrome. All figures at transmitted light. EP sample coordinates: Long. 10°19'20"; Lat. 44°00'12". Fil1 sample coordinates: Long. 10°19'32"; Lat. 43°59'36": 9.1) Recrystallized calpionellid with slender caudate tintinnopselliform lorica (Sample EP 6099A, Ricavo); 9.2) Calpionellid with recrystallized ovoid lorica dubitatively attributed to an oblique section of *Tintinnopsella* (Sample Fil1, Filucchia east of Stazzema); 9.3) Wackestone with scattered specimens of *"Caucasella" hoterivica* (Subbotina) (Sample EP 6099, Ricavo); 9.4) Axial section of *"Caucasella" hoterivica* (Subbotina) (Sample EP 6099, Ricavo); 9.5) *Hedbergella sigali* Moullade, dorsal view (Sample EP 6098, Ricavo); 9.6) *Hedbergella sigali* Moullade, axial section (Sample EP 6099, Ricavo).

In the current geological literature (e.g. FELLIN *et alii*, 2007; MOLLI, 2008) the above radiometric ages are widely accepted as highly reliable data documenting the first (compressional) and the second (extensional) deformation phases *sensu* CARMIGNANI & KLIGFIELD (1990), as well as the end of the metamorphic conditions in the Alpi Apuane Unit. However, the occurrence of a Ligurian-derived olistostrome in the Pseudomacigno Formation highlights internal contradictions between an age of metamorphism as old as 27 Ma and the palinspastic model currently adopted by the Apennine geologists. The latter relocates the original domain of the Tuscan Nappe west of the Massa plus Alpi Apuane domains which in turn had to be located west of the Romagna-Umbria Domain. According to this reconstruction, the thrust belt-foredeep-foreland system migrated regularly from west to the east, the progressive incorporation of foreland segments in the foredeep basin being evidenced by the age of the flysch deposits becoming younger from the western areas (Macigno and Pseudomacigno Formations in the Tuscan Domains) to the eastern ones (Marnoso-Arenacea Formation in the Romagna-Umbria Domain). In addition, the time-space migration of the flysch deposits was accompanied by the time-space migration of the olistostrome emplacement at the front of the advancing Ligurian and Sub-Ligurian Nappes (LUCENTE & PINI, 2008 and references therein). In such a regional framework, the upper portion of the Pseudomacigno Formation is expected to be coeval with or slightly younger than the upper portion of the more internal Macigno Formation. The occurrence of Ligurian-derived materials in the Pseudomacigno Formation fully agrees with the above kinematic scheme and suggests that the olistostromes included in the upper portion of the Macigno Formation and the olistostrome included in the Pseudomacigno Formation were both supplied from the thrust front of the advancing Ligurian/Subligurian Nappes in a time not older than the Aquitanian, i.e. not older than 22-23 Ma, when the Macigno sedimentation still persisted and both Internal and External Tuscan Domains had not yet been affected by tectonic shortening. A different framework has been presented by FESTA *et alii* (2010) who have considered the top of the Pseudomacigno Formation roughly coeval with the base of the Macigno Formation (see fig. 2 in the quoted paper). In this framework the ensialic subduction zone that had to develop between the Internal and the External Tuscan Domains allowing the burial and the metamorphism of the Massa and Alpi Apuane Units began to be active after the deposition of the Pseudomacigno Formation in the External Tuscan Domains and before the deposition of the Macigno Formation in the Internal Tuscan Domain. However, the occurrence of *Nephrolepidina morgani* in the lower part of the Pseudomacigno sequence and the occurrence of a Ligurian-derived olistostrome in the upper part of the Pseudomacigno are sufficient for discarding this scenario.

An alternative paleogeographic model postulating a provenance of the Tuscan Nappe from the east, i.e. from a paleogeographic realm located between the original domain of the metamorphic Tuscan Units and the Romagna-Umbria-Marche Domains, was proposed around the end of the seventies (Dallan Nardi & Nardi, 1978; Boccaletti *et alii*, 1980). Following such a model, the Ricavo olistostrome could be slightly older than the olistostromes in the Macigno Formation but anyway younger than the first occurrence of *Nephrolepidina morgani* (26.7 Ma according to Fenero *et alii*, 2012) and thus younger than the 27 Ma age commonly accepted as representative of the metamorphic peak of the D_1 deformation event in the Alpi Apuane Unit.

Let us to reconsider the original data of Kligfield *et alii* (1986). 31 K/Ar measurements on white micas provided ages ranging from 10.4±0.5 Ma to 31.8±3.8 Ma, with 20 samples between 10.4±0.5 and 19.5±1.1 Ma, 7 samples between 21.2±1.2 and 24.9±0.9 Ma, two samples between 26.5±0.9 and 27.0±1.0 Ma, one sample at 28.2±2.8 and one sample at 31.8±3.8 Ma. The dataset has very high dispersion, with empty spaces just in the intervals 20-21, 25-26, 27-28 and 29-31 Ma. The only important concentration (8 samples) falls between 11.5±0.7 and 12.7±0.7 Ma. The original data of Kligfield *et alii* (1986) also include 10 analyses of $^{40}Ar/^{39}Ar$ incremental gas release carried out on 6 samples. The patterns of incremental heating are usually irregular, showing staircase trajectories rather than plateaux except, may be, for the ages 10.3±0.8, 11.7±0.8 and 12.7±0.9 Ma (see figs. 5, 6, 7, 9 and 10 in Kligfield *et alii*, 1986). Consequently, the choice of older total gas ages appears to be quite subjective. In conclusion, we believe that the reliability of the available radiometric data is not very high and we think that new radiometric measurements would be necessary for comparing absolute and relative ages.

Presently, the front of the Tuscan Nappe is located about 40 Km NE of the south-westernmost outcrops of the Pseudomacigno Formation. Therefore, 40 kilometres represent in the retrodeformation the minimum space we must remove after the olistostrome emplacement (not older than 22-23 Ma) and before burial and metamorphism. In addition, we must include a supplementary shortening of about 50 kilometres along the ensialic subduction zone in order to reach the depth around 30 kilometres required by the metamorphic peak. Assuming for the tectonic shortening a slip vector averaging 1 cm/y (values higher than 1.0-1,5 cm/y are not realistic in the northernmost sectors of the Apennines, see also Cowan & Brandon, 2008), the minimum time we need between the emplacement of the Ricavo olistostrome and the metamorphic peak of the Alpi Apuane sequence averages 9 million years. This means that the metamorphism cannot be older than 13-14 Ma. These values approach the 12 Ma concentration in the data of Kligfield *et alii* (1986), which could actually be representative of the major metamorphic event in the Alpi Apuane Unit. We wish to recall that a comparable age (11 Ma) was already proposed by Giglia & Radicati di Brozolo (1970).

CONCLUSIVE REMARKS

An olistostrome evidenced by a series of aligned olistoliths features a well-defined lens-shaped body in the Pseudomacigno Formation of the Stazzema Zone (Alpi Apuane Unit). The olistoliths consist of Lower Cretaceous dark-grey siliceous limestones referable to the "Argille a Palombini Formation" of the Internal Ligurian Units.

The occurrence of a Ligurian-derived olistostrome in the Pseudomacigno Formation highlights some contradictions existing between the paleogeographic model commonly adopted by the Apennine geologists, according to which the original domains of the metamorphic Tuscan Units were located east of the Tuscan Nappe domain, and the 27 Ma metamorphic peak in the Alpi Apuane Unit commonly accepted by geologists as a sort of golden spike for any kinematic analysis in the Northern Apennines.

The base of the Macigno Formation is roughly coeval with the base of the Pseudomacigno Formation. Therefore, it is logical to assume that both stratigraphic successions were deposited in the same foredeep basin. In this framework and following the aforementioned paleogeographic restoration, the Ricavo olistostrome cannot be older than the olistostromes included in the upper portion of the Macigno Formation (Aquitanian, 22-23 Ma). Consequently the metamorphism of the Alpi Apuane sequence must be significantly younger than 22-23 Ma. An age of metamorphism of 27 Ma would lead us to the paradox that the Alpi Apuane sequence underwent metamorphic conditions before its upper portion was deposited. A metamorphism at 27 Ma, on the other hand, is unrealistic also in a palinspastic reconstruction that relocated the Tuscan Nappe east of the Alpi Apuane and Massa domains since the Pseudomacigno deposits are younger than 26.7 Ma.

We believe possible that already published radiometric data indicating a metamorphic peak at 11-12 Ma are actually representative of the age of metamorphism of the Alpi Apuane Unit. In any case, new radiometric measurements are desirable.

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