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# Mediterranean Neogene historical stratotype sections and Global Stratotype Section and Points (GSSP): state of the art

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(With 51 figures)

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**Abstract**

The development of interdisciplinary stratigraphic studies and the construction of stratigraphic guidelines resulted in a new scenario with the introduction and definition of the Global Stratotype Section and Points (GSSP) replacing the Mediterranean Neogene historical stages and also the guiding criteria used to define their bases. At present, all the Mediterranean Neogene Stages (except Burdigalian and Langhian Stages) are defined by GSSPs, in land-based deep marine sections astronomically tuned (excluding the Aquitanian Stage) allowing the construction of the Astronomical Tuned Neogene Time Scale (ATNTS2004). Interdisciplinary research studies are now devoted to find sections suitable for the definition of the Langhian and Burdigalian GSSPs. At present, two deep marine Mediterranean sections (La Vedova in Conero area, central Italy and S. Peter's Pool in Malta) are identified as potential candidate to define the base of the Langhian while, suitable sections for the base of the Burdigalian are not yet documented.

**Keywords:** Stratigraphy, Stratotypes, Cenozoic, Neogene, Mediterranean, GSSP, Geological Time Scale

## Introduction

During the last 25 years, much progress has been made in the standardization of the Neogene Global Chronostratigraphic Scale clearly associated to the evolution of the Geological Time Scale from Harland et al. (1990), passing through the works of Berggren et al. (1985, 1995) to the Astronomical Tuned Neogene Time Scale (ATNTS) of Lourens et al. (2004).

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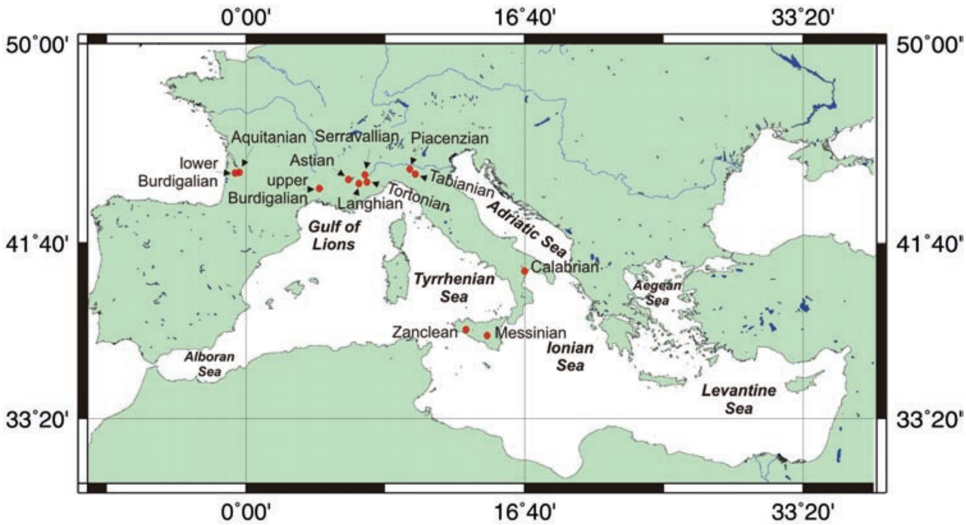



Fig. 1. Location map of the historical Mediterranean Neogene stratotypes

The development of multiple stratigraphic methodologies (paleomagnetic stratigraphy, astro-cyclostratigraphy, high resolution integrated calcareous plankton biostratigraphy, Ar/Ar dating method) and the creation of common stratigraphic guidelines (HEDBERG 1976; SALVADOR 1994) resulted in a new scenario with the introduction and definition of the Global Stratotype Section and Point (GSSP) replacing the historical sections of the Mediterranean Neogene stages and also the guiding criteria used for the identification of their bases.

The GSSP concept has been formally formulated in the International Stratigraphic Guide of SALVADOR (1994). In particular, the definition of a stage is restricted to its lower boundary globally recognisable and defined in a deep marine section. As a consequence, all Mediterranean Neogene GSSPs defined by now are astronomically tuned in land-based sections (excluding the Aquitanian GSSP).

The superimposition of all sedimentary sequences containing the Neogene GSSPs form the ~last 13.5 Ma of the ATNTS2004 (LOURENS et al. 2004). Recently, the ATNTS2004 has been extended back to 15.29 Ma (HÜSING et al. 2010). At present, the time interval relative to the Early Miocene is the goal of several integrated stratigraphic studies to find out sections where to define the base of the Langhian and Burdigalian.

The Mediterranean area, in general, and Italy, in particular, played an important role in developing the principles of stratigraphy since the early days of geological thinking, strongly supported by the recover of well-exposed, thick, tectonically undisturbed Neogene sections showing favourable, possibly hemipelagic sediments, turbidite- free (to avoid reworking), in order to reconstruct the evolution of microfaunas or nannofloras in successions where the only variable was time.

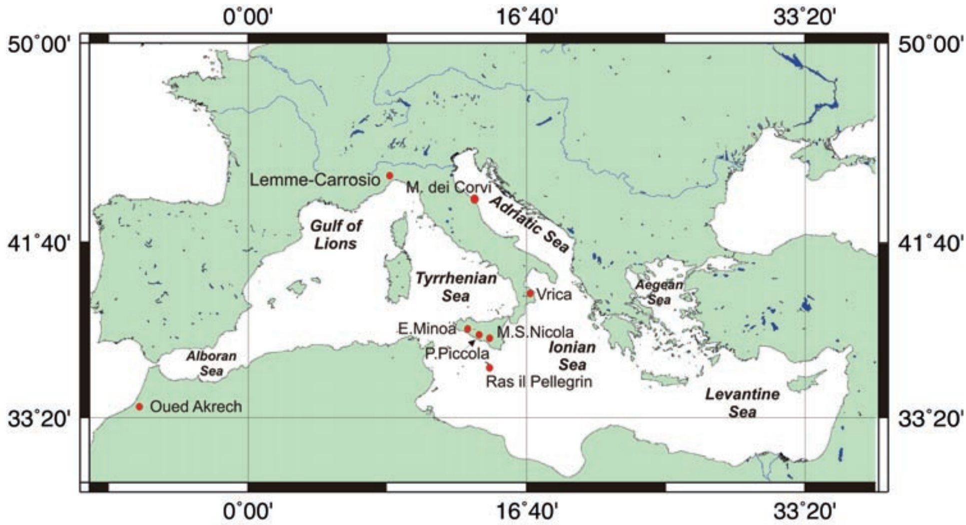



Fig. 2. Location map of the Neogene Global Stratotype Section and Points (GSSPs)

The Neogene historical stages are defined with old stratigraphic concepts in northern and southern Italy and southern France, as follows (Fig. 1): Aquitanian (south east of France) and Burdigalian (southern France), Langhian, Serravallian and Tortonian in the Tertiary Piedmont Basin (Piedmont region, northern Italy), Messinian in Sicily (southern Italy), Tabianian (Parma province, northern Italy), Zanclean in Sicily (southern Italy), Piacenzian (Castell'Arquato, Piacenza Province, northern Italy), Astian (Asti, northern Italy), Calabrian (S. Maria di Catanzaro, southern Italy). All the original documents related to the Mediterranean Neogene historical stratotypes are available on the Regional Committee on Mediterranean Neogene Stratigraphy (RCMNS) website (http://www.geomare.na.cnr.it/RCMNS.html, or in CARLONI et al. (1971) and STEININGER & NEVESSKAJA (1975).

Basically, the sections selected for historical stages mainly consist of sedimentary records, which are at present badly or no more outcropping (often these sections were sampled along rivers and at least part of them are now covered) and belonging to different environments (often shallow water shelf or platform environments) not suitable for high resolution studies. Historically, stages have been defined referring to a lithologic unit with a specific paleontologic content. Stages were defined where lithology and palaeontology changed over a broad area. Mainly, the base of the historical stratotypes corresponded to sequence boundary and consequentially is not an isochronous surface. The resulting chronostratigraphy, strongly controlled by local features, was not easily applicable to deep environments or in other paleoceanographic contexts rendering global correlation difficult.

These conditions made it necessary to find new marine sections more suitable for the definition of the bases of the Neogene stages following, if possible, the driving criteria selected for the historical stratotypes.

At present, GSSPs formally defined in deep marine environments are (Fig. 2): the base of the Pleistocene (Neogene/Quaternary boundary), the base of the Gelasian (Middle/Late Pliocene boundary), the base of the Piacenzian (Early/Middle Pliocene boundary), the base of the Zanclean (Miocene/Pliocene boundary), the base of the Messinian, the base of the Tortonian (Middle/Late Miocene boundary), the base of the Serravallian and the base of the Neogene (Oligocene/Miocene boundary). All these GSSPs gave rise to the construction of the Astronomical Tuned Neogene Time Scale (ATNTS 2004) (Lourens et al. 2004).

The main goal of this work is to present a general overview of the Mediterranean Neogene stages, including: 1) the original documentation of the historical stratotypes and sections (figures and/or photos); 2) the problems associated to the their definition and consequently to their applicability in global correlation; 3) the various scientific researches carried out through time on the stratotypes (planktonic foraminifera, calcareous nannofossils biostratigraphy, magnetostratigraphy, stable isotopes) and finally 4) the description of the Neogene Global Stratotype Section and Points (GSSPs).

## Aquitanian

### Historical stratotype (Vigneaux & Marks 1971)

The Aquitanian Stage (from *Aquitania*, the Latin name for Aquitaine) was introduced by Mayer (1858) and associated to mainly lagoonal deposits in the Aquitanian Basin, France (Fig. 1). Mayer (1858) defined the stratotype near the villages La Brède and Saucats to the south of Bordeaux (south-western France) and the geographic location of the stratotype was designated and more precisely defined by Dollfus (1909) along the Saint-Jean-d'Étampes (Saucats) stream between Moulin de Bernachon (Fig. 3a) and Moulin de l'Eglise (Fig. 3b). The stratotype was ratified and confirmed at several international conferences on the Mediterranean Neogene (Aix-en Provence, 1958; Vienna, 1959; Bologna, 1967).

The major fossil groups recorded in the stratotype section are represented by bivalves, gastropods, bryozoans, ostracods, planktonic and large benthic foraminifera (miogypsinids) (Cossman & Peyrot 1909–1924; Moyes 1966; Drooger et al. 1955; Jenkins 1966; Pujol 1970; Vigneaux 1949). In particular, the fossils marker used to correlate the stratotype with other deposits were: *Turritella desmaresti* and *Corbula basteroti* (both molluscs), *Miogypsina tani* (large benthic foraminifer) (Vigneaux & Marks 1971) and *Globorotalia kugleri* (planktonic foraminifer) (Jenkins 1966). Poignant & Pujol (1976) and letteron Poignant et al. (1997) published a revision of the Aquitanian stratotype, placing the base of the Aquitanian stratotype within the planktonic foraminiferal Zone N4 and the top in the lower part of Zone N5 of Blow zonation (1969). In terms of calcareous nannofossils (Müller & Pujol 1979), the Aquitanian falls within the Zone NN1 of Martini (1971). Sr-isotope data (Cahuzac et al. 1997) point to an age close to 23 Ma for the base of the

Fig. 3A

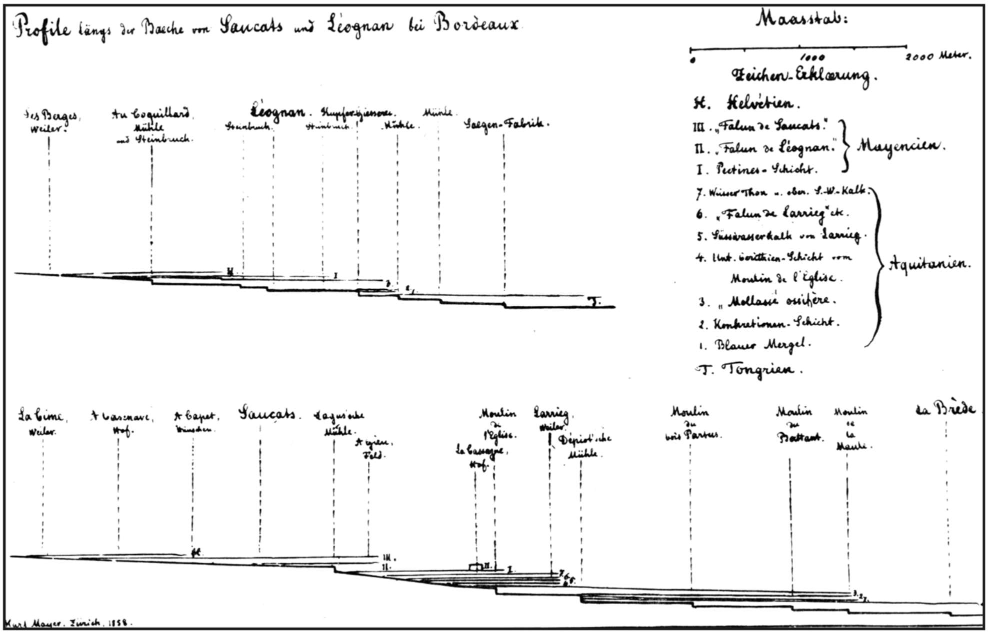



Fig. 3B

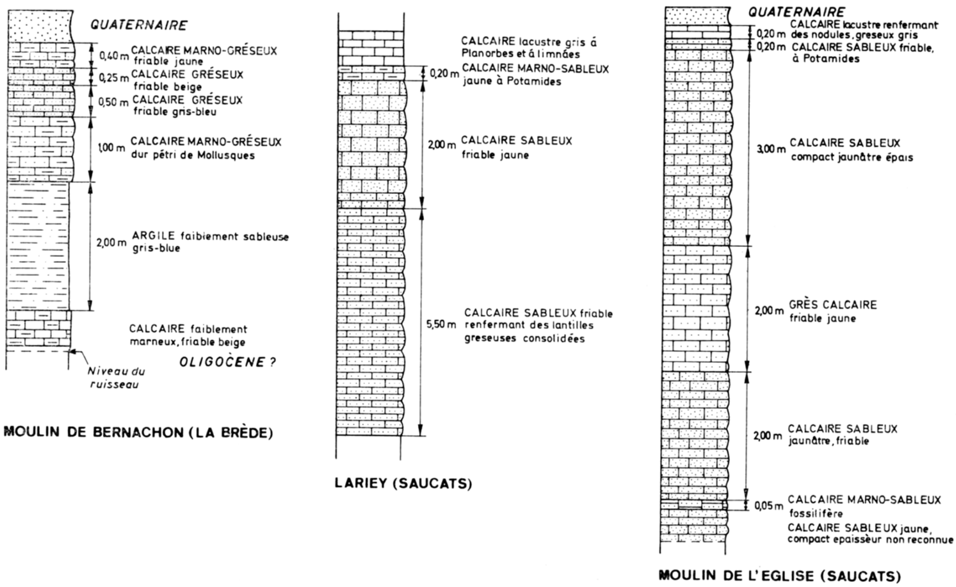



Fig. 3. **A**: Position of the Aquitanian historical stratotypes reported by MAYER (1858) in the Bordeaux area; **B**: lithologic logs of the Aquitanian historical stratotype (VIGNEAUX & MARKS 1971)


Fig. 4. Lemme-Carrosio section (north-west Italy): GSSP of the Oligo-Miocene boundary

type Aquitanian according to the Time Scale of Berggren et al. (1995) and suggest that the complete outcropping Aquitanian sequence ranges from 22.5 to 20.5 Ma (Parize et al. 2008). Recently, sedimentologic and sequence stratigraphic analysis performed on the Aquitanian stratotype evidenced the sequences along the Saucats stream, can be related to the third-order cycles within the large transgression regression cycle of the Neogene (Parize et al. 2008).

### Aquitanian GSSP (base of the Neogene and base of the Miocene (Steininger et al. 1997)

The shallow deposits and therefore the unfavourable conditions for a detailed integrated stratigraphy of the Aquitanian historical stratotype forced the stratigraphers to find a new section suitable for the definition of the GSSP of the base of the Neogene and the base of the Miocene. The working group on the Paleogene/Neogene boundary created in 1976 proposed in 1997 the GSSP of the base of the Neogene (Steininger et al. 1997).

The Global Stratotype Section and Point (GSSP) of the base of the Neogene (Early Miocene) and of the Aquitanian, is located at the Lemme-Carrosio section (Piedmont Tertiary Basin, north Italy), on the right side of the Lemme river (very close to the Carrosio village) (Fig. 2). The Lemme-Carrosio section is 63 meter thick, belongs to the Rigoroso Formation and is sub-divided in three lithologic units (Roetzel & Ottner 1996). It is mainly characterised by a monotonous thin-bedded succession of mudstone and siltstone strongly controlled by a turbiditic system (Fig. 4).

The GSSP has been defined in correspondence of the magnetic reversal boundary (35 meter downward from the top of the section) between chron C6Cn.2r and chron C6.Cn.2n (Fig. 5). Biostratigraphic events that may be used to approximate this boundary are the short total range of *Sphenolithus capricornutus* and the First Occurrence (FO) of *S. delphix*

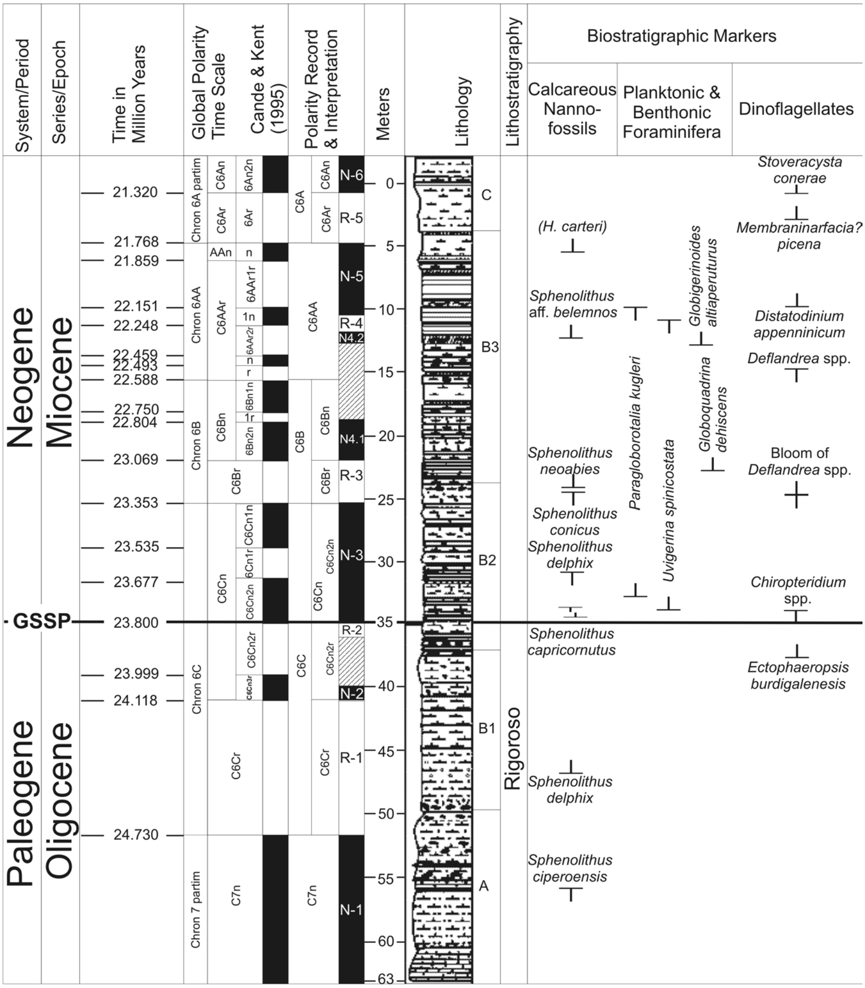



Fig. 5. Integrated Stratigraphy of the Aquitanian GSSP (Oligo-Miocene boundary) by STEININGER et al. (1997)

among the calcareous nannofossils (AUBRY & VILLA 1996) as well the FO of planktonic foraminifer *Paragloborotalia kugleri* (IACCARINO et al. 1996). Lately, FORNACIARI & RIO (1996) and RAFFI (1999) proposed a revisitation of the distribution pattern of *Sphenolithus delphix* at Lemme-Carrosio section (Fig. 6a) and pointed out the good correlation of biostratigraphic position of this datum between this section and extra-Mediterranean deep marine records, confirmed by their similar magnetostratigraphic position (across the lower normal polarity interval of chron C6Cn) and below the GSSP (Fig. 6b).

According to STEININGER et al. (1997) the Aquitanian GSSP is 23.8 Ma, which is strongly different to 22.9±0.1Ma proposed more recently, by SHACKLETON et al. (2000) using a detailed calcareous nannofossil correlations between the Lemme-Carrosio section, the

Fig. 6A

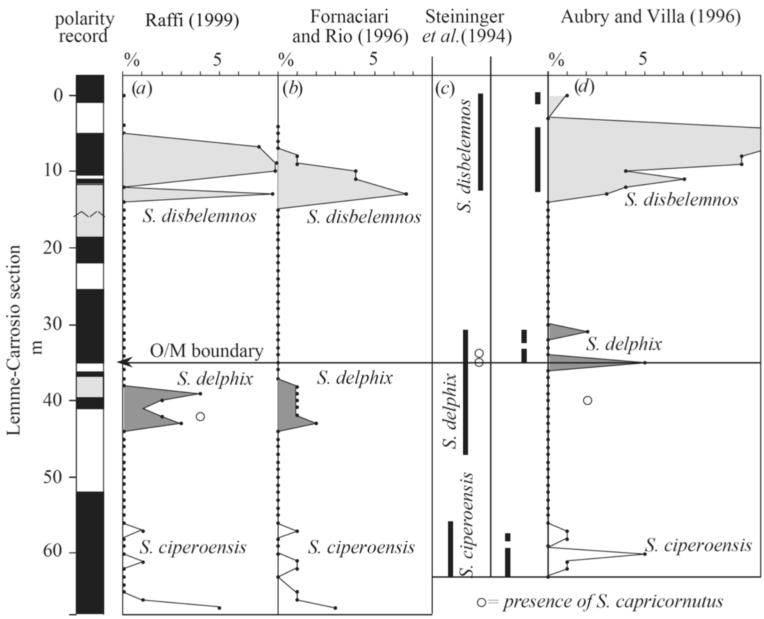
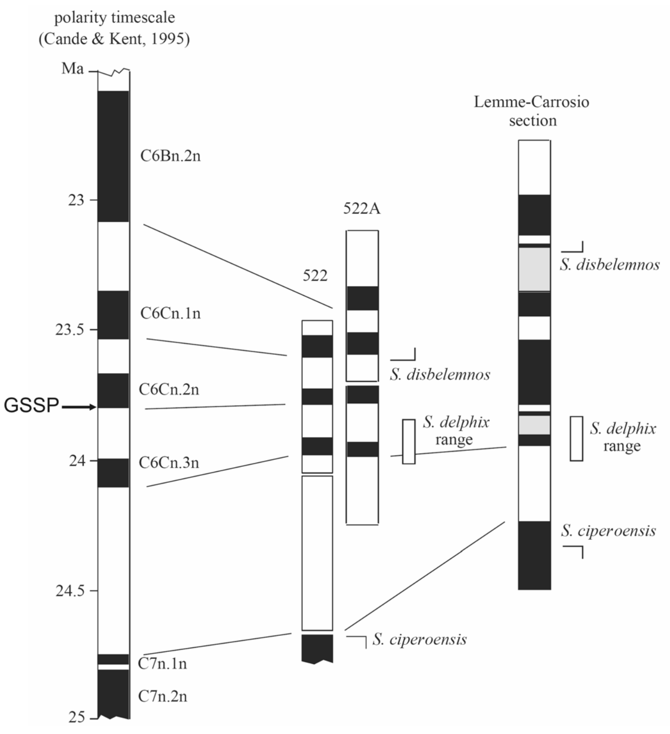

polarity record
Raffi (1999)
Fornaciari and Rio (1996)
Steininger et al.(1994)
Aubry and Villa (1996)
Lemme-Carrosio section m
O/M boundary
S. disbelemnos
S. delphix
S. ciperoensis
○= presence of S. capricornutus

Fig. 6B


polarity timescale (Cande & Kent, 1995)
Ma
C6Bn.2n
C6Cn.1n
C6Cn.2n
C6Cn.3n
C7n.1n
C7n.2n
GSSP
522
522A
Lemme-Carrosio section
S. disbelemnos
S. delphix range
S. ciperoensis

DSDP Site 522 and the ODP Site 926 (Raffi 1999). Lourens et al. (2004) retuning the ODP Site 926 proposed an age of 23.03 Ma for the base of the Miocene.

The Lemme Carrosio section, due to its turbiditic environments, is not suitable for cyclostratigraphic studies which could improve the ages of the bio-magneto-stratigraphic events recognised in the GSSP section.

## Burdigalian

### Historical stratotype (Vigneaux 1971)

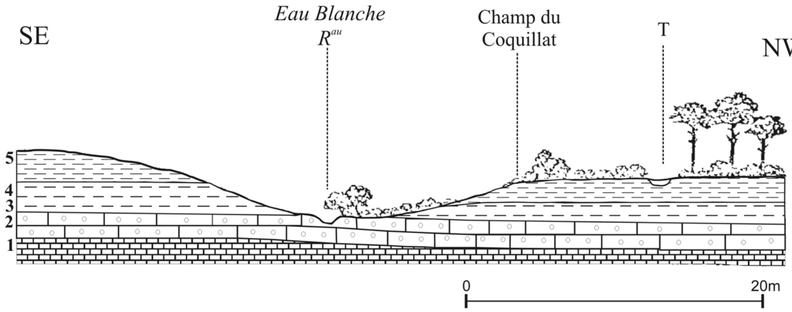
The Burdigalian (from *Burdigala*, Latin name for the city of Bordeaux in Roman times) Stage was introduced by Depéret (1892) suggesting Bordeaux as reference area. Successively, Dollfus (1909) and lately Vigneaux (1971) designated the Coquillat section at Léognan as the Burdigalian stratotype in the Bordeaux area and the Pont-Pourquey cliff (Saucat, France) as reference section (Figs 7a and 7b).

The major fossil groups recovered in the stratotype section are represented by bivalves, gastropods, bryozoans, ostracods, planktonic foraminifera and large benthic foraminifera (miogypsinids) (Cossman & Peyrot 1909–1924; Moyes 1965; Drooger et al. 1955; Julius 1960; Jenkins 1966; Pujol 1970; Vigneaux 1949). In particular, the marker fossils used to correlate the stratotype with other deposits were: *Pecten burdigaliensis*, *Pyrula cornuta*, *Tudicula rusticula*, *Ficula condita*, *Ostrea gingensis*, *Lucina culumbella*, *Buccinum baccatum*, *Oliva basteroti* (all molluscs); *Miogypsina globulina*, *M. burdigaliensis*, *M. intermedia* (large benthic foraminifera) (Vigneaux 1971) and planktonic foraminifera of the *Globigerinatella insueta-Globigerinoides trilobus* Zone (Jenkins 1966).

Successively, Poignant & Pujol (1978) and Müller & Pujol (1979) indicated that the lower part of the Burdigalian belongs to the planktonic foraminiferal N5–6 Zones of Blow (1969), and to the calcareous nannofossil NN2 Zone of Martini (1971). Demarcq & Carbonnel (1975) designated the St-Paul-Trois-Chateaux section in the Rhône valley (see Pouyet et al. 1997) as the stratotype for the (upper) Burdigalian. Planktonic foraminifera indicate that the upper part of the Burdigalian starts in Zone N5 and ends in Zone N7 of Blow (1969). Martini (1988) placed the base of the stratotype of the Rhône valley within the calcareous nannofossil Zone NN2 and the top in NN2–NN3. Berggren et al. (1995) suggested placing the Aquitanian /Burdigalian boundary with the top of magneto-chron C6An.

◄ Fig. 6. **A**: Distribution patterns of selected *Sphenolithus* species in the GSSP of the Oligocene/Miocene boundary at Lemme-Carrosio Section; **B**: Bio-magnetostratigraphic correlation between DSDP Site 522 and Oligocene/Miocene GSSP (Lemme-Carrosio Section). Data from Raffi (1999).

Fig. 7A




5 Falun du Coquillat à *Euthriofusus burdigalensis*, *Cancellaria ocutangula*, *Turritella tcrebralis*, *Meretrix crycinoides*; 4 Lit à *Pectunculus*; 3 Sables à Operculines et à *Echinolampas Richardi*; 2 Molasse ossifere à *Scutella leognanensis*, *Squalodon Grateloupi*; 1 Calcaire d'eau douce de l'Aquitanien supérieur.

Fig. 7B

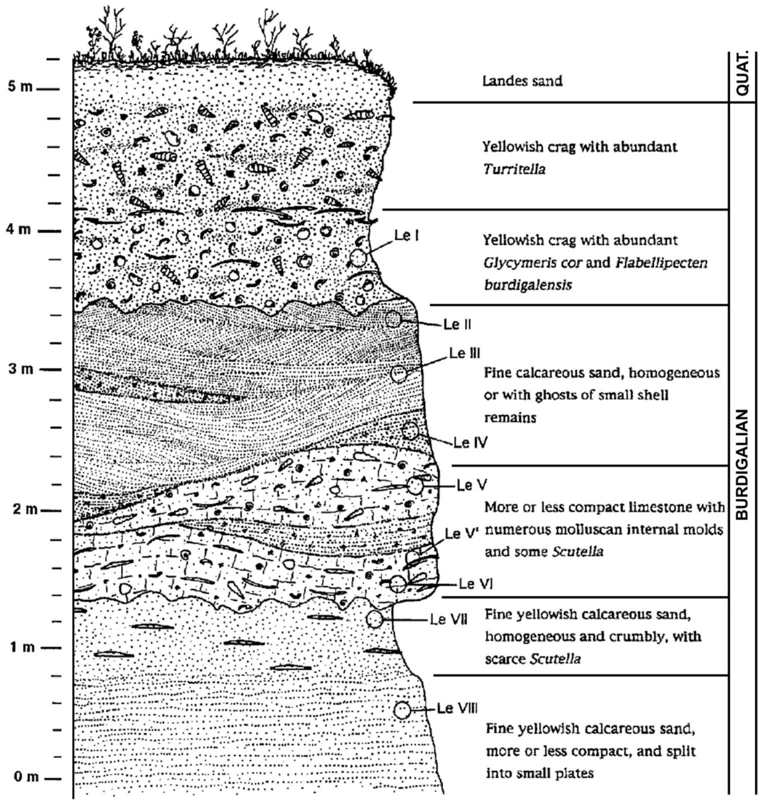



Fig. 7. **A**: Schematic section of lower and middle the Burdigalian historical stratotype of Le Conquilla section (Leognan) according to Daguin (1948); **B**: Burdigalian historical stratotype lithological log from Leognan section reported by Londeix & Chene (1998)

Sr-isotope stratigraphy from the lower crags with *Glycymeris cor* from the Coquillat section provided an age of ~20 Ma (Cahuzac et al. 1997) in agreement with the age of Bergreen et al. (1995).

In the recent literature different criteria have been adopted to identify or approximate the Aquitanian /Burdigalian boundary. In terms of calcareous plankton criteria, Berggren et al. (1995) proposed the LO of *P. kugleri*, Fornaciari & Rio (1996) used the FO of *Helicosphaera ampliaperta*, Haq et al. (1987) proposed the FO of *Sphenolithus belemnos*, and more recently Lourens et al. (2004) following Fornaciari & Rio (1996) placed the Aquitanian/Burdigalian boundary coinciding with the FO of *H. ampliaperta*. In addition, Berggren et al. (1995) suggested to place the Aquitanian/Burdigalian boundary with the magneto-chron C6An(y).

At present, potential candidate land sections where to define the Burdigalian GSSP are not documented. The Composite Contessa section (Montanari et al. 1997b) and the Santa Croce di Arcevia section (Coccioni et al. 1997) cropping out in the Umbria-Marche region (central Italy) are reported as two deep marine sequences containing all the bio-magneto-stratigraphic events spanning the Aquitanian/Burdigalian boundary. Unfortunately, the not well preserved planktonic foraminifera, the hard lithology and the poor bio-magnetostratigraphic correlation with the Lemme-Carrosio section (Aquitanian GSSP) make these two sections not suitable for high resolution studies (see Montanari et al. 1997b and Coccioni et al. 1997 for details).

The alternative option to define this boundary in ODP cores is seriously considered by the Subcommission on Neogene Stratigraphy (SNS). Anyway this option is very far from one of the main criteria used for defining a GSSP: accessibility. In fact, the choice of an ODP-Site means that it will not be possible to replay several time high resolution integrated studies. No specific working group has been designed for this issue by the SNS.

### Burdigalian GSSP

For the reasons listed above a GSSP for the Burdigalian has yet not been defined.

## Langhian

### Historical stratotype (Cita 1971)

The term Langhian was introduced by Pareto (1865), but no precise type locality was given for this stage of the Miocene, bracketed between the Bormidian (Vervoelet 1966; Cita 1971) below and the Serravallian above, and characterised dominantly by greyish sandy marls, Successively, Mayer-Eymar (1868) modified the concept of the Langhian limiting the term to the upper part of the succession mainly represented by marly lithologies with common Pteropods (Pteropods marls) ascribing to the Aquitanian the lower terrigenous facies.

Fig. 8A

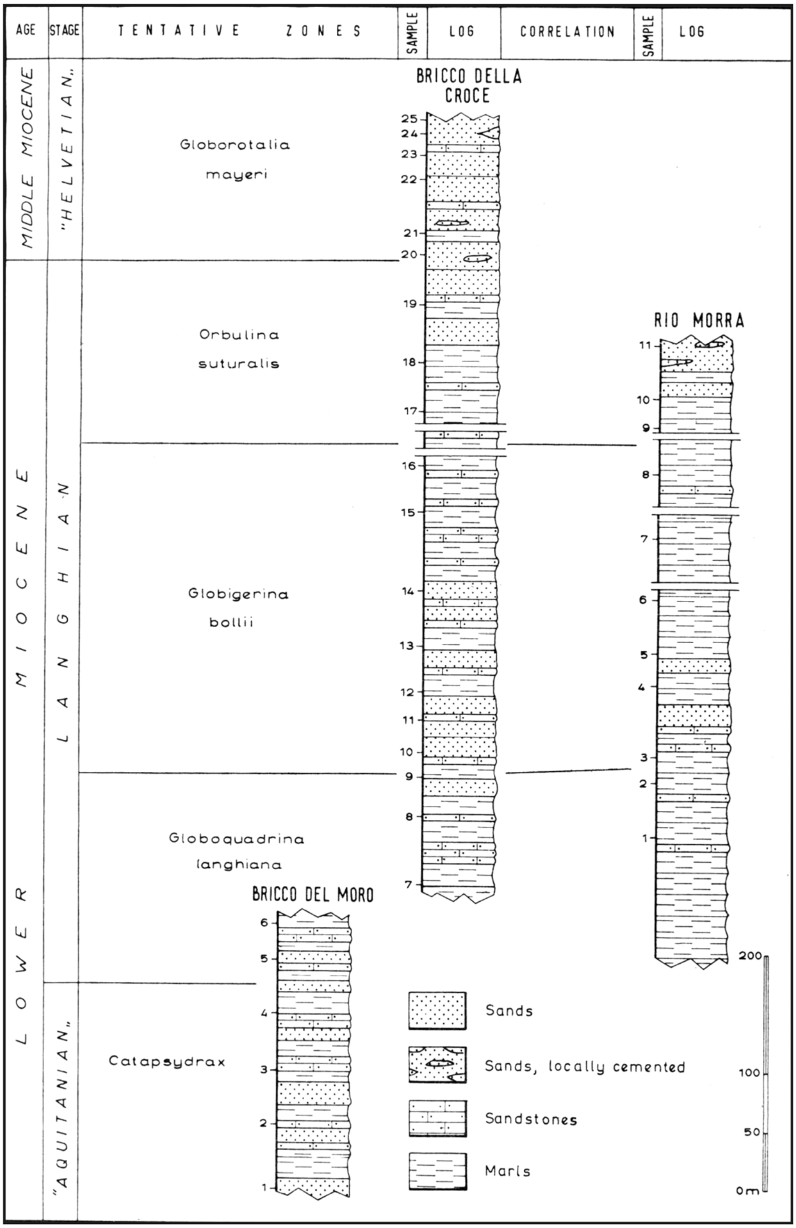
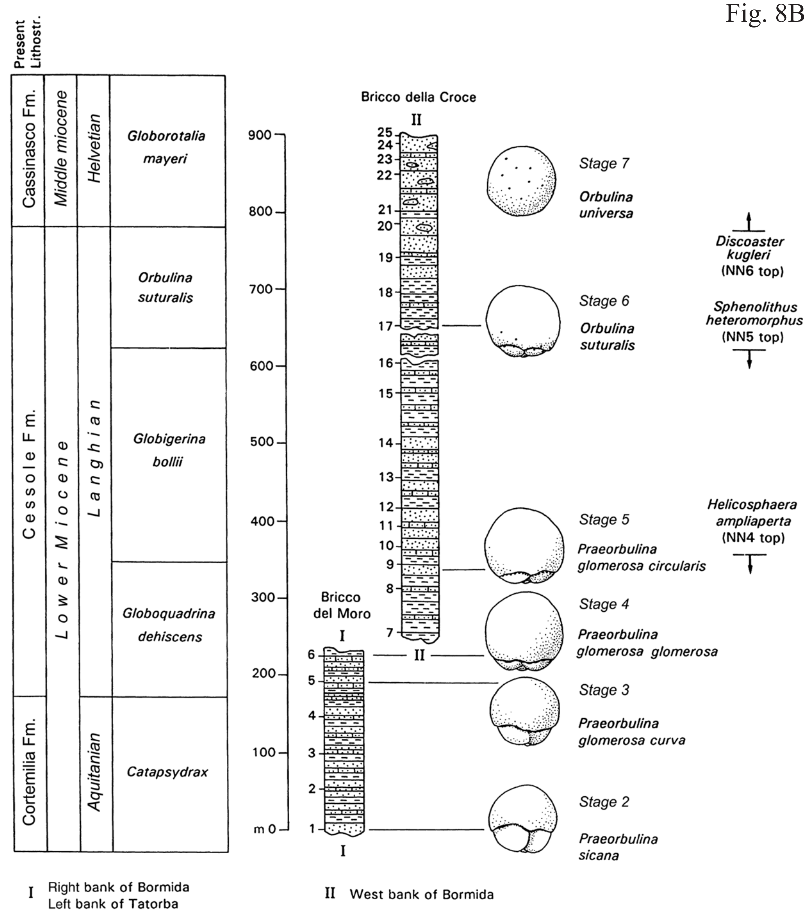



Fig. 8. **A**: Langhian stratotype of Cita & Premoli Silva (1960); **B**: Summary of the biostratigraphy data for the Langhian stratotype section with the main stages of the *Praeorbulina-Orbulina* evolutionary lineage after Rio et al. (1997). Calcareous nannofossils data after Martini (1971).

Fig. 8B




The type section of the Langhian (Fig. 1) described by Cita & Premoli Silva (1960) near the Cessole village, within the Langhe area (Bormida valley, Piedmont northern Italy) is composed of Bricco del Moro and Bricco della Croce sections (Fig. 8a). The type Langhian is represented by marly sediments (Pteropod marls), known in literature as Cessole Formation (Vervloet 1966) or Cessole Marls (Boni 1967; Gelati 1968). Gelati et al. (1993) assigned the type Langhian to a single depositional sequence which has been correlated to the 3rd-order cycle2.3, supercycle TB2 of the Global Cycle Chart of Haq et al. (1988).

Calcareous plankton biostratigraphy has been firstly produced by Cita & Premoli Silva (1960) (Fig. 8a) and by Martini (1968, 1971). According to their data the first evolutionary appearance of the planktonic foraminifer *Praeorbulina glomerosa* has been detected at the base of the type Langhian (very close to the base of the Cessole Marls) (Fig.8b). Therefore, historically, the base of the Langhian has been approximated by the *Praeorbulina* datum. This criterion for defining the base of the Langhian stage has

Fig. 9A

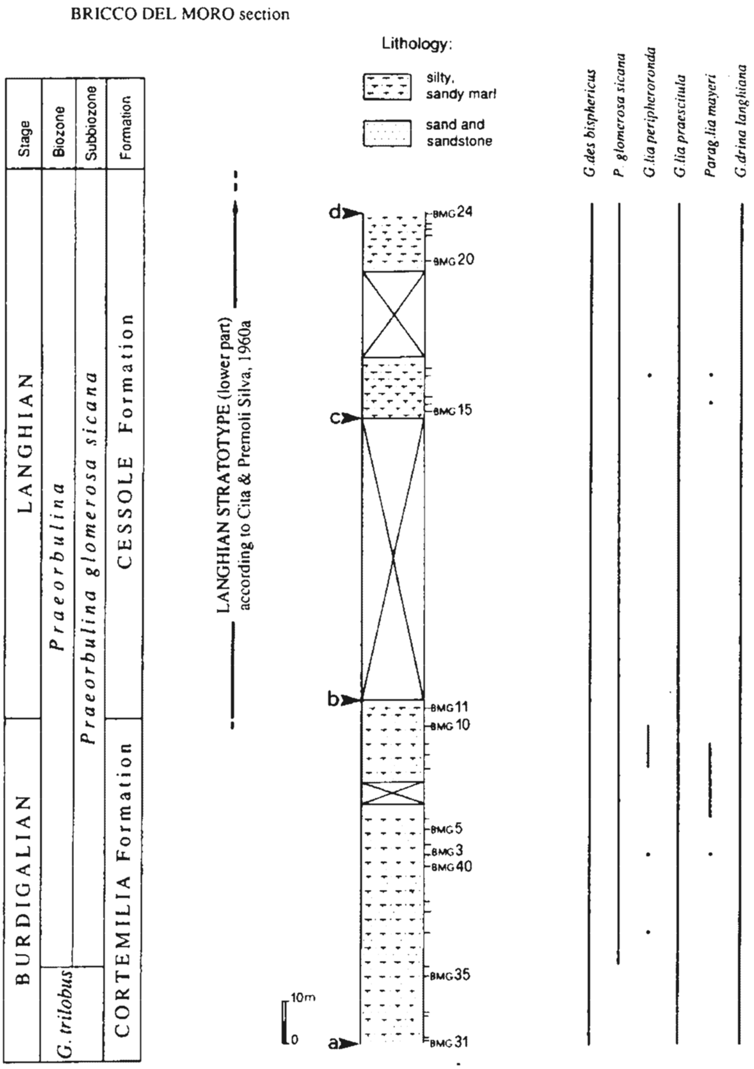
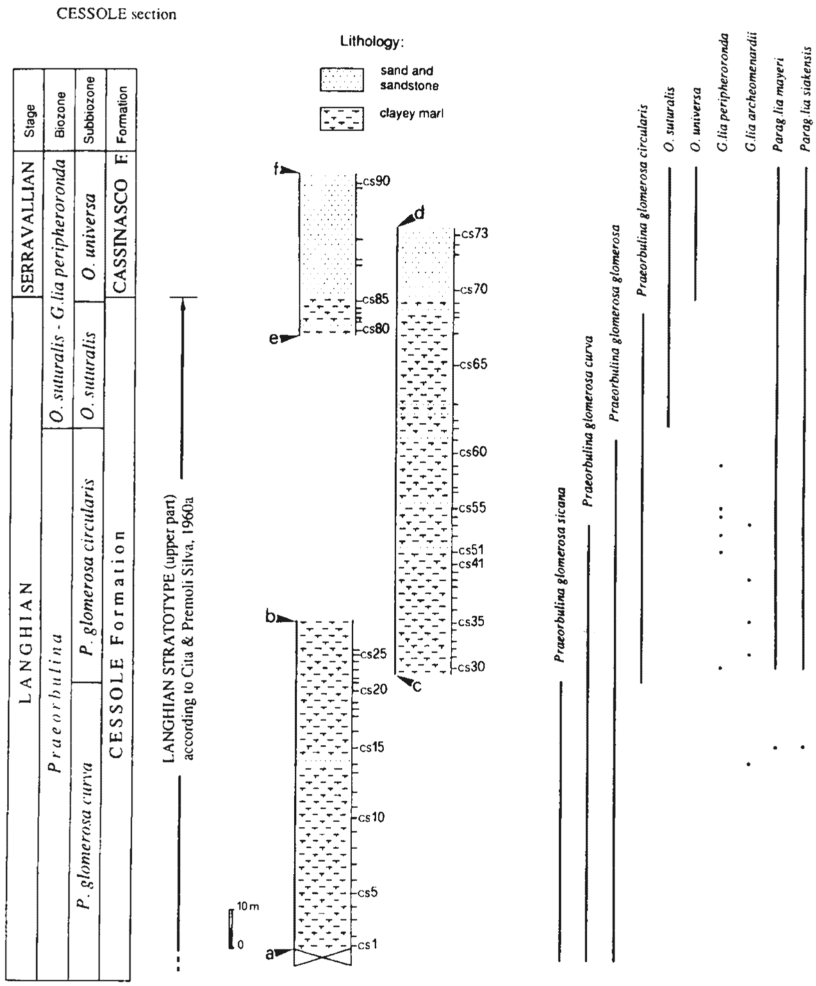



Fig. 9. Planktonic foraminiferal biostratigraphy of the middle (**A**) and upper (**B**) part of historical Langhian stratotype after MICULAN (1994)

been adopted in the modern Geological Time Scale (i.e. BERGGREN et al. 1985, 1995). In terms of calcareous nannofossils, MARTINI (1968, 1971) suggested that the base of the Langhian predates the last occurrence (LO) of *H. ampliaperta* and contains *Sphenolithus heteromorphus* (NN4 Zone of MARTINI 1971).

MICULAN (1994) proposed a first update planktonic foraminifer biostratigraphy of the Langhian stratotype (Figs 9a and 9b), which was revisited also by FORNACIARI et al.

Fig. 9B




(1997) combining planktonic foraminifera and calcareous nannofossils data (Fig. 10). In both papers the *Praeorbulina* datum (given as FO of *P. sicana*) occurs within the Cortemilia Formation about 100 meters below the base of the Cessole Marls. *Praeorbulina glomerosa curva* first occurs at the base of the Cessole Marls (MICULAN 1994; FORNACIARI et al. 1997a). The FO of *Orbulina universa* (last step of the *Globigerinoides*-*Orbulina* evolutionary lineage) is recorded at the top of the Cessole Marls (MICULAN 1994; FORESI 1993; FORNACIARI et al. 1997a) (Fig. 10). *H. ampliaperta* and *S. heteromorphus* are common and continuously present in the Bricco del Moro, while in the Bricco della Croce *H. ampliaperta* is missing and *S. heteromorphus* is in very low abundance in the lowermost 30 m (paracme). Therefore the Langhian stratotype extends from Zone NN4 (pars) to NN5 of MARTINI (1971) (FORNACIARI et al. 1997a) (Fig. 10).

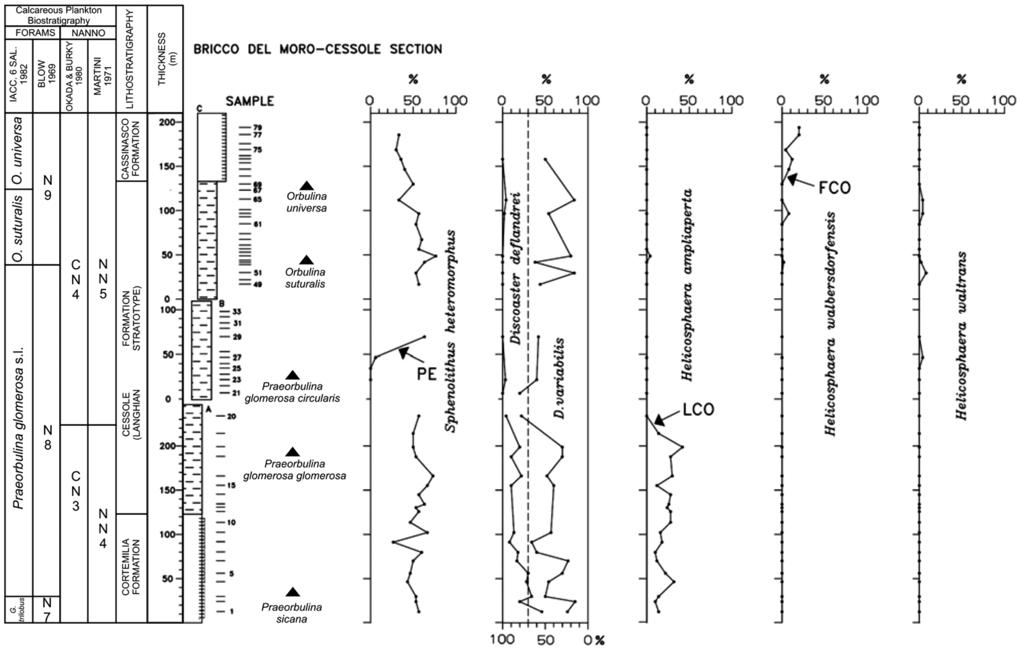



Fig. 10. Calcareous plankton biostratigraphy of historical Langhian stratotype after FORNACIARI et al. (1997)

## Langhian GSSP (not yet defined)

According to RIO et al. (1997) the GSSP of the Langhian should be close to Chron C5Cn and the *Praeorbulina* datum. LOURENS et al. (2004), in the new ATNTS2004 provisionally placed the Langhian GSSP as coinciding with the top of C5Cn.1n dated astronomically at 15.974 Ma.

During the last RCMNS congress held in Naples (2009) TURCO (University of Parma) and FORESI (University of Siena) illustrated the integrated stratigraphy respectively of the La Vedova (Conero Area, Central Italy, IACCARINO et al. 2009) and S. Peter's Pool (Malta Island, MAZZEI et al. 2009) sections. Both sections could be potential candidate to locate the Langhian GSSP. At present, Italian and Netherland research groups are working for the identification of the best candidate section to define the Langhian GSSP and also for the selection of the best criteria identifying the base of the Langhian (TURCO et al. in press; FORESI et al. in press, IACCARINO et al. submitted). In fact, the *Praeorbulina* datum, the historical bioevent approximating the base of the Langhian, is generally very rare, difficult to be detected.

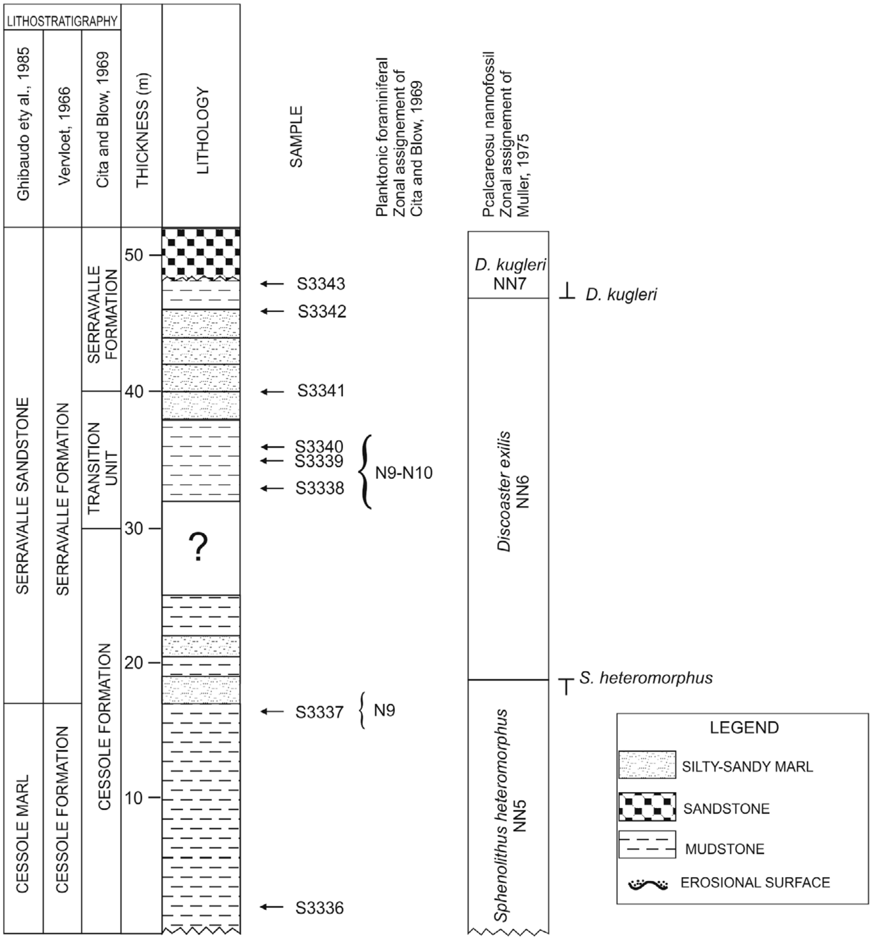



Fig. 11. Summary of calcareous plankton data of the historical Serravallian stratotype section provided by CITA & BLOW (1969) and by MÜLLER (1975) after RIO et al. (1997)

## Serravallian

### Historical stratotype (BONI & SELLI 1971)

The Serravallian Stage was introduced by PARETO in 1865, but after its introduction, it was soon abandoned in favour of the Helvetian erected by MAYER-EYMAR in 1858. Lately, the term Serravallian was revived (CITA & ELTER 1960; CITA 1964; VERVLOET 1966) after it was realized that the type Helvetian was time-equivalent with the Burdigalian [Regional Committee on Mediterranean Neogene Stratigraphy (RCMNS) congress, Vienna, 1959]. In 1975 at the Bratislava RCMNS Congress, the Serravallian was officially introduced in the Standard Chronostratigraphic Scale as the stage above the Langhian and below the Tortonian.

Fig. 12A

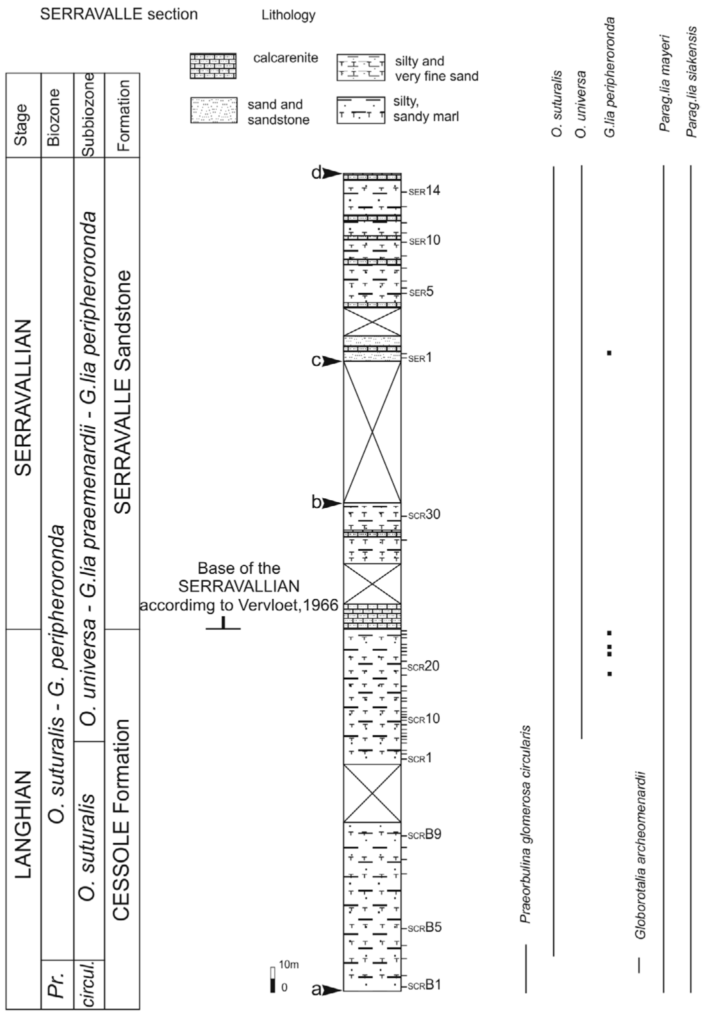
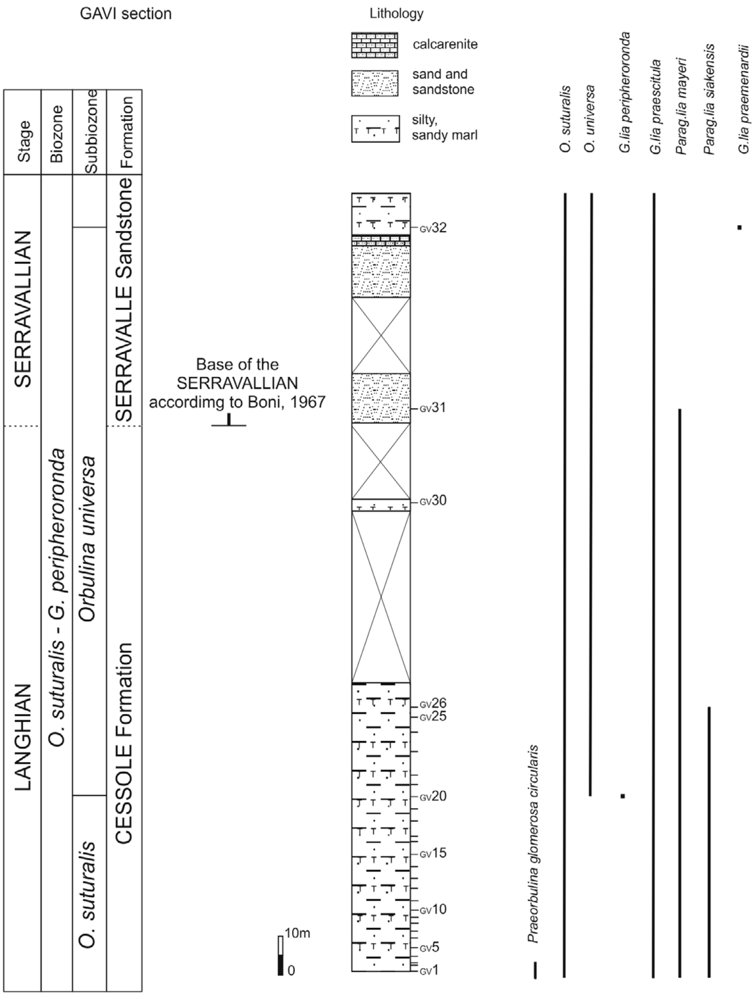



Fig. 12. Planktonic foraminiferal biostratigraphy of the historical Serravallian stratotype (**A**) and historical parastratotype (**B**) after MICULAN (1994).

Fig. 12B




The Serravallian stratotype section was described by VERVLOET (1966), along the western bank of the Scrivia river, close to the Serravalle Scrivia village (Piedmont Tertiary Basin, northern Italy) (Fig. 1). The Serravallian stratotype corresponds to the Serravalle Formation (VERVLOET 1966) which is mainly composed of a shallow-water sandy unit (CAPRARA et al. 1985; GHIBAUDO et al. 1985; GNACCOLINI 1989) overlying the deep-water Cessole Formation (Langhian stratotype) (Fig. 11). In IACCARINO (1985) all the biostratigraphic data of VERVLOET (1966) and CITA & BLOW (1969) who recorded *O. universa* and *G. peripheroronda* (Fig. 11, by RIO et al. 1997), are reported. Lately by FORESI (1993) and MICULAN (1994) (Figs 12a and 12b) recorded the FO of *O. universa* in the uppermost part of the Cessole formation. Calcareous nannofossils, previously studied by MÜLLER (1975), have again been studied by FORNACIARI et al. (1997b) (Fig. 13).

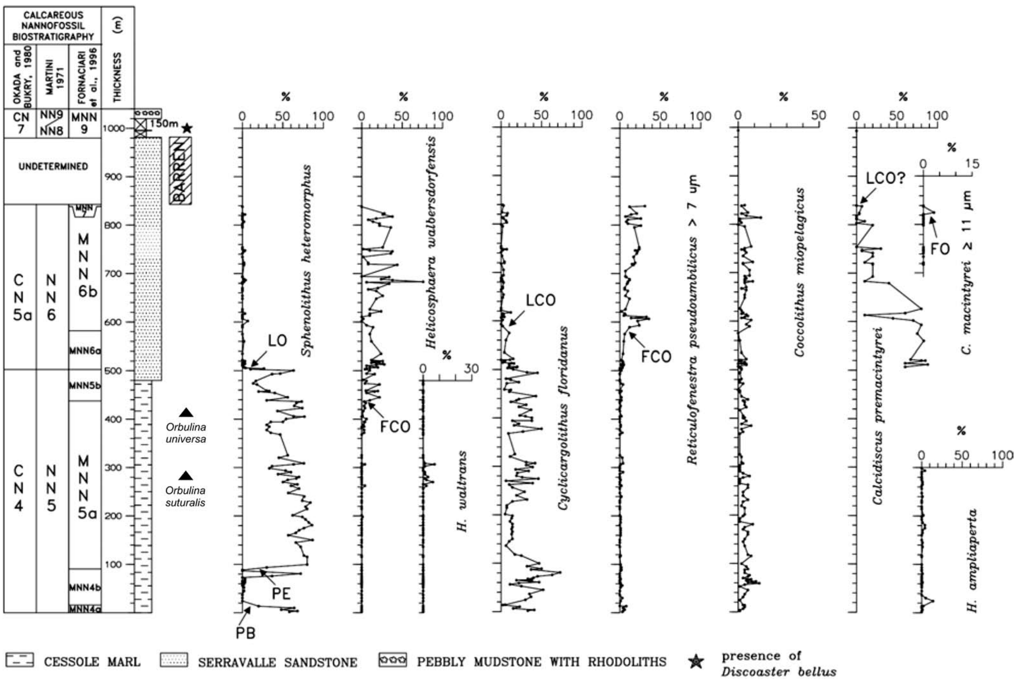



Fig. 13. Calcareous plankton biostratigraphy of historical Serravallian stratotype after FORNACIARI et al. (1997).


Fig. 14. Ras il Pellegrin section (Malta): GSSP for the base of the Serravallian Stage (Middle Miocene).

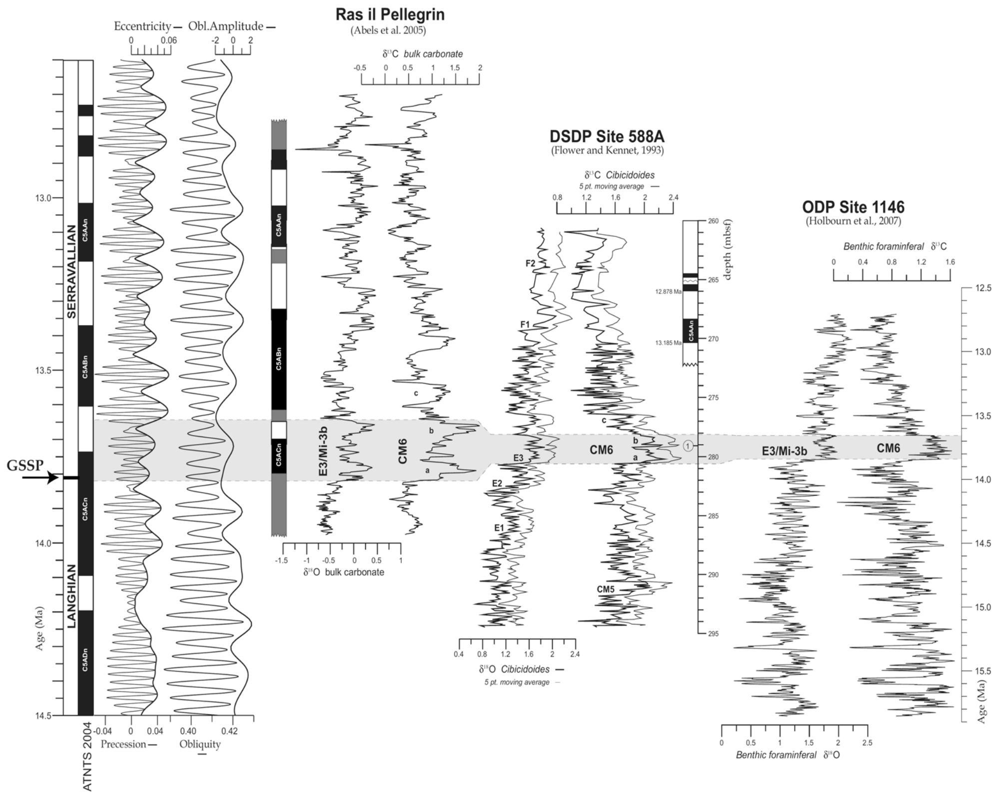



Fig. 15. Ras il Pellegrin section: position of the major Miller glaciation event Mi-3b, astronomically dated at 13.82 Ma and globally recorded in the Mediterranean and oceanic areas by oxygen isotopes (ABELS et al. 2005)

At present, all the authors agree that the base of the Serravallian stratotype postdates the FO of *O. universa* (Fig.12: VERVLOET 1966; BONI 1967). Calcareous nannofossils (FORNACIARI et al. 1997a, 1997b) indicated that the base of Serravallian corresponds almost perfectly with the *S. heteromorphus* LO (Fig. 13). According to this calcareous nannofossil datum, also combined with that recorded in oceanic areas, RIO et al. (1997) and FORNACIARI et al. (1997b) clearly recommended to use the LO of *S. heteromorphus*, as the driving criterion in selecting the Serravallian GSSP, in agreement with the position in time of the base of the historical stratotype which is unsuitable as reference record because of its shallow water sediments.

## Serravallian GSSP (HILGEN et al. 2009)

The Global Stratotype Section and Point (GSSP) for the base of the Serravallian Stage (Middle Miocene) is defined in the Ras il Pellegrin section located in the coastal cliffs along the Fomm Ir-Rih Bay on the west coast of Malta Island (HILGEN et al. 2009, Fig. 14).

Fig. 16A

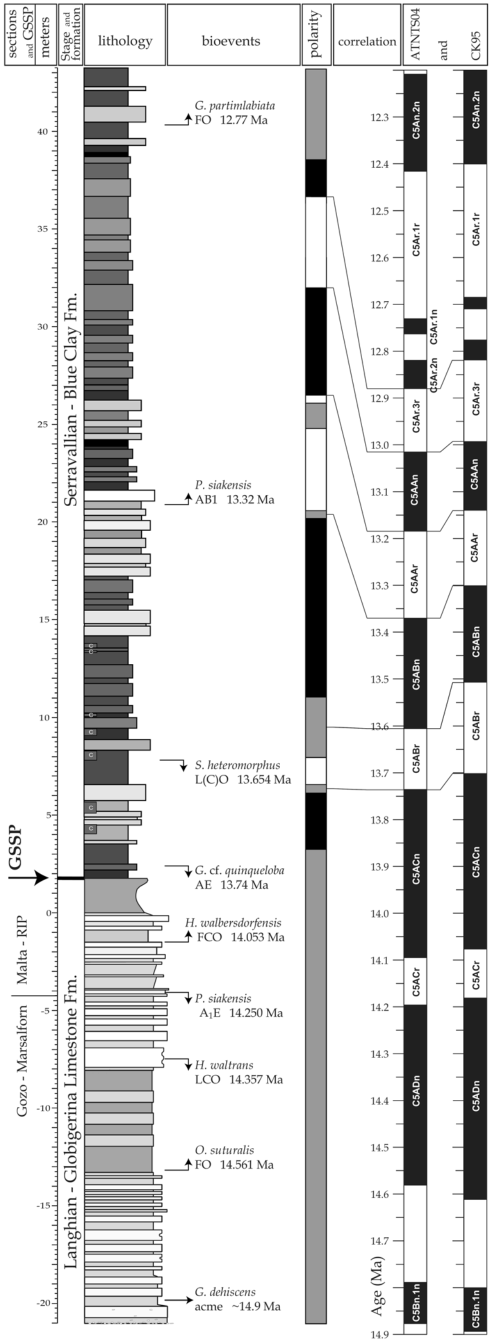
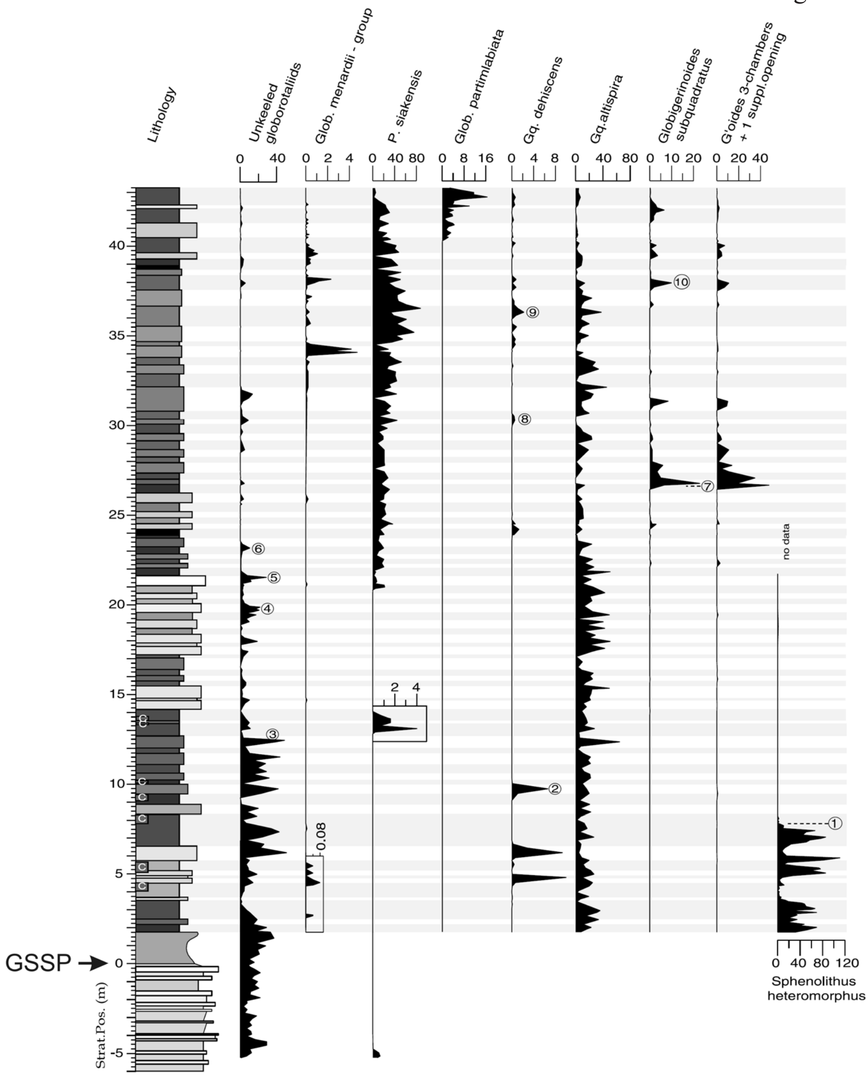



Fig. 16. Ras il Pellegrin section: **A**: Bio-magneto-stratigraphic framework (HILGEN et al. 2009); **B**: quantitative distribution of selected planktonic foraminifers and calcareous nannofossils (ABELS et al. 2005).

Fig. 16B




The Langhian/Serravallian boundary coincides with the end of the major Miller glaciation event Mi-3b (Fig. 15), astronomically dated at 13.82 Ma, and globally recorded in the Mediterranean and oceanic areas by oxygen isotopes (ABELS et al. 2005; HOLBOURN et al. 2005, 2007). The glaciation event Mi-3b is associated to the major glacio-eustatic sea-level drop corresponding with sequence boundary Ser1 of HARDENBOL et al. (1998) and theoretically with the TB2.5 sequence boundary of HAQ et al. (1987).

Fig. 17A

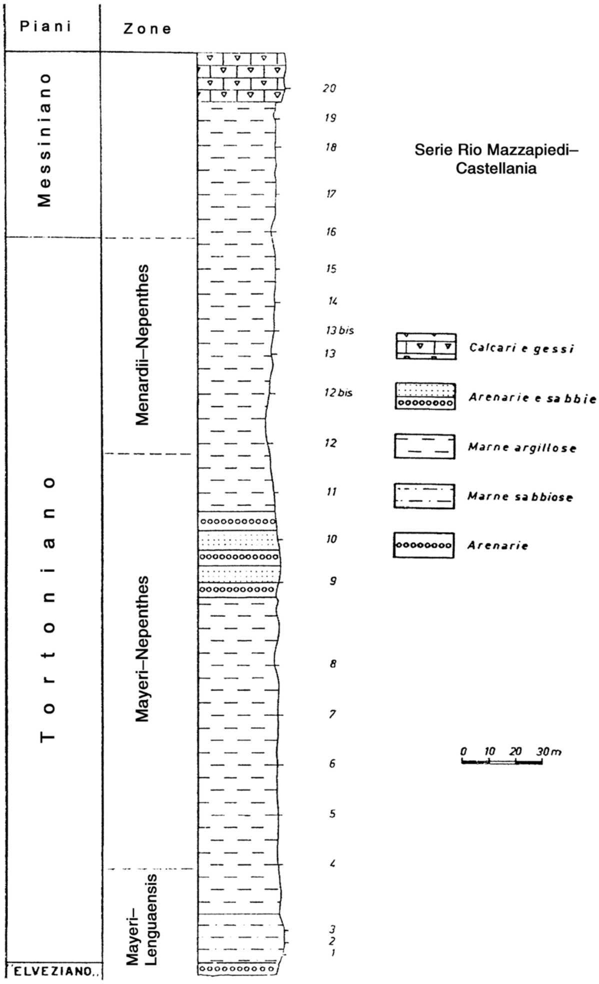
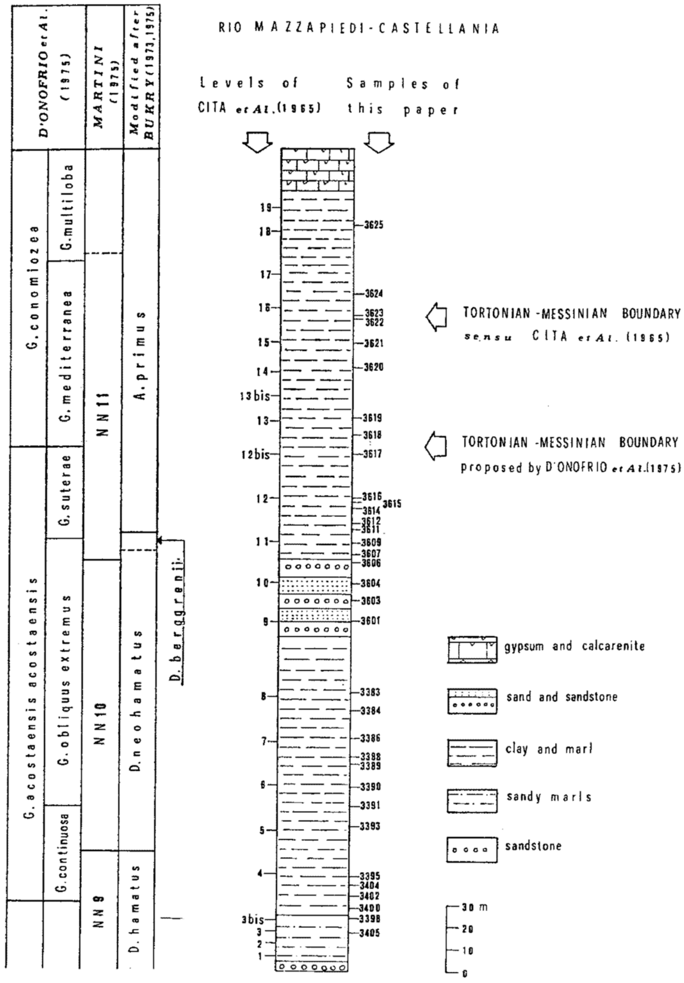



Fig. 17. **A**: Lithology and zonation of the historical Tortonian stratotype after Cita et al. (1965); **B**: calcareous plankton biostratigraphy of historical Tortonian stratotype (Mazzei 1977)

The GSSP is located at the base of the greyish clayey Blue Clay Formation, at the top of the transitional bed of the yellowish marly Upper Globigerina Limestone at the Ras il Pellegrin section (see for detail Hilgen et al. 2009; Abels et al. 2005; Foresi et al. 2002b). The entire Ras il Pellegrin section, 64 meters thick, is composed of the uppermost 23 m of Globigerina Limestone and 41 m of Blue Clay (Abels et al. 2005 for details). In particular, the Blue Clay Formation reveals six whitish coloured marly intervals separated by intervals dominated by grey marls (Fig. 14), corresponding to the large-scale cyclicity previously recognised by Sprovieri M. et al. (2002), John et al. (2003) and Abels et al.

Fig. 17B



(2005). The astronomical tuning of the Blue Clay provided ages for all the bio-magneto-stratigraphic events (ABELS et al. 2005; HILGEN et al. 2009). The GSSP occurs within the top part of magneto-Chron C5ACn, predates (166 kyr) the LCO of *S. heteromorphus* (see DI STEFANO et al. 2008 and ABDUL AZIZ et al. 2008 for a complete discussion concerning the LO and LCO of *S. heteromorphus*), the guiding criterion suggested by RIO et al. (1997) to define the base of the Serravallian and postdates the FCO of *Helicosphaera walbersdorfensis* (Figs 16a and 16b). The first useful planktonic foraminiferal bio-event close to the GSSP is the LO of G*loborotalia peripheroronda* which is about 270 kyr younger than the base of the Serravallian (Fig. 16b).

## Tortonian

### Historical stratotype (Cita 1971)

The Tortonian Stage ("Tortonische Stufe") was introduced by Mayer in 1858 and the stratotype of the Tortonian has been designated by Gianotti (1953) in the section outcropping in the valley of Rio Mazzapiedi and Rio Castellania some 10 km south of Tortona (Alessandria, north Italy) (Fig. 1). The stratotype consists of marly sediments [(the Sant' Agata Fossili marls of Ghibaudo et al. (1985) and Castellania Formation *sensu* Vervloet (1966)], which are subdivided into two members (Clari & Ghibaudo 1979). The lower member is composed of bioturbated fine sandstones alternating with clayey siltstones (180 meter thick) while the upper member consists of an 80 m thick succession of blue-grey hemipelagic silty marls with thin turbidites in the upper part. Biota and lithofacies associations indicate an outer shelf and slope environment, respectively.

After the first studies on the foraminifera (Gianotti 1953; Cita et al. 1965) (Fig. 17a), calcareous plankton has been studied by Cita & Blow (1969) and D'Onofrio et al. (1975) (planktonic foraminifera) and by Martini (1971) and Mazzei (1977) (calcareous nannofossils) (Fig. 17b). Magnetostratigraphic investigation was carried out by Nakagawa et al. (1974), but the obtained results were not quite confident (Rio et al. 1997).

Historically, the biohorizon most used to rcognised the base of the Tortonian was the FO of *Neogloboquadrina acostaensis* recorded from the basal part Tortonian stratotype section of Rio Mazzapiedi-Castellania (Cita & Blow 1969; D'Onofrio et al. 1975; Miculan 1997) (Figs18a and 18b). In terms of calcareous nannofossils the basal part of the Tortonian was assigned to nannofossil Zone NN9 on the basis of the presence of the zonal marker *Discoaster hamatus* (Mazzei 1977) (Fig. 17b).

Rio et al. (1997) first pointed out biostratigraphic problems concerning the base of the Tortonian, suggesting that the FO of *N. acostaensis* in the Tortonian stratotype section might be a delayed entrance, possibly related to the unfavourable ecological conditions. Foresi et al. (1998) throughout the re-examination of the calcareous plankton biostratigraphy of the historical stratotype suggested that the LO of *Paragloborotalia siakensis*, the FCO of *N. acostaensis* and the FO of *Discoaster hamatus*, occurring close to the base of the historical stratotype, showed that the *N. acostaensis* FO at Rio Mazzapiedi-Castellania does not represent the true first occurrence of this taxon, as confirmed by the presence of rare specimens of *N. acostaensis* in the top part of the Serravalle Sandstones just below the base of the Tortonian stratotype (Miculan 1997) (Fig. 18b) and Foresi et al. (1998) (Figs 19a and 19b). These data confirmed that the base of the Tortonian stratotype post-dates the FO of *N. acostaensis* rendering useless this datum as guiding criterion to identify the base of this stage. In particular, the base of the Tortonian stratotype coincides almost

Fig. 18A

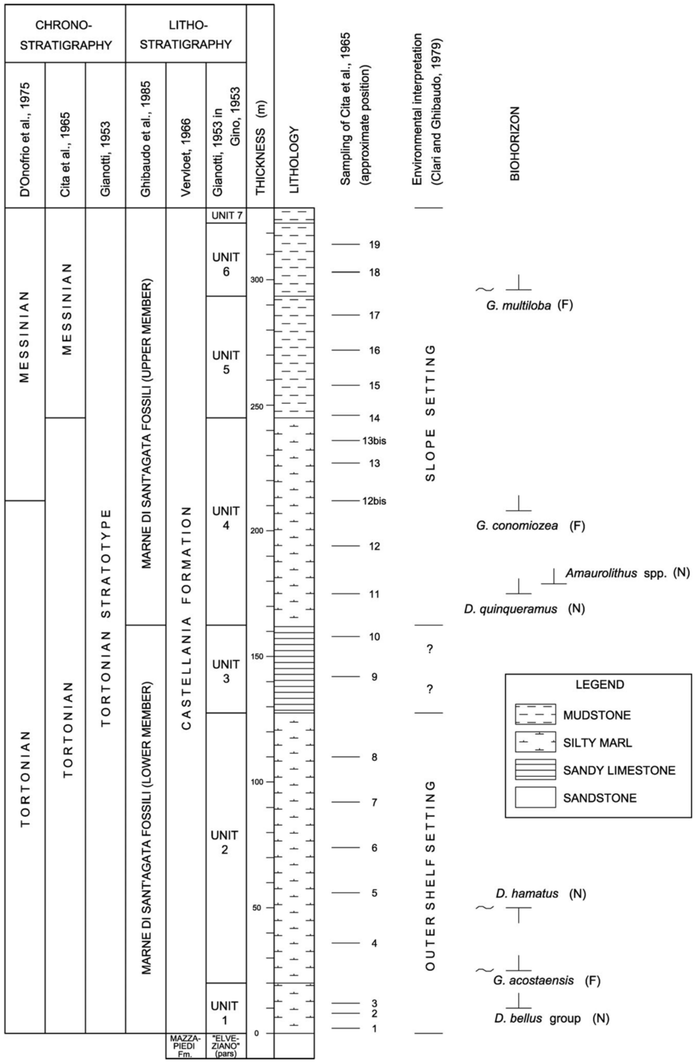
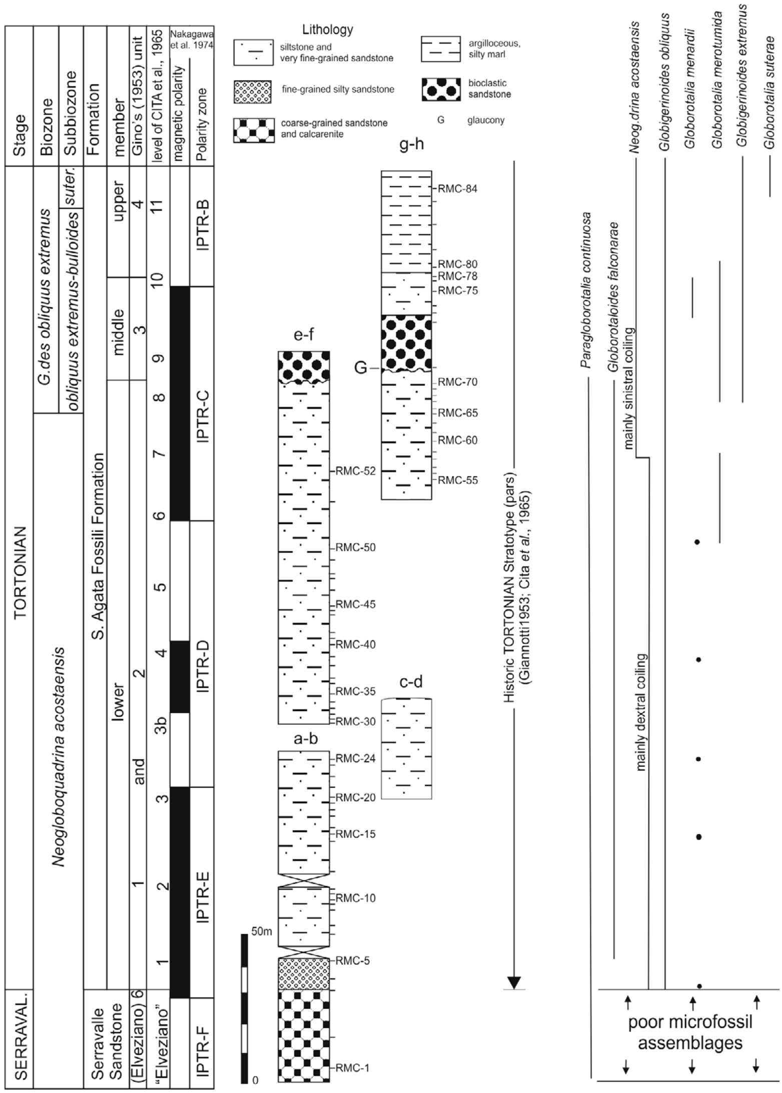



Fig. 18. **A**: Summary of calcareous plankton data for the historical Tortonian stratotype section provided by CITA & BLOW (1969), MARTINI (1975), D'ONOFRIO et al. (1975) and MARTINI (1977) after RIO et al. (1997); **B**: Planktonic foraminiferal biostratigraphy of the historical Tortonian stratotype after MICULAN (1997).

Fig. 18B




with the First Regular Occurrence (FRO) of *N. acostaensis* (=FCO in Foresi et al. 1998) dominantly right coiled (see for a deep explanation Foresi et al. 1998; Hilgen et al. 2000, 2005) which occurs below the *D. hamatus* FO (Hilgen et al. 2000b), well lower respect to that reported by Foresi et al. (1998) (Figs 19a and 19b).

Foresi et al. (2002b) suggested the LCO of *Globigerinoides subquadratus* as a potential criterion to paleontologically recognise the GSSP of the Tortonian, for its synchroneity between Mediterranean and low latitude ocean as reported by Turco et al. (2002) and Lirer & Iaccarino (2005).

Fig. 19A

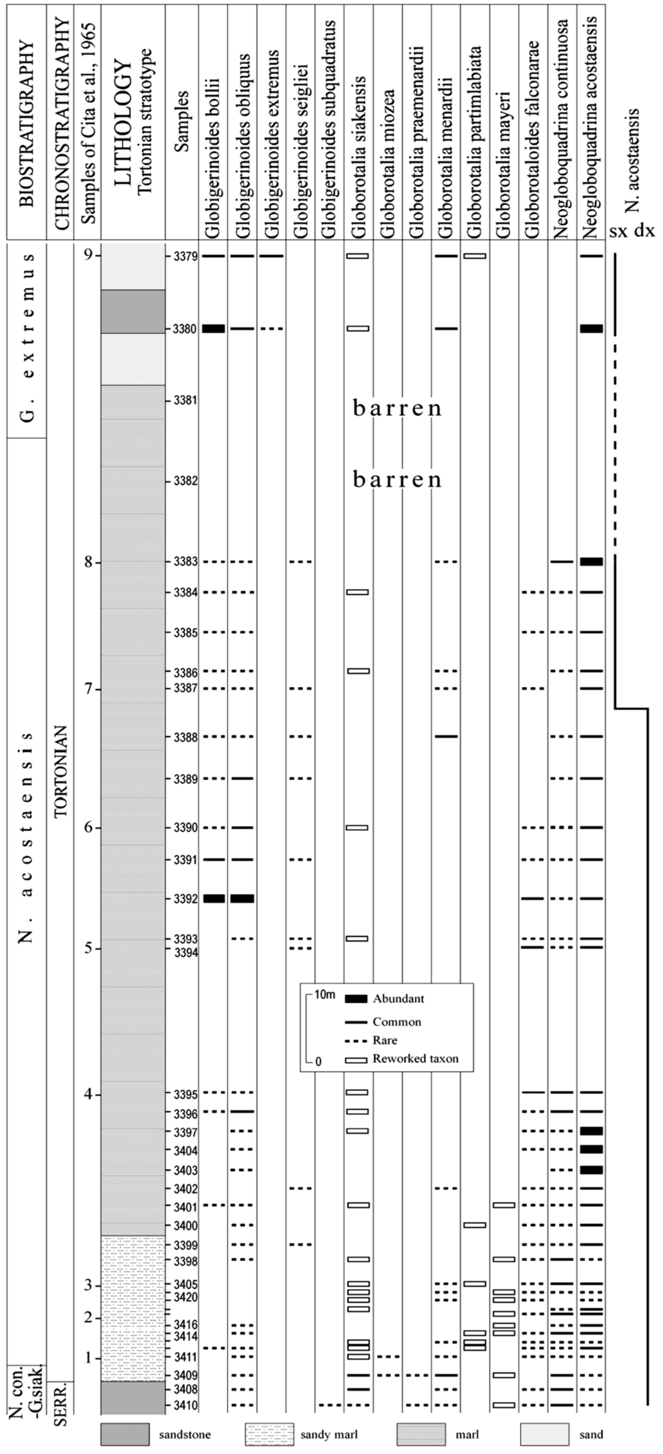
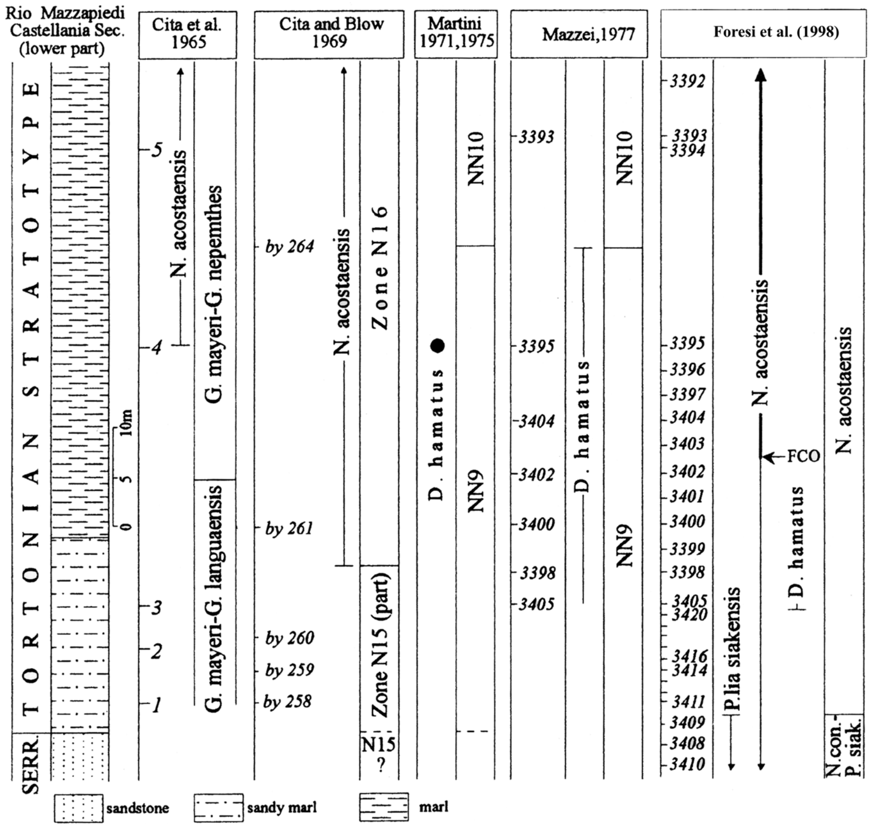


Fig. 19. **A**: planktonic foraminiferal biostratigraphy of historical Tortonian stratotype after FORESI et al. (1998); **B**: comparison of the biostratigraphy data reported for the base of the historical Tortonian stratotype after FORESI et al. (1998).

Fig. 19B




## Tortonian GSSP (Hilgen et al. 2005)

The GSSP for the base of the Tortonian Stage (Late Miocene) is defined in the Monte dei Corvi beach section (Hilgen et al. 2005) in the Conero area (northern-central Italy). The Monte dei Corvi Beach section (Montanari et al. 1997a), 91 meters thick, contains the upper part of the marly Schlier Formation and consists of a cyclic alternation of greenish-grey marls, whitish marly limestones and brown coloured organic-rich layers (sapropels). In addition, two biotite-rich volcanic ash layers occur, named Respighi and Ancona (Fig. 20) dated 12.94 Ma and 11.68 Ma respectively with 40Ar/39Ar (see Hilgen et al. 2005 for details).

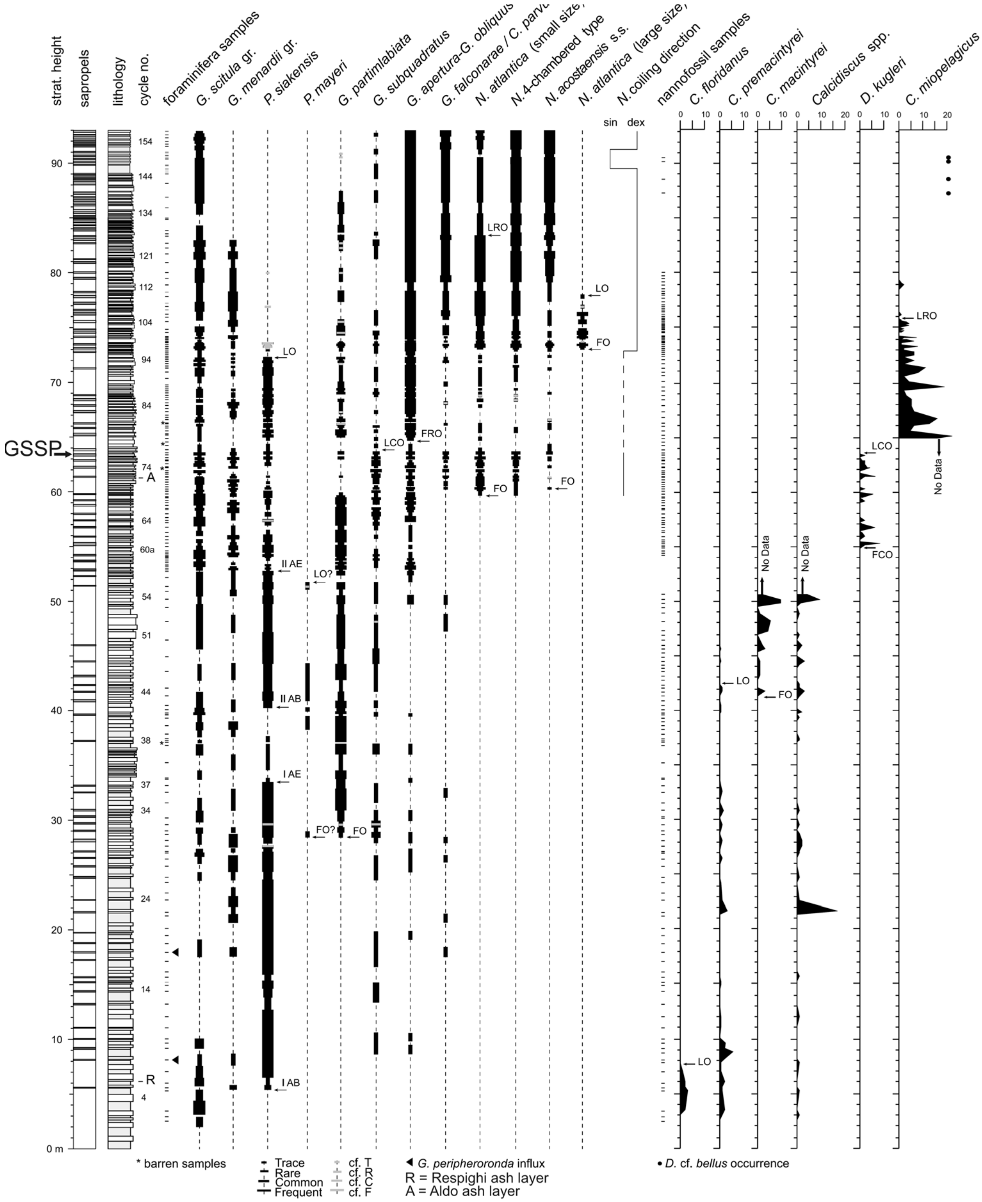



Fig. 20. Quantitative distribution of planktonic foraminifers and selected calcareous nannofossils from Monte dei Corvi section (Tortonian GSSP) (HILGEN et al. 2005).

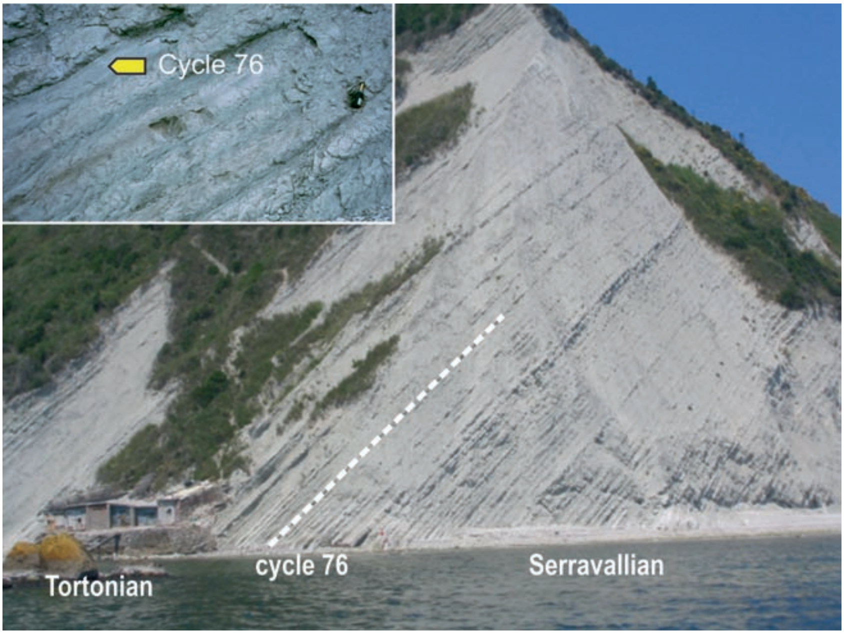



Fig. 21. Monte dei Corvi section (Conero area, central Italy): GSSP for the base of the Tortonian Stage. Cycle 76 corresponds to the Tortonian GSSP.

The GSSP coincides with lithological cycle 76 (Fig. 21) astronomically dated at 11.6 Ma (Hilgen et al. 2003, 2005), is close to the LCO of *Discoaster kugleri* and the LCO of *G. subquadratus* (Fig. 20) which are synchronous events between the mid- and low-latitudes (Lourens et al. 2004; Lirer & Iaccarino 2005), and it is associated with the short normal subchron C5r.2n (Fig. 22).

The Tortonian GSSP level closely approximates the oxygen isotope glaciation event Mi-5 of Miller et al. (1991) and it is associated to the glacio-eustatic sea-level low-stand of supercycle T3.1 (Fig. 23). Unfortunately, a reliable stable isotope record has not been obtained from Monte dei Corvi Beach section due to the poor preservation of the planktonic and benthic foraminiferal tests, so that this interpretation is based on stable isotope data from Monte Gibliscemi (Sicily) section used as the auxiliary section for the Serravallian-Tortonian boundary (see Turco et al. 2001). The detailed high resolution calcareous plankton biostratigraphy of Gibliscemi and Monte dei Corvi sections strongly confirms the cyclostratigraphic (“bed-to-bed”) correlation between the two deep marine records (Hilgen et al. 2003).

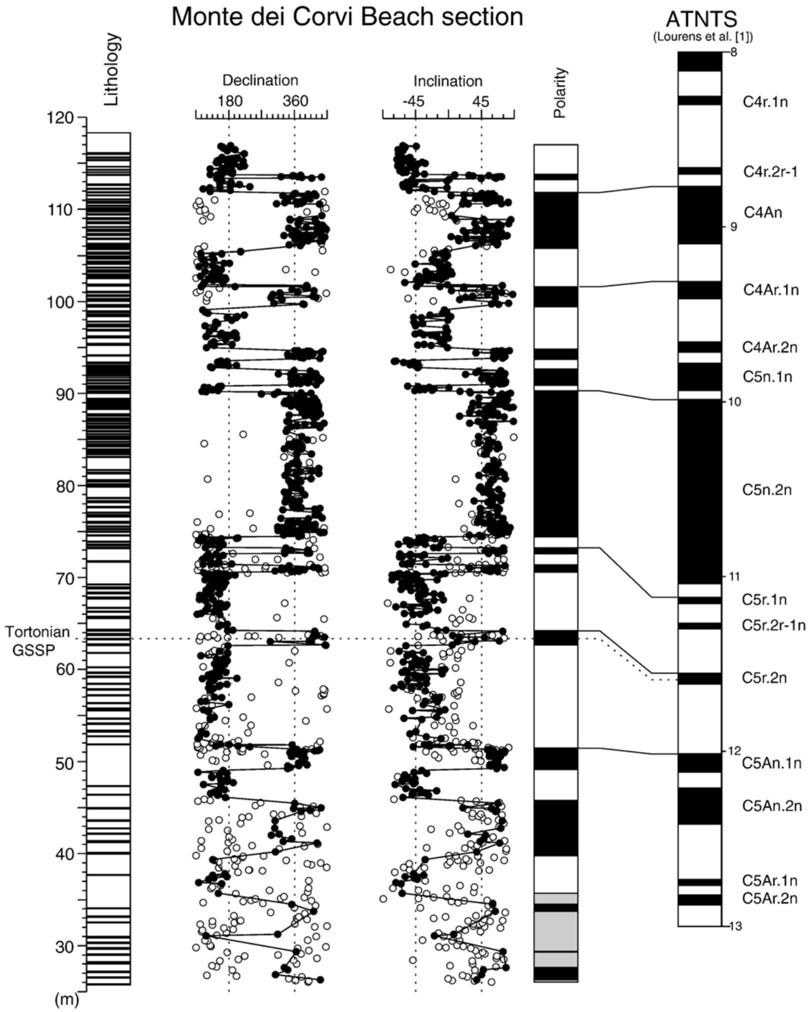



Fig. 22. Monte dei Corvi section: Magnetostratigraphy of the Tortonian GSSP (HÜSING et al. 2007).

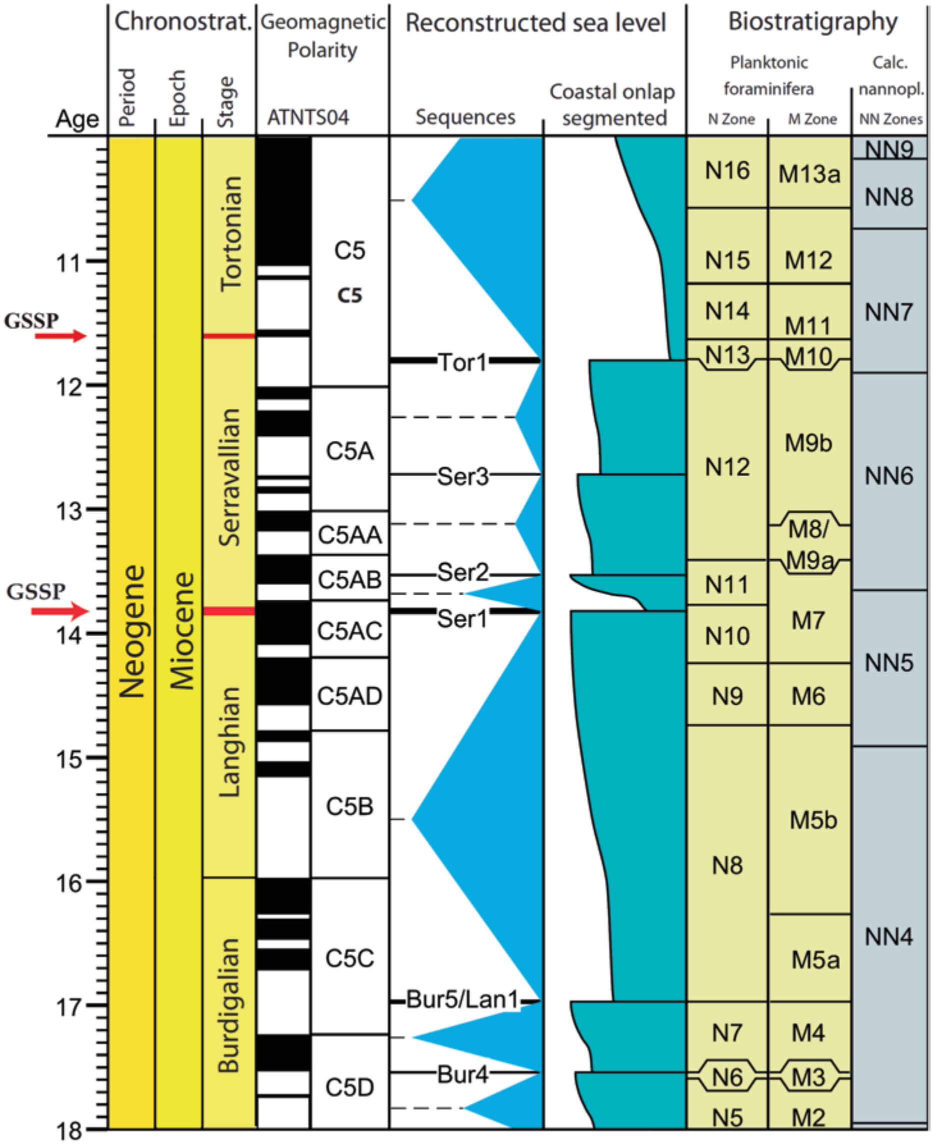



Fig. 23. Bio-magneto-integrated stratigraphy with the position of the Tortonian and Serravallian GSSPs, the reconstructed sea level and segmented coastal onlap (after HARDENBOL et al. 1998), the planktonic foraminiferal N and M biozones (BLOW 1969 and BERGGREN et al. 1995) and the calcareous nannofossil NN zones (after RAFFI et al. 2006) (HILGEN et al. 2009)

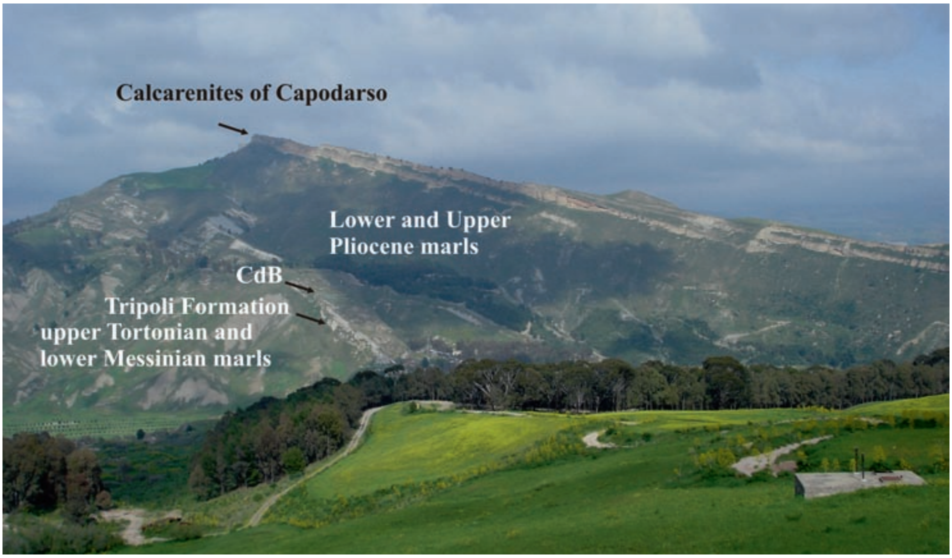



Fig. 24. Pasquasia-Capodarso section (Sicily): Historical Messinian stratotype. Photo gently offered by A. Caruso.

Fig. 25A

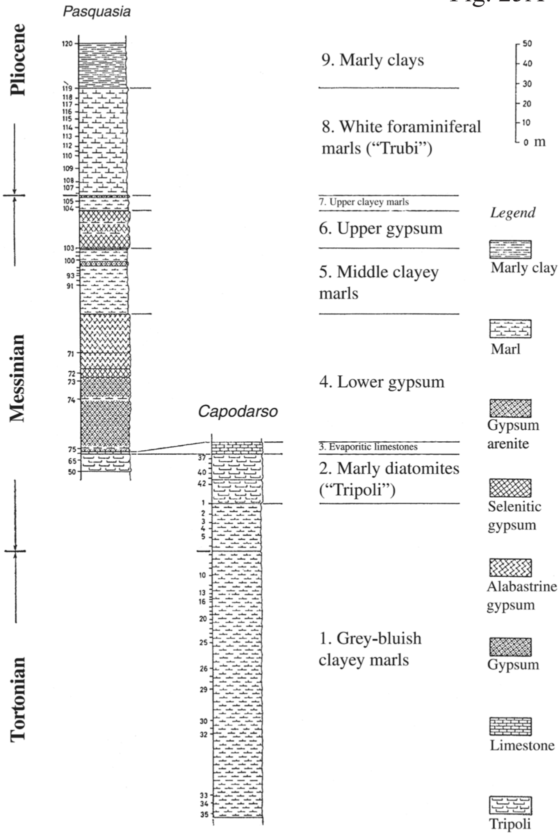
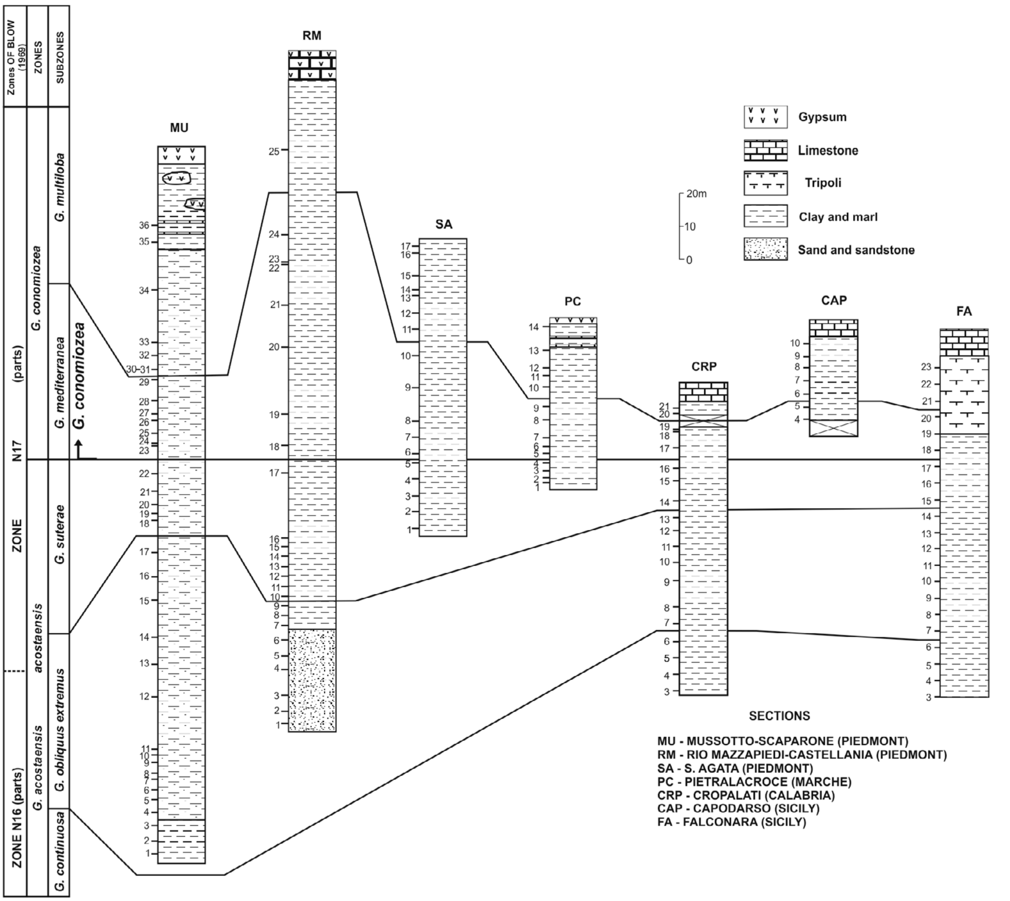



Fig. 25. **A**: Pasquasia-Capodarso section: Lithologic log and stratigraphy of the historical Messinian stratotype (SELLI 1960); **B**: biostratigraphic correlation of several sections spanning the Tortonian/Messinian boundary with the position of the FO of planktonic foraminifer *Globorotalia conomiozea* (D'ONOFRIO et al. 1975); **C**: comparison of the different position of the Tortonian/Messinian boundary as proposed by GIANOTTI (1953), CITA et al. (1965) and D'ONOFRIO et al. (1975). (after D'ONOFRIO et al. 1975); **D**: calcareous plankton biostratigraphy and distrubution range of selected taxa of Falconara section (COLALONGO et al. 1979)

Fig. 25B

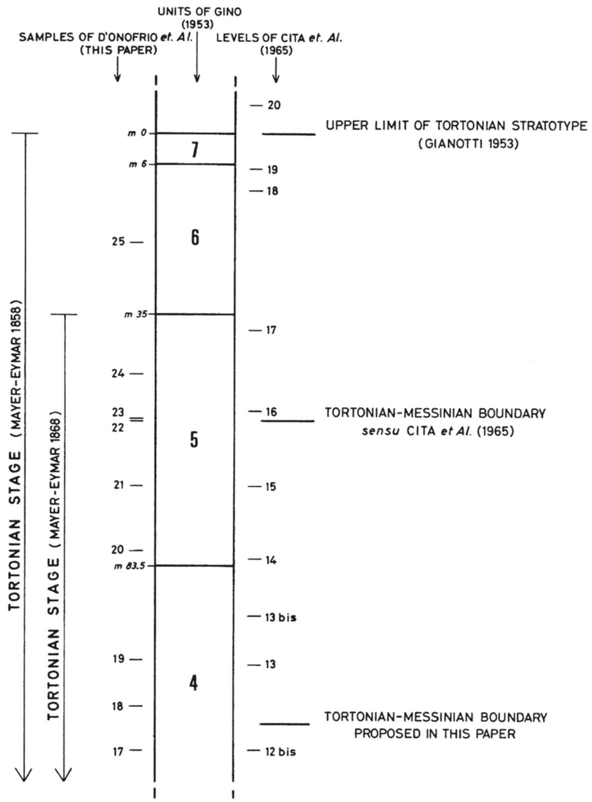



## Messinian

### Historical stratotype (Selli 1971)

The Messinian stage was introduced by Mayer-Eymar (1867) and only in 1868 Mayer-Eymar pointed out that the Messinian is located between the Tortonian and the Astian stages (Mayer-Eymar in 1867 associated the Astian to the whole Pliocene). Successively, Selli (1960) produced a clear definition of the Messinian "as the time interval between the Tortonian (Tortona beds) and the Pliocene (Tabiano beds), characterised in Italy essentially by a hypersaline environment and by evaporitic sediments", and indicated the Pasquasia-Capodarso section as a neostratotype of the Messinian stage (Fig. 24). This section is located in Sicily, between the towns Enna and Caltanissetta. The Pasquasia-Capodarso section is composed of 8 formations and the base of the Messinian was placed 25 m below the marly diatomites ("Tripoli", formation 2 of Selli) coinciding with the remarkable environmental change associated to the rapid impoverishment in number of

Fig. 25C




species and a dominance of dystrophic forms (Fig. 25a) preceding the well known salinity crisis.

The calcareous plankton biostratigraphy was carried out in the Pasquasia-Capodarso section by D'ONOFRIO (1964), COLALONGO (1970). D'ONOFRIO et al. (1975) re-studying the Tortonian stratotype, following CRESCENTI et al. (1973) and IACCARINO et al. (1975), remarked that the FO of *Globorotalia conomiozea* was the most important event suitable to recognise the base of the Messinian (Fig. 25b) and proposed an emendation of the Tortonian/ Messinian boundary (Fig. 25c). Successively, due to the fact that the lower part of the Pasquasia-Capodarso section is covered by a landslide, COLALONGO et al. (1979) proposed the Falconara section (southern Sicily) where the FO of *G. conomiozea* occurs 6 meter below the base of the Tripoli unit (Fig. 25d) as the most suitable section for the T/M boundary. This section is located in the southern slope of Monte Cantigaglione, between Licata and Gela. Unfortunately, no good magnetostratigraphic signal was available for Falconara section (LANGEREIS & DEKKERS 1992). Later on several integrated biostratigraphic and cyclostratigraphic studies were performed on Falconara and Capodarso sections (HILGEN & KRIJGSMAN 1999; SPROVIERI et al. 1996a, 1996b; SUC et al. 1995).

Fig. 25D

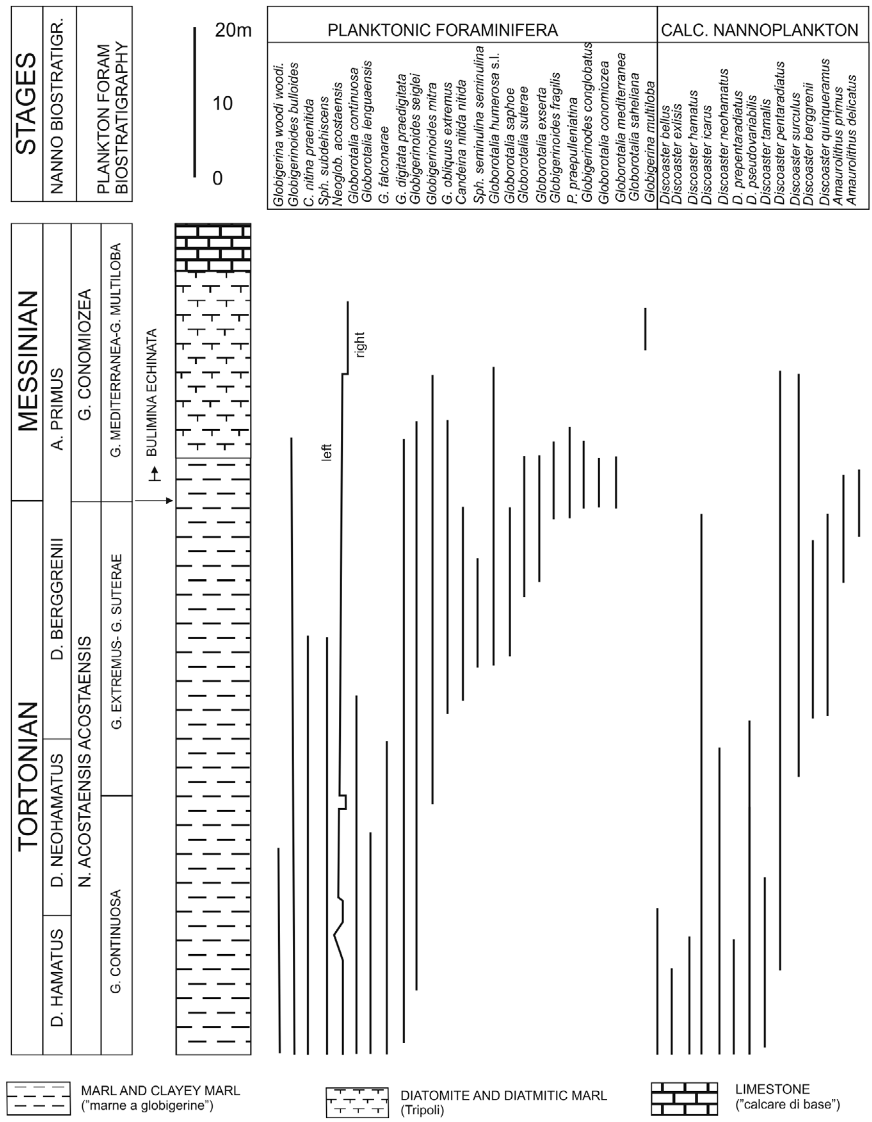

STAGES
NANNO BIOSTRATIGR.
PLANKTON FORAM BIOSTRATIGRAPHY
20m
10
0
PLANKTONIC FORAMINIFERA
CALC. NANNOPLANKTON
Globigerina woodi woodi.
Globigerinoides bulloides
C. nitina praenitida
Sph. subdehiscens
Neoglob. acostaensis
Globorotalia continuosa
Globorotalia lenguaensis
G. falconarae
G. digitata praedigitata
Globigerinoides seiglei
Globigerinoides mitra
G. obliquus extremus
Candeina nitida nitida
Sph. seminulina seminulina
Globorotalia humerosa s.l.
Globorotalia saphoe
Globorotalia suterae
Globorotalia exserta
Globigerinoides fragilis
P. praepulleniatina
Globigerinodes conglobatus
Globorotalia conomiozea
Globorotalia mediterranea
Globorotalia saheliana
Globigerina multiloba
Discoaster bellus
Discoaster exilisis
Discoaster hamatus
Discoaster icarus
Discoaster neohamatus
D. prepentaradiatus
D. pseudovariabilis
Discoaster tamalis
Discoaster pentaradiatus
Discoaster surculus
Discoaster berggrenii
Discoaster quinqueramus
Amaurolithus primus
Amaurolithus delicatus
MESSINIAN
TORTONIAN
A. PRIMUS
D. BERGGRENII
D. NEOHAMATUS
D. HAMATUS
G. CONOMIOZEA
N. ACOSTAENSIS ACOSTAENSIS
G. MEDITERRANEA-G. MULTILOBA
G. EXTREMUS- G. SUTERAE
G. CONTINUOSA
BULIMINA ECHINATA
right
left
MARL AND CLAYEY MARL
("marne a globigerine")
DIATOMITE AND DIATMITIC MARL
(Tripoli)
LIMESTONE
("calcare di base")

Fig. 26A


Fig. 26B

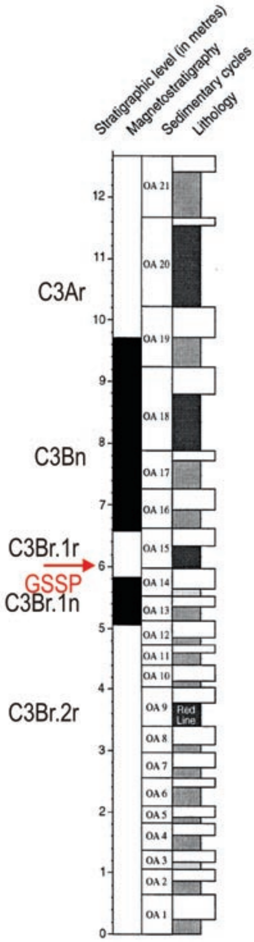



Fig. 26. **A**: Oued Akrech section (Morocco): Messinian GSSP; **B**: Oued Akrech section (Morocco): Lithologic log and magnetostratigraphy of Messinian GSSP (HILGEN et al. 2000 modified);

## Messinian GSSP (HILGEN et al. 2000a)

The GSSP for the base of the Messinian Stage (Late Miocene) is defined in the Oued Akrech section (Rabat, Morocco) where marine sedimentation was continuous across the Tortonian/Messianian boundary (HILGEN et al. 2000a). The Oued Akrech section consists of 12 meter of deep marine marls, known as Blue Marls and the sedimentary record is composed by an alternation of yellow-beige marls with reddish coloured bands (Figs 26a and 26b).

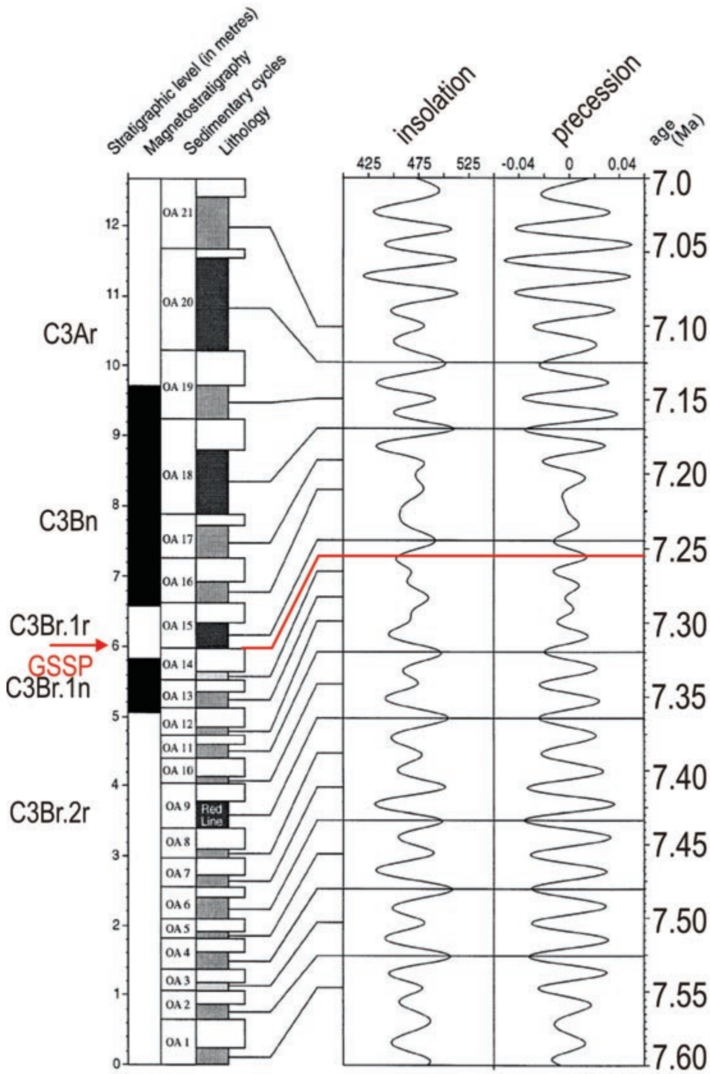



Fig. 27. Oued Akrech section (Morocco): Astronomical tuning (HILGEN et al. 2000).

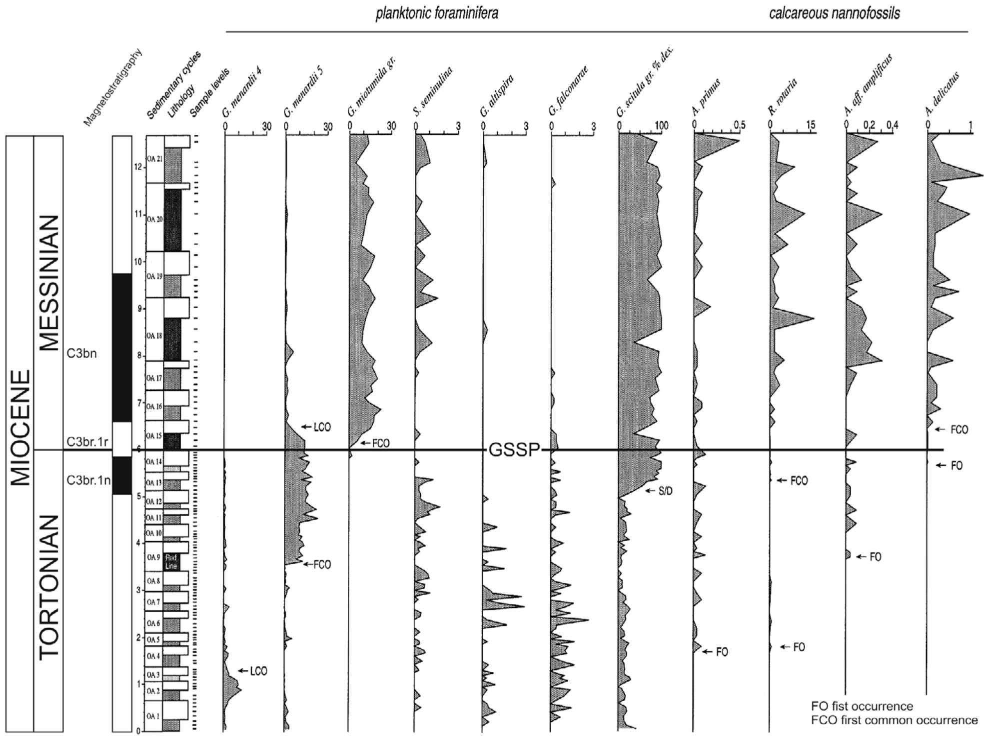
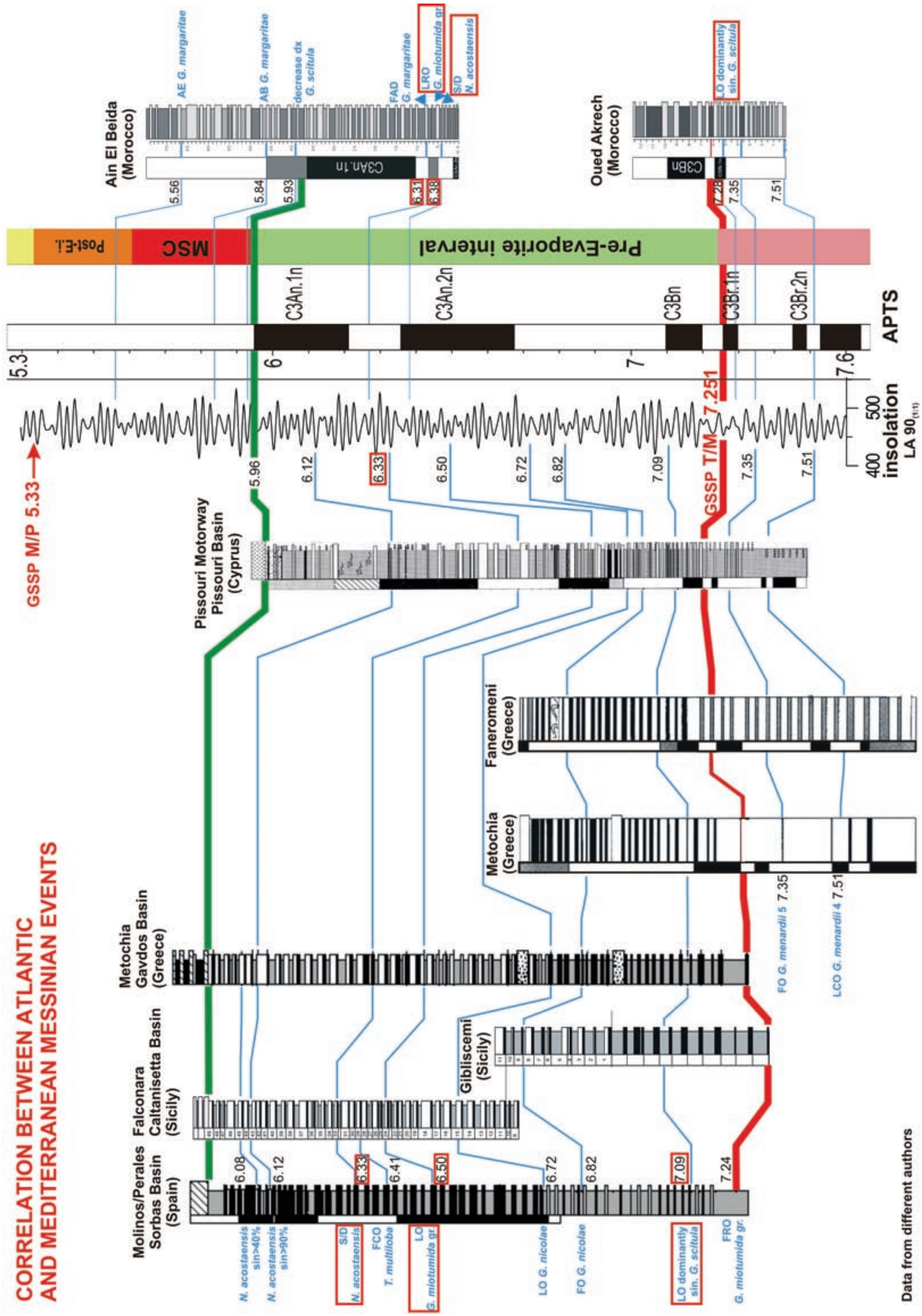


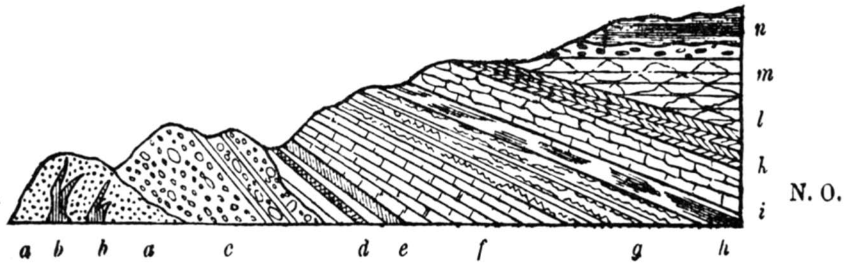

Fig. 28. Oued Akrech section (Morocco): Bio-magnetostratigraphy and quantitative distribution of selected calcareous plankton bioevents (HILGEN et al. 2000)

The GSSP is placed in correspondence of the distinct red layers of the sedimentary cycles 15 (Figs 26a and 26b), astronomically dated at 7.251 Ma (HILGEN et al. 2000a) (Fig. 27), and of the FRO of *Globorotalia miotumida* gr. It is important to remark that the *G. miotumida* gr. includes, according to SIERRO et al. (1993) and KRIJGSMAN et al. (1995), all the high conical keeled globorotaliids, also including the *G. coniomiozea* s.s., used to identify the base of the Messinian by D'ONOFRIO et al. (1975) and COLALONGO et al. (1979). In terms of calcareous nannofossils, the FO and FCO of *Amaurolithus delicatus* occur just below and above the GSSP, respectively (Fig. 28).

The GSSP falls within the lower most part of magneto-Chron C3Br.1r (Fig. 28). LOURENS et al. (2004) re-tuned the GSSP at 7.246 Ma. In terms of stable isotopes, the boundary is located within the global Chron 6 carbon shift as recognized in section Oued Akrech (HODELL et al. 1994). The Tortonian/Messinian boundary represents one of the most studied time interval and it is recorded in many areas of the Mediterranean (Fig. 29) (KRIJGSMAN et al. 2004).


CORRELATION BETWEEN ATLANTIC AND MEDITERRANEAN MESSINIAN EVENTS
GSSP M/P 5.33
GSSP T/M 7.251
Ain El Beida (Morocco)
Oued Akrech (Morocco)
Pissouri Motorway Pissouri Basin (Cyprus)
Faneromeni (Greece)
Metochia (Greece)
Metochia Gavdos Basin (Greece)
Falconara Caltanisetta Basin (Sicily)
Gibliscemi (Sicily)
Molinos/Perales Sorbas Basin (Spain)
Post-E.I.
MSC
Pre-Evaporite interval
C3An.1n
C3An.2n
C3Bn
C3Br.1n
C3Br.2n
APTS
insolation LA 90
AE G. margaritae
AB G. margaritae
decrease dx G. scitula
FAD G. margaritae
LRO G. miotumida gr.
S/D N. acostaensis
LO dominantly sin. G. scitula
N. acostaensis sin>40%
N. acostaensis sin>90%
FCO T. multiloba
LO G. miotumida gr.
LO G. nicolae
FO G. nicolae
FRO G. miotumida gr.
FO G. menardii 5
LCO G. menardii 4
Data from different authors

Coupe théorique des terrains tertiaires du versant oriental des monts Péloritains (Gravitelli, près de Messine).




T. cristallins. { *a* Gneiss.
*b* Filons de granite et de pegmatite.

Miocène (*Tortonien*, Mayer). { *c* Poudingues ou conglomérats de cailloux cristallins avec des couches de grès.
*d* Argiles lacustres avec des bancs de lignite.
*e* Argiles marines.
*f* Sables.

Pliocène. { *Zancléen* { *g* Marnes à foraminifères alternant à la partie inférieure avec des couches de sables.
*h* Calcaire à polypiers et à brachiopodes.
*i* Marnes sableuses très-riches en brachiopodes et en foraminifères.
*Astien.* | *k* Calcaire à brachiopodes.

Quaternaire. { *l* Sables et grès.
*m* Conglomérat.
*n* Alluvion.

Fig. 30. Succession of the Tertiary deposits cropping out on the east part of the Peloritani mountain at Gravitelli (Messina, Sicily) by SEQUENZA (1868), after RODA (1971).

## Zanclean

### Historical stratotype (RODA 1971)

The Zanclean Stage was defined by SEGUENZA (1868) as the lower part of the Pliocene, to complement MAYER's Astian Stage in the upper Pliocene (see also VAI 1997, for a review).

The author described mainly the geology of Messina area (Sicily) but not a specific stratotype section and reported for the Gravitelli exposure eight formations (strongly different in lithology) (Fig. 30) and basically associated the formation labelled as *g*, *h* and *i* to the Zanclean (RODA 1971) and the overlying formation *k* to the Astian. Lately, SEQUENZA (1873, 1880) considered the Gravitelli section as stratotype of the Zanclean (RODA 1971).

◀ Fig. 29. Biostratigraphic correlation of the Mediterranean sections spanning from the base of the Messinian (KRIJGSMAN et al. 2004).

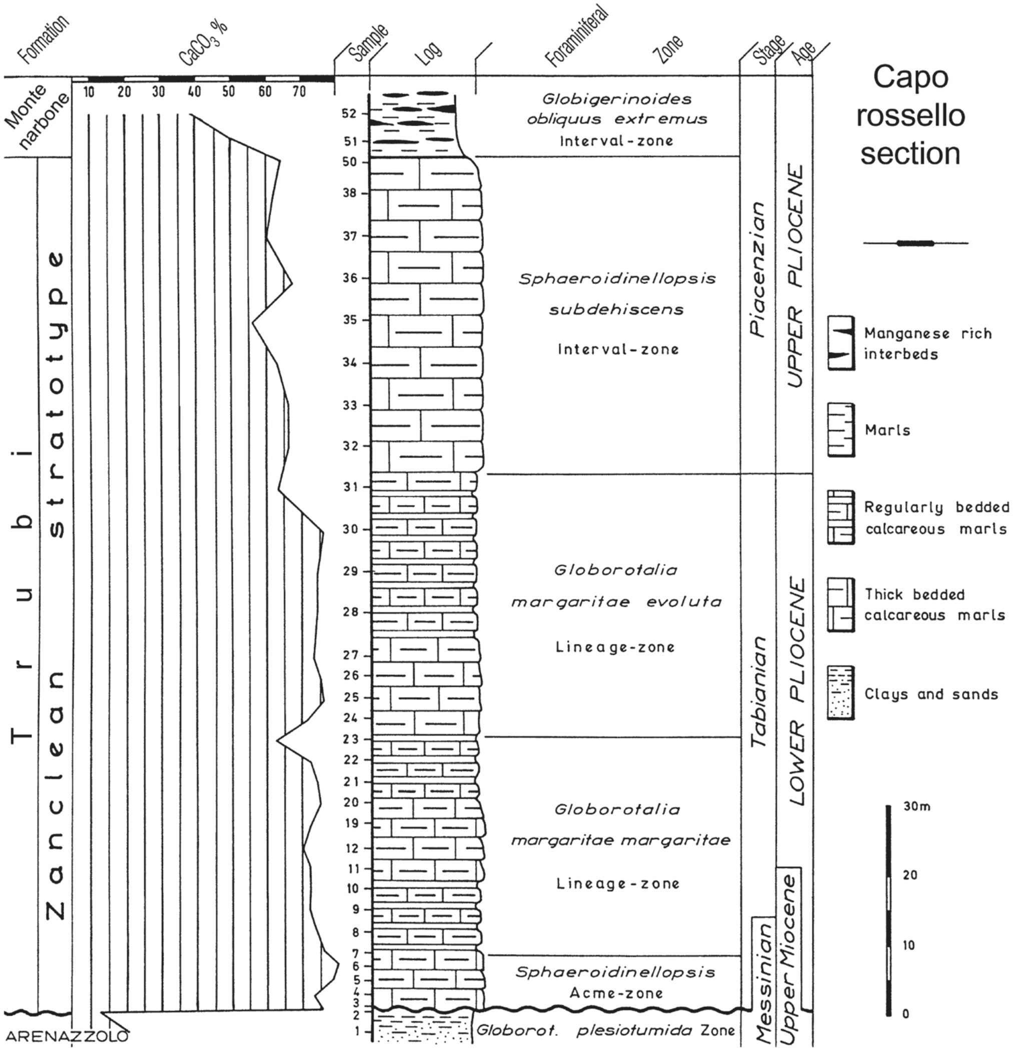



Fig. 31. Planktonic biostratigraphy of the Mio/Pliocene boundary (Zanclean stratotype) at Capo Rossello section (Cita & Gartner 1973).

At present, the formations *h* and *i* (les "calcaires à polypiers et à brachiopods" et "les marnes sableuses très riches en brachiopods et en foraminifères") (Fig. 30), are considered to belong to the Piacenzian (Van Couvering et al. 2000). Roda (1971) reported that the white marls as well the boundary with the lower sandy deposits of Gravitelli outcrop were clearly visible. A short list of planktonic foraminifer published by Sequenza (1868) indicates the presence of *Orbulina*, *Globigerina* and *Globigerinoides*. These white marls rich in globigerinids well known as "Trubi" are largely exposed in the central-southern part of the Sicily (Roda 1971).

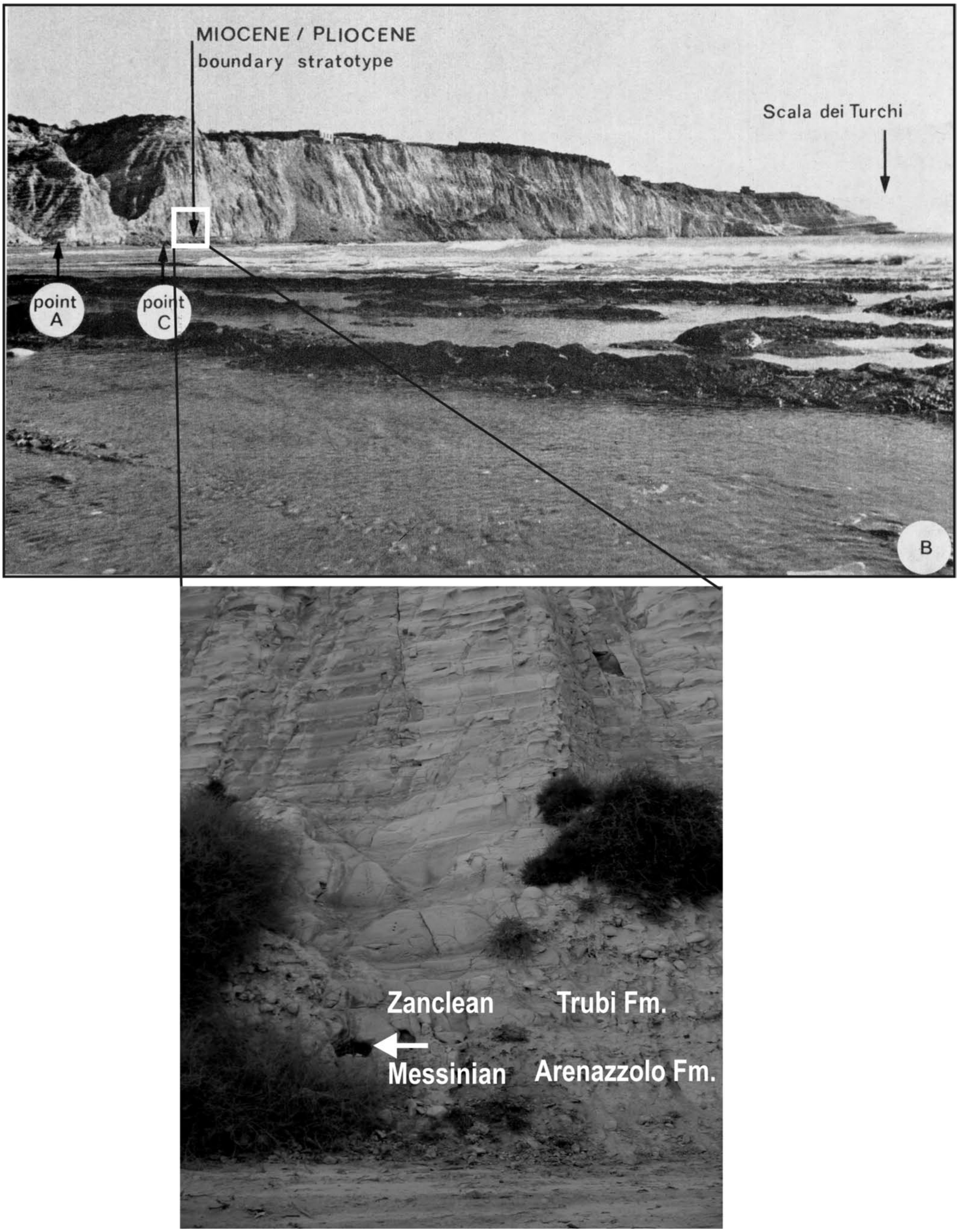



Fig. 32. Capo Rossello section: Mio/Pliocene boundary (Zanclean stratotype) (CITA & GARTNER 1973).

Fig. 33A

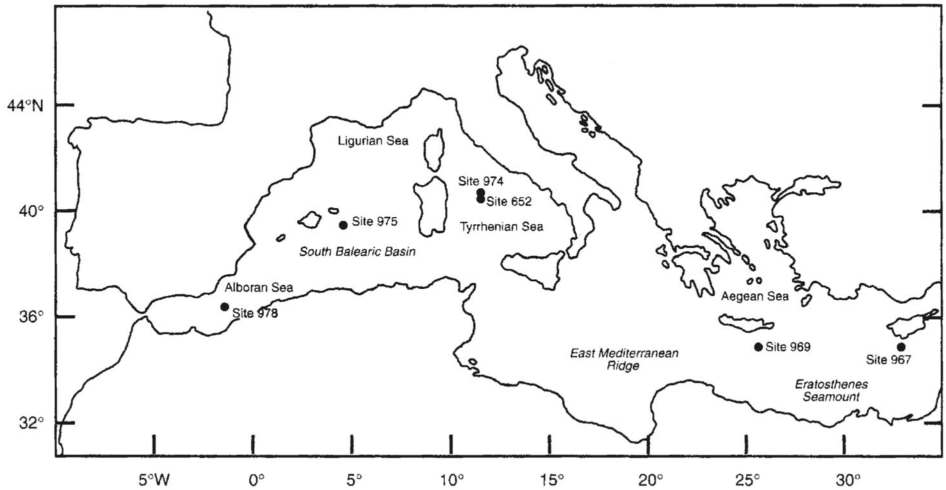



Fig. 33. **A**: Location map of the DSDP-ODP sites where is recovered the base of the Zanclean; **B**: base of the Zanclean at Eraclea Minoa section (Zanclean GSSP) and detail of the boundary between the Arenazzolo and Trubi Formations (Sicily)

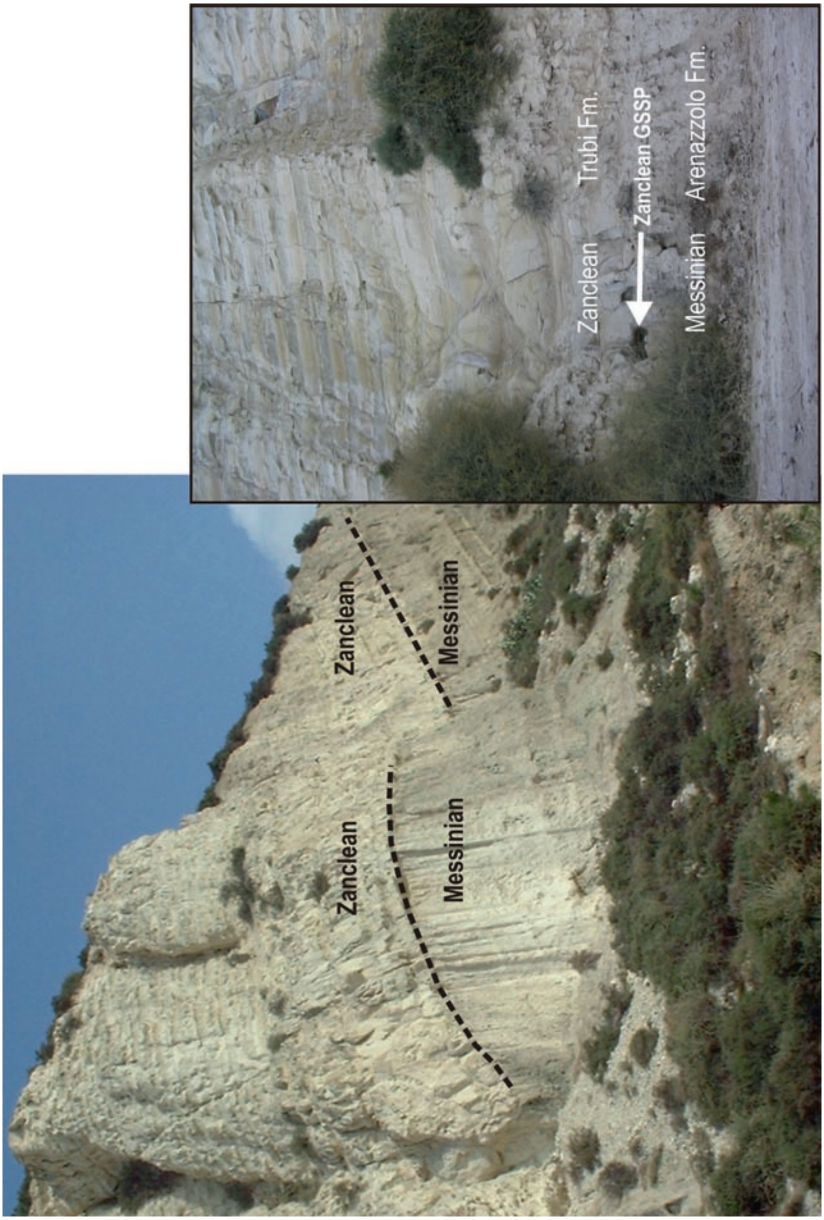
Unfortunately, as reported by Roda (1971), the Gravitelli exposure was covered by vegetation and therefore no more accessible. Cita & Gartner (1973, see also Cita 1975a) formally designated and described the Zanclean stratotype in sea cliffs at Capo Rossello, on the southern coast of Sicily west of Agrigento (Fig. 31), where the Trubi exceeded 100 m in thickness and the sequence was more complete than at Gravitelli area. In this section, the base of the Trubi marls was in conformable contact with dark, sandy clays of the Upper Messinian "Arenazzolo Formation" (Fig. 32).

Calcareous plankton biostratigraphic studies have been carried out on Capo Rossello section by several authors (e.g. Cita & Gartner 1973; Cita 1975b; Rio et al. 1984; Zachariasse et al. 1989, 1990; Sprovieri 1992, 1993; Di Stefano et al. 1996) showing the great biostratigraphic value of this deep marine record. These integrated biostratigraphic studies strongly supported the following decision to define the GSSP of the Zanclean in this area.

**Zanclean GSSP (base of the Pliocene) (Van Couvering et al. 2000)**

The GSSP for the base of the Zanclean Stage (Early Pliocene) is located at the Eraclea Minoa section on the southern coast of Sicily (Italy), at the base of the Trubi Formation (Van Couvering et al. 2000). This formation consists of rhythmically bedded foraminiferal pelagic ooze widely exposed in the Upper Cenozoic nappes of Sicily and Calabria, and recovered in cores from different parts of the Mediterranean Basin (Fig. 33a).

Fig. 33B


Trubi Fm.
Zanclean
Zanclean GSSP
Messinian
Arenazzolo Fm.
Zanclean
Messinian
Zanclean
Messinian

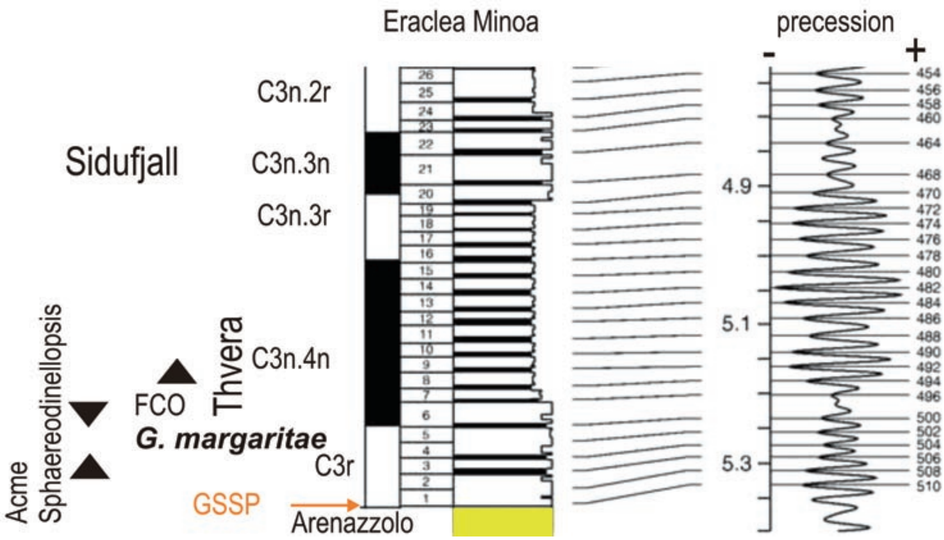
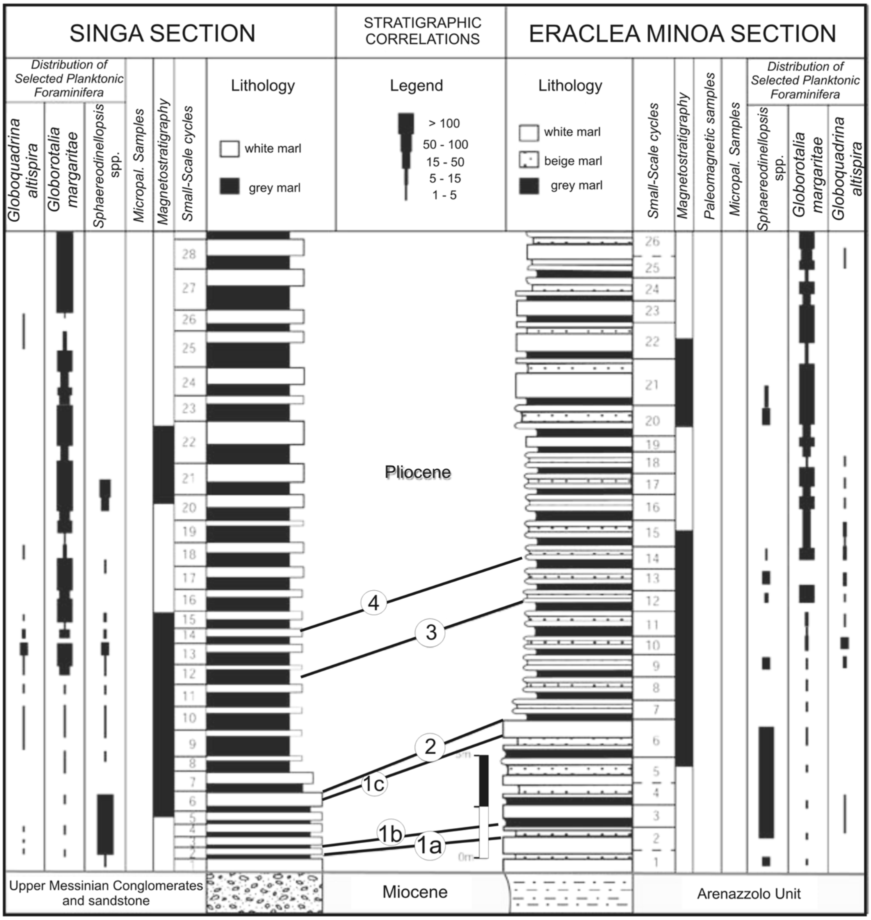



Fig. 34. Bio-magnetostratigraphy and astronomical tuning of Eraclea Minoa section (Zanclean GSSP). Data from LOURENS et al. (1996) and HILGEN et al. (2006).

The GSSP of the Zanclean and the base of the Pliocene is located at the base of the small-scale carbonate cycle no. 1 of the Trubi marls which overlie the brownish coloured sandy Arenazzolo (VAN COUVERING et al. 2000) (Fig. 33b). This level corresponds to the insolation cycle 510 (LOURENS et al. 1996a; 2004) (Fig. 34) with an astronomical age of 5.33 Ma and lies within the lowermost reversed episode of the Gilbert Chron (C3n.4r), below the Thvera normal subchron, providing a very good approximation of the Messinian/Zanclean (Miocene/Pliocene) boundary (Fig. 34).

The Eraclea Minoa section, 30 meter thick, consists of a cyclic alternation of grey, white and beige marls organized in quadripartite lithological cycles (see HILGEN 1991b for details). In terms of calcareous plankton bio-events the Acme Base (AB) of *Sphaeroidinellopsis* (Zone MPl1 of CITA 1975b), two influxes of *N. acostaensis* left coiled and the paracme interval of *Reticulofenestra pseudoumbilicus* approximate the base of the Zanclean (Fig. 35). DI STEFANO & STURIALE (2009) suggested the FO of the recently described *Reticulofenestra zancleana* DI STEFANO & STURIALE. as a high biostratigraphical potential to approximate the base of the Zanclean in terms of calcareous nannofossils (Fig. 36).

The Eraclea Minoa section represents the basal segment of the Rossello Composite Section (i.e., LANGEREIS & HILGEN 1991; HILGEN et al. 2006), which is made up of overlapping sections to the east in sea cliffs at Capo Rossello, Punta di Maiata, Punta Grande and Punta Piccola (Fig. 37). This composite section constitutes the Lower and part of the Middle Pliocene of the present Astronomical Polarity Time Scale (HILGEN 1991a 1991b; LOURENS et al. 1996a).




Review of the magnetostratigraphy, biostratigraphy and cyclostratigraphy of Miocene/Pliocene boundary sections of the trubi Formation in southern Calabria and Sicily. Number indicates the calcareous plankton biostratigraphic events close to the M/P boundary. 1a) base *Sphaeroidinellopsis* acme, 1b) first influx *N. acostaensis* l.c.,1c) base paracme interval *R. pseudoumbilicus*, 2) top *Sphaeroidinellopsis* acme, 3) FCO *Globorotalia margaritae* and 4) end paracme interval *R. pseudoumbilicus*

Fig 35. Modified bio-magnetostratigraphy and cyclostratigraphy of the Zanclean GSSP (Mio/Pliocene boundary) in Sicily and Calabria (HILGEN & LANGEREIS 1988). The bioevents 1a, 1b, 1c and 4 are not present in the original document of HILGEN & LANGEREIS (1988).

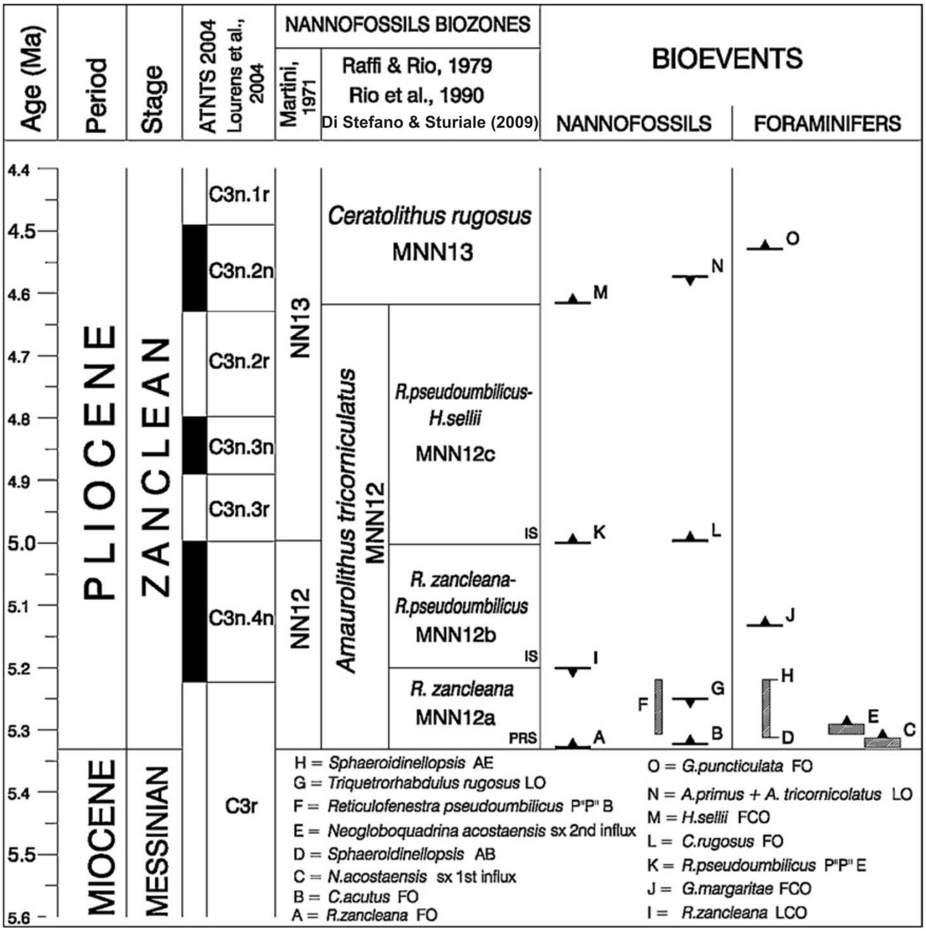



Fig. 36. Mediterranean calcareous plankton biostratigraphic scheme for the Mio/Pliocene (Di Stefano & Sturiale, 2009).

## Tabianian

### Historical stratotype (Barbieri & Selli 1971)

The Tabianian stage was introduced by Mayer (1867), corresponding to the blue marly clay with *Ficus ficoides*, and considered by Selli (1960), due to microfaunistic similitude, as synonym of Zanclean (Lower Pliocene) (in Roda 1971). Successively, the stratotype section was designed and described by Iaccarino (1967) at Tabiano (Parma province, northern Italy) in two sections: Chiesa Nuova and Est Terme (Figs 38a and 38b). Previous palaeontological studies have been carried out by Cocconi (1873); Capellini (1876); Ruggieri & Selli (1948); Pelosio (1967).

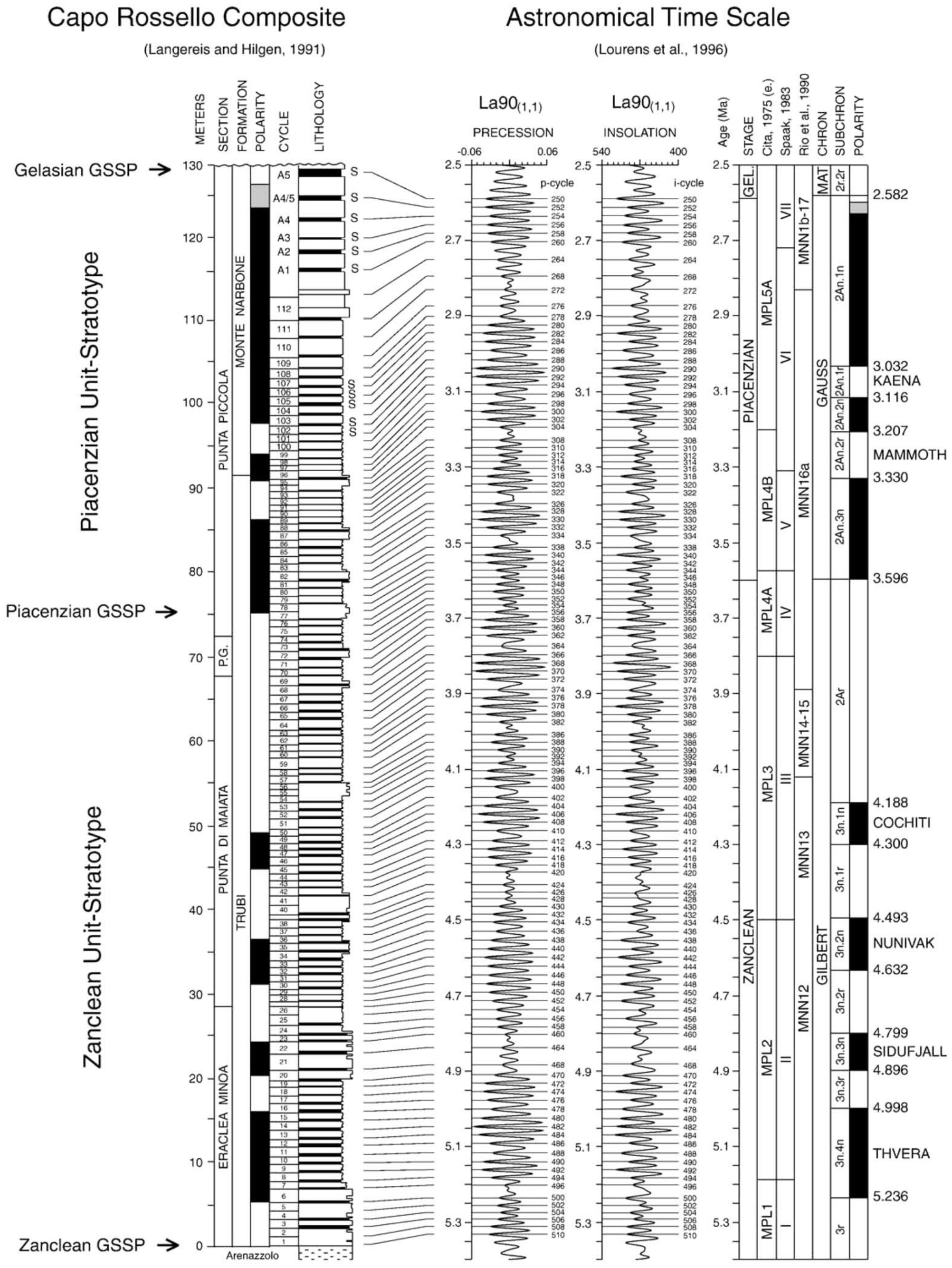



Fig. 37. Capo Rossello Composite section with the position of the Zanclean, Piacenzian and Gelasian GSSPs, the astronomical tuning and the calcareous plankton biostratigraphy (HILGEN et al. 2006)

Fig. 38A

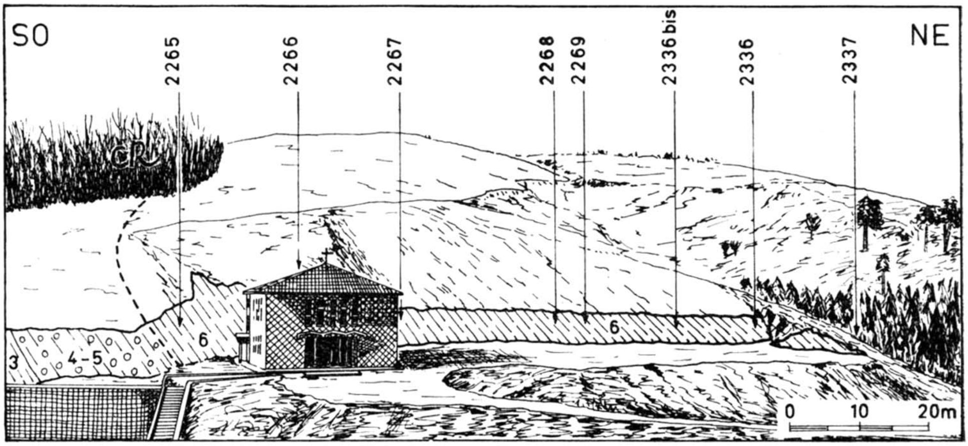



Fig. 38B

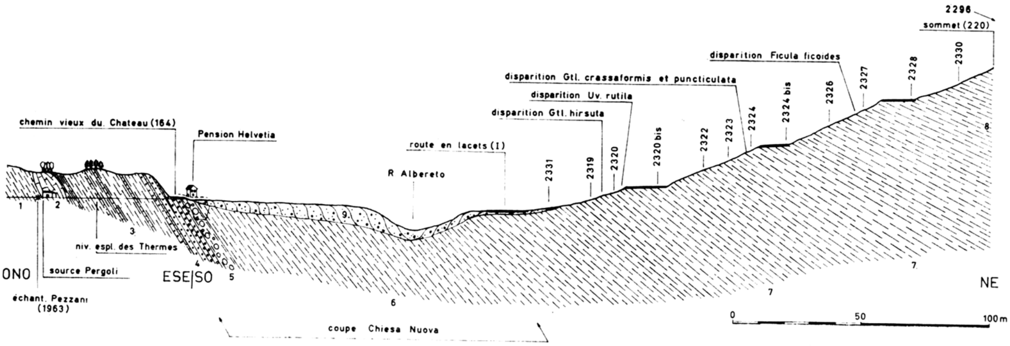



Fig. 38. The Tabianian historical stratotype sections designed by Iaccarino (1967) at Tabiano (northern Italy). **A**: Chiesa Nuova and **B**: Est Terme.

Blow (1969) correlated the Tabianian with the Zanclean and considered the former less extended downwards, therefore the two stages are not completely time synchronous. In fact, the planktonic foraminiferal Zone MPl 1 is missing in the type Tabianian. Consequently the Tabianian is only partly coinciding with the Zanclean.

Barbieri (1967) suggested placing the upper boundary of the Tabianian coinciding with the base of the overlying stage, the Piacenzian which was defined by the disappearance of *Globorotalia margaritae* and *Uvigerina rutila* (benthic foraminifer). However, in the Tabianian type section, *G. margaritae* LO slightly predates last occurrence of *U. rutila*. After the designation and description of the stratotype of the Zanclean, the Tabianian has been completely abandoned.

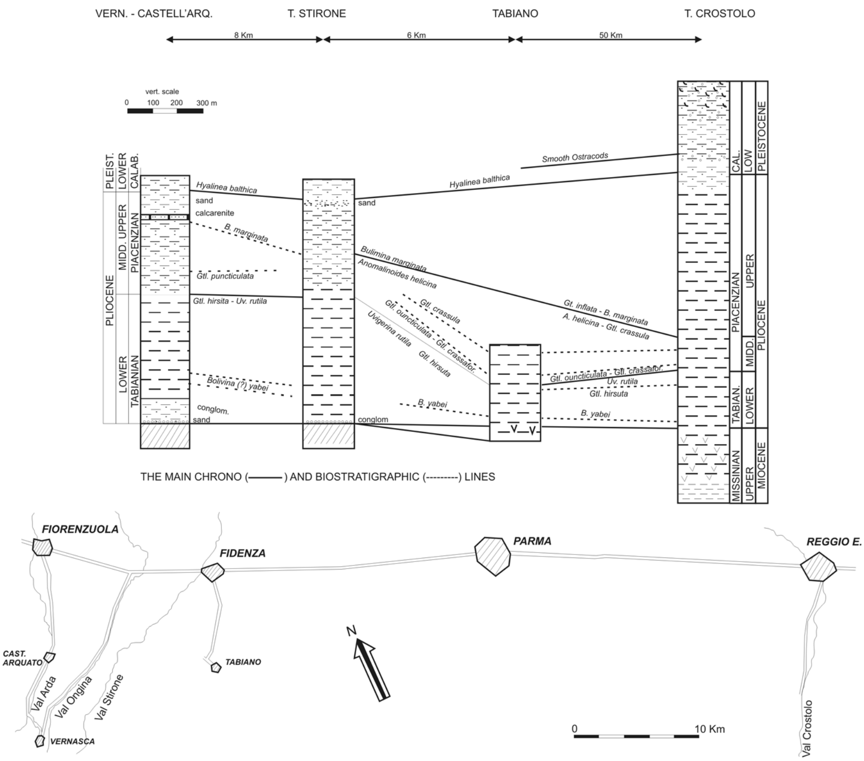



Fig. 39. Piacenzian historical stratotype at Castell'Arquato section designed by BARBIERI (1967) and biostratigraphic correlation with well known sections cropping out in the same area.

## Piacenzian

### Historical stratotype (BARBIERI 1971)

The Piacenzian Stage has been introduced by MAYER (1858) and adopted by PARETO (1865), who indicated the fossiliferous sediments ("blue clays") outcropping between Castell'Arquato and Lugagnano (Piacenza province, Northern Apennine) as typical of the unit. The stratotype has been successively designed by BARBIERI (1967) identifying the base of the Piacenzian close to the lithofacies change from slope-basin to outer-shelf sediments and coincident with the LO of *G. margaritae* and the LO of *Uvigerina rutila* (Fig. 39). This planktonic foraminiferal event was subsequently used in most geologic time scales to mark the base of the Piacenzian (e.g., CITA 1973; BERGGREN & VAN COUVERING 1974; BERGGREN et al. 1985, 1995; HAQ et al. 1988; HARLAND et al. 1982, 1990).

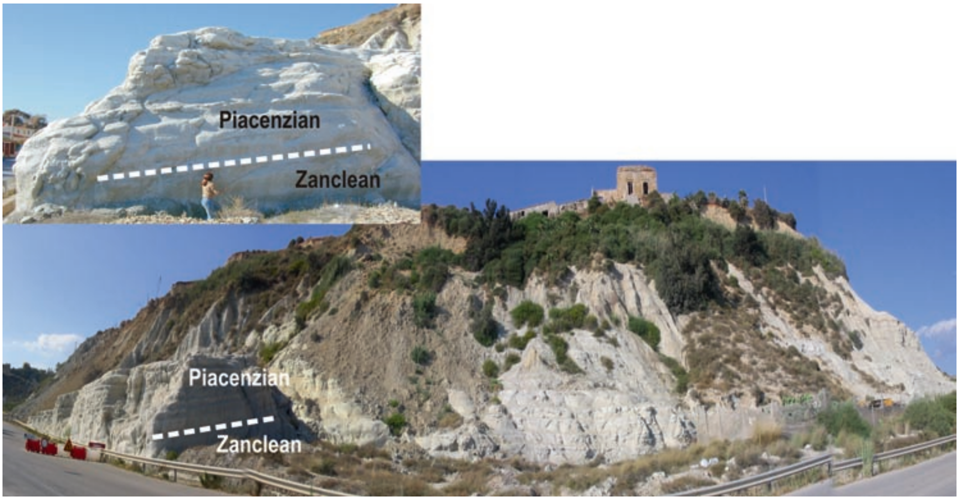



Fig. 40. Punta Piccola section (Sicily): Piacenzian GSSP. Photo gently offered by S. BONOMO and E. DI STEFANO.

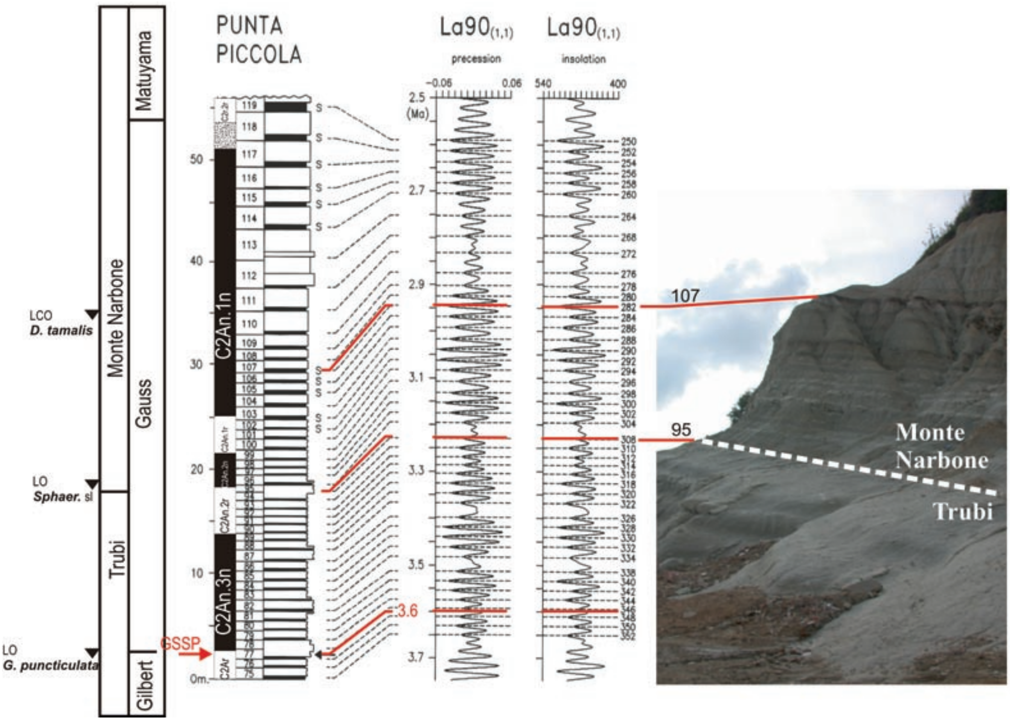



Fig. 41. Bio-magnetostratigraphy and the astronomical tuning of Punta Piccola section (Piacenzian GSSP) and photo showing the position of the boundary between Trubi and Monte Narbone Formations. After HILGEN et al. (2006), CASTRADORI et al. (1998) and HILGEN (1991b).

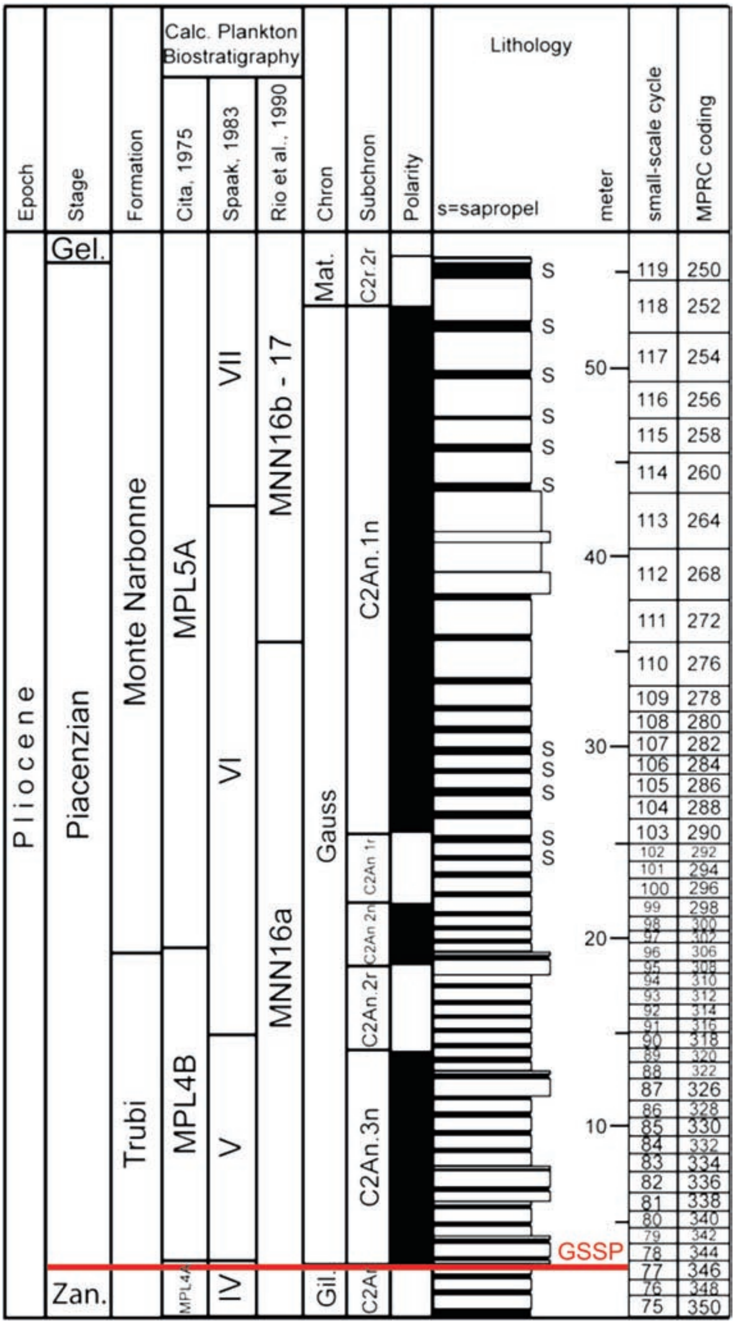


Fig. 42. Bio-magnetostratigraphy and cyclostratigraphy of the Piacenzian GSSP. After CASTRADORI et al. (1998) and HILGEN (1991b).

The integrated calcareous plankton biostratigraphic studies carried out on the Castell'Arquato section by Rio et al. (1988) and Raffi et al. (1989) clearly showed that a hiatus is present at the base of the type Piacenzian section and that the disappearance of *G. margaritae* does not correspond to its extinction datum (LO). These data suggested that the base of the Piacenzian has to be placed between the LO of *R. pseudoumbilicus* and the temporary disappearance in the Mediterranean of *Globorotalia puncticulata*. Unfortunately, the occurrence of this hiatus made the Piacenzian type-section of Castell'Arquato not appropriate to formally define the base of the Piacenzian Stage.

### Piacenzian GSSP (Castradori et al. 1998)

The GSSP for the base of the Piacenzian Stage (Middle Pliocene) is located in the Punta Piccola section (Castradori et al. 1998) (Fig. 40) in Sicily (Italy) along the road from Porto Empedocle to Realmonte, 4 km to east of Capo Rossello. The Punta Piccola section, 60 meter thick, representing the upper part of the Rossello Composite Section (Hilgen et al. 2006) (Fig. 37), contains the transition from Trubi Formation (Zanclean stage) to the marly Monte Narbone Formation, which is characterized by the cyclical occurrence of laminated (sapropelic) layers.

Calcareous plankton studies have been carried out on the Punta Piccola section by numerous authors (Brolsma 1978; Spaak 1983; Rio et al. 1984; Driever 1988; Zachariasse et al. 1989, 1990; Sprovieri 1992, 1993; Lourens et al. 1996a; Sprovieri et al. 2006).

The base of the beige marl bed of the small-scale carbonate cycle 77 is the approved base of the Piacenzian Stage. The GSSP of the Piacenzian, located, in correspondence of the insolation cycle 347, with an astrochronological age of 3.6 Ma (Lourens et al. 1996a), is virtually coincident with the Gilbert-Gauss magnetic reversal, which is worldwide accepted as a tool to identify of the base of the Piacenzian Stage (Figs 41 and 42).

The calcareous plankton bio-events used to approximate the base of the Piacenzian Stage, are the LO of *G. puncticulata* (3.57 Ma; Lourens et al. 1996a), the first influx of *Globorotalia crassaformis* (3.60 Ma; Lourens et al. 1996a), the end of the paracme interval of *Discoaster pentaradiatus* (3.61 Ma; Lourens et al. 1996a), and the LO of *Sphenolithus* spp. (3.70 Ma; Lourens et al. 1996a).

In terms of oxygen stable isotope excursion, the base of the Piacenzian is located in obliquity-related $\delta^{18}O$ stage MG8 (Shackleton et al. 1995; Tiedemann et al. 1994).

## Astian

### Historical stratotype (Ferrero 1971)

The Astian stage was introduced by De Rouville (1853), but no specific locality has been assigned for the stratotype of this stage. Mayer-Eymar (1868) and Mayer-Eymar

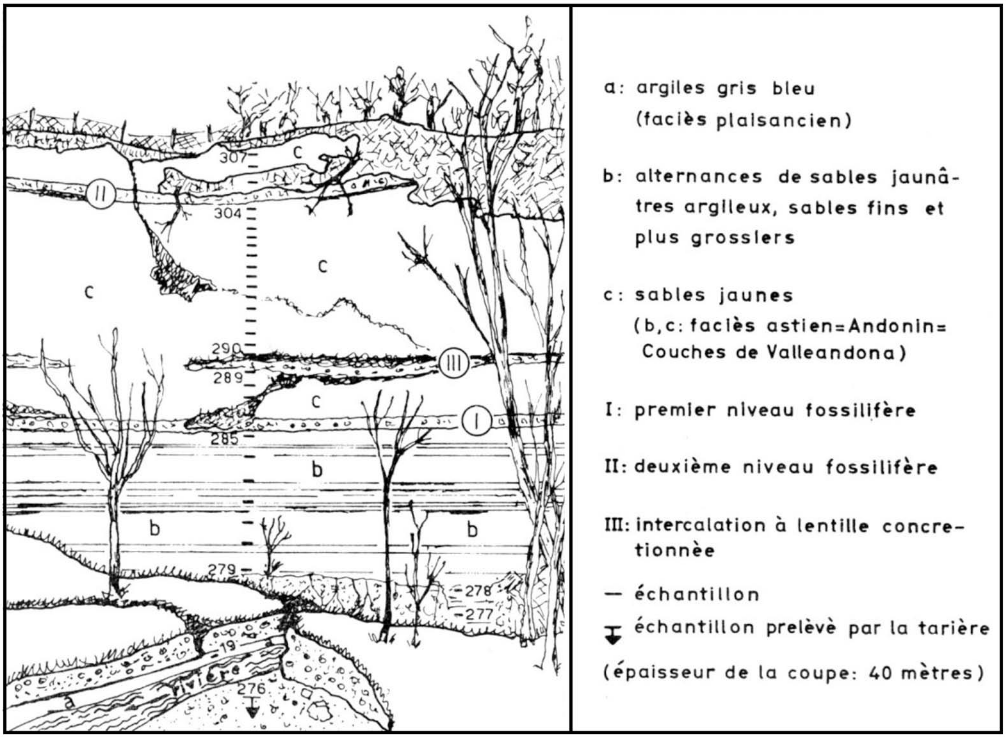



Fig. 43. Astian historical stratotype at Castello section (west of Asti), FERRERO (1971)

(1889) clearly indicated the Valleandona area as a type locality. In particular, close to the Valleandona village (west of Asti), the 42 meters thick Castello section has been considered as reference section for this stage (Fig. 43). The section is composed from the base to the top as follows: grey-bluish clay (2 meter thick), alternation of greyish sandy clay and fine and coarse grained yellowish sand (16 meter thick), yellow sand (24 meter thick) with the presence of two fossiliferous layers at the base and at the top, respectively (FERRERO 1971). SAMPÒ et al. (1968) reported a detailed list of fossils for these two layers.

Several authors (DE STEFANI 1891; GIGNOUX 1913; MARTINIS 1954; SAMPÒ et al. 1968) clearly suggested that the Astian cannot be used as chronostratigraphic meaning, being represented by shallow water sandy facies, most probably Early to Middle Pliocene in age (SAMPÒ et al. 1968).

RIO et al. (1991, 1994) demonstrated that the top of the Piacenzian stratotype falls within a key point of the evolution of Earth climatic system and the Astian does not cover the time interval between the top of the Piacenzian historical stratotype (BARBIERI 1967) and the base of the Pleistocene at Vrica (AGUIRRE & PASINI 1985). For this reason the Gelasian has been introduced as the uppermost stage of the Pliocene.

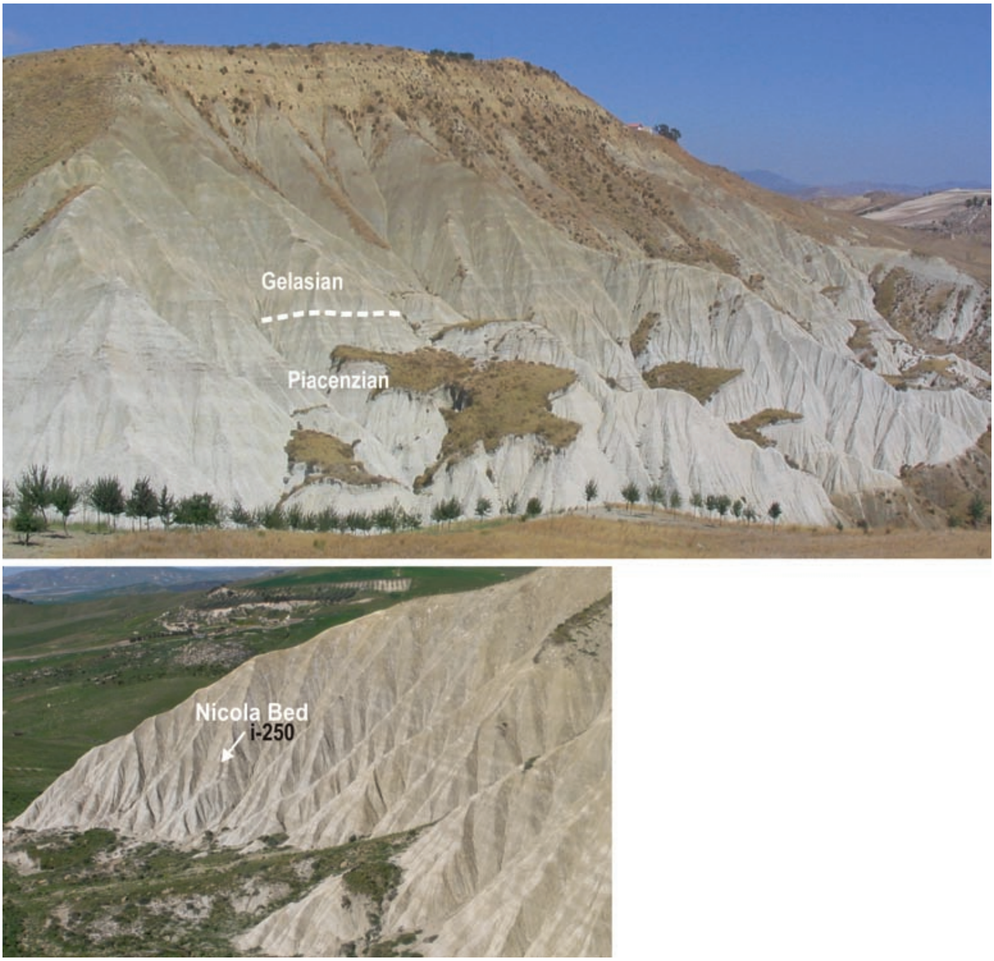



Fig. 44. Monte San Nicola section (Sicily): Gelasian GSSP and the position of the Nicola bed (insolation cycle i-250). Photo gently offered by S. Bonomo and E. Di Stefano

## Gelasian

### Gelasian GSSP (Rio et al. 1998)

The GSSP for the base of the Gelasian Stage (Late Pliocene) is located in the Monte S. Nicola section (near Gela, Sicily, Italy) (Fig. 44). The Monte S. Nicola section, 161 meter thick, contains in the lower part the well-known transition between the bedded marls and limestones of the Trubi Formation and the marly-silty Monte Narbone Formation (Rio et al. 1998).

The GSSP of the base of the Gelasian is located in correspondence with the base of the marly layer overlying sapropel MPRS (Mediterranean Precession Related Sapropels) 250 (at 62 m from the base of Monte San Nicola section) with an astrochronological

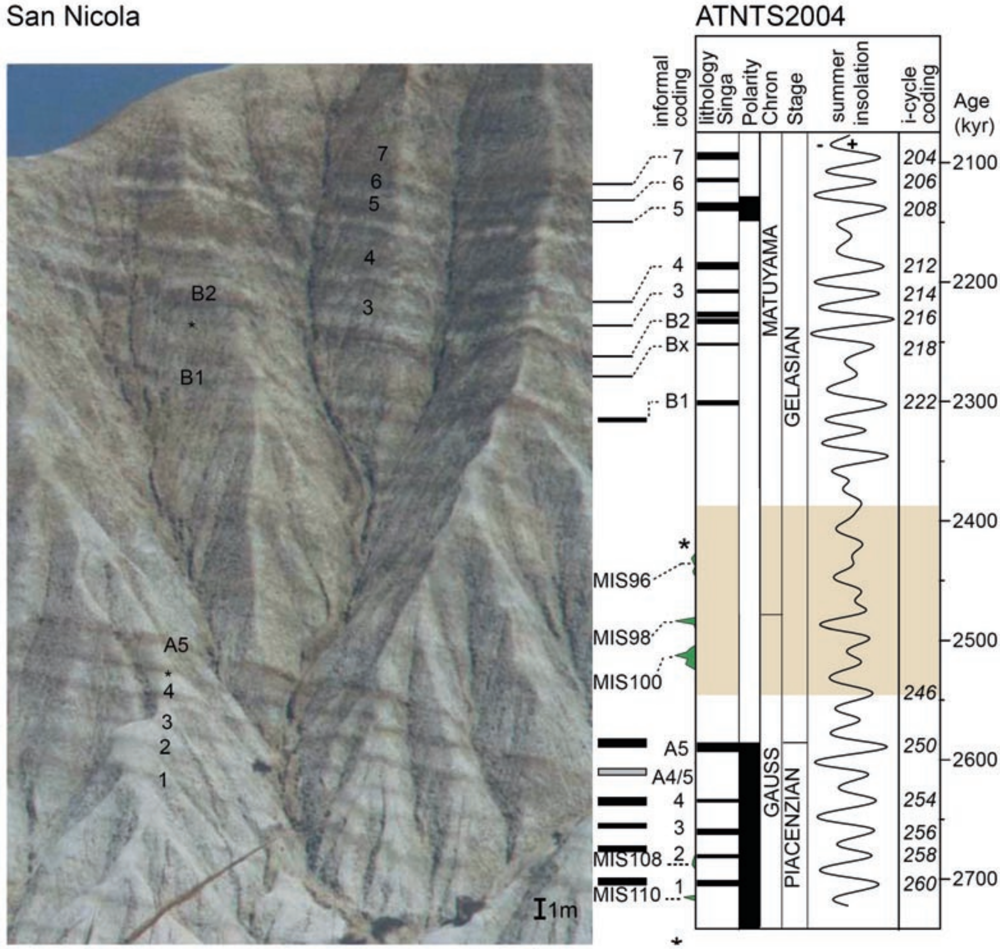



Fig. 45. Astronomical tuning of the Monte San Nicola section (Gelasian GSSP) and the distribution of *Neogloboquadrina atlantica* used for the identification of the Marine Isotopic Stage (MIS). The insolation cycle i-250, base of the Gelasian, corresponds to the informal coded sapropel A5 (see BECKER et al. 2005 for details)

age of 2.588 Ma (LOURENS et al. 1996a) (Fig. 45). Magnetostratigraphically, the Gauss/Matuyama boundary, located about 1 m below the GSSP level, is worldwide accepted as a good approximation of the base of the Gelasian (Fig. 46).

Numerous integrated calcareous plankton studies (SPAAK 1983; BONADUCE & SPROVIERI 1984; SPROVIERI 1992, 1993; SPROVIERI et al. 1986; DRIEVER 1988; BERTOLDI et al. 1989; CHANNELL et al. 1992) suggested that the LO of *Discoaster pentaradiatus* and *D. surculus*, the LO of *Globorotalia bononiensis* and the influxes of *Neogloboquadrina atlantica* (in correspondence of MIS 96, 98 and 100) well approximate the Gelasian GSSP (Figs 45 and 46). Finally, in terms of oxygen stable isotope excursion, the base of the Gelasian corresponds to isotopic stage 103 of RAYMO et al. (1989).

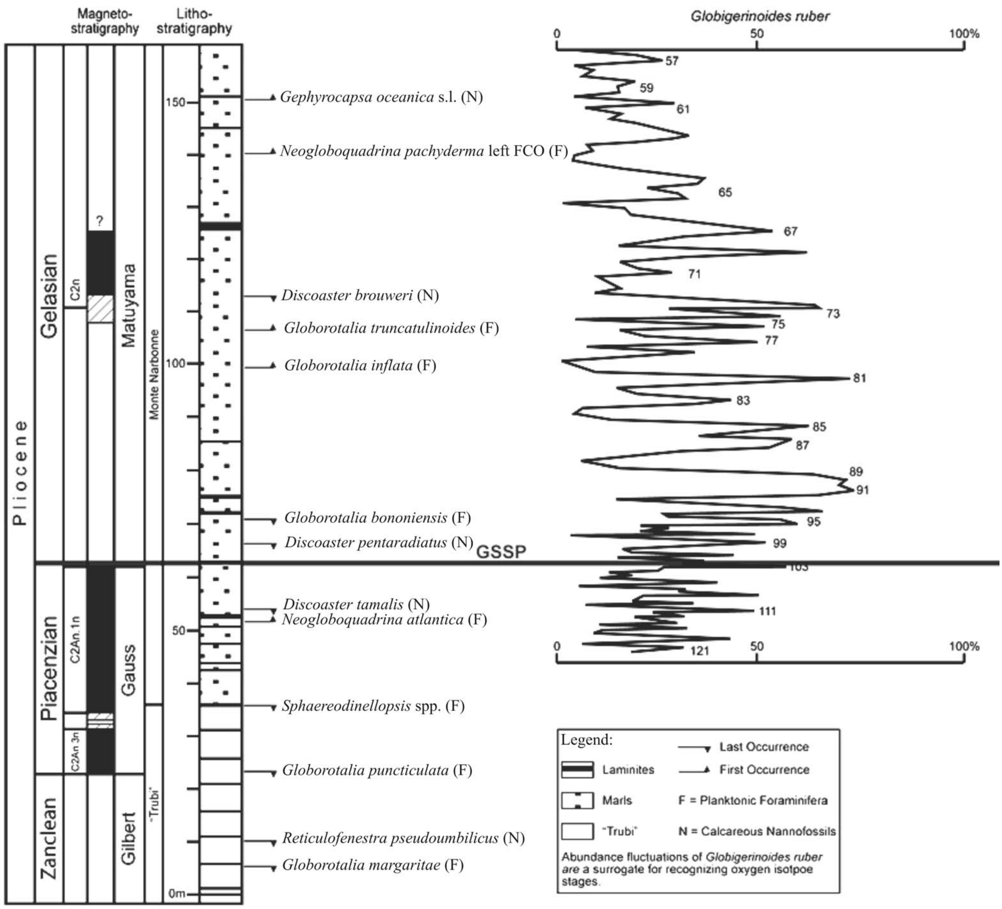



Fig. 46. Bio-magneostratigraphy of Monte San Nicola section (Gelasian GSSP) (RIO et al. 1998)

## Calabrian

### Historical stratotype (GIGNOUX 1913)

The Calabrian stage was introduced by GIGNOUX (1913) designating the S. Maria di Catanzaro section (Fig. 47) as reference area where to place the base of the Calabrian [references for S. Maria di Catanzaro locality: GIGNOUX (1910, 1913); BAYLISS (1969); SMITH (1969); SELLI (1971); SPROVIERI et al. (1973) and BROLSMA & MEULENKAMP (1973)]. According to GIGNOUX (1910, 1913), the Calabrian corresponds to the Post-Pliocene of DE STEFANI (1891) and is characterised by the occurrence of the first northern guests. In particular, GIGNOUX (1913) suggested to locate the base of the Calabrian stage at the bottom of the calcarenite layer (G-G1 bed), coincident with the first appearance of the northern

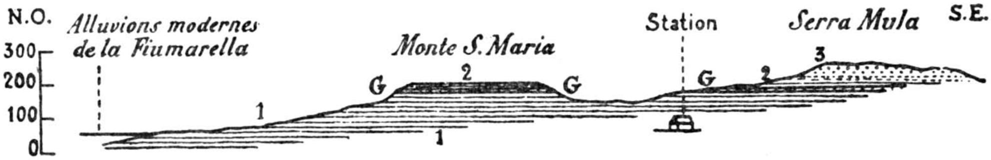



**FIG. 5. — Coupe des collines de S. Maria di Catanzaro**

(Echelle des hauteurs et des longueurs, environ 1/25.000)

3. — Graviers et sables très fossilifères . . . . . . } Pliocène supérieur
2. — Sables argileux et argiles . . . . . . . . . .
G. — Banc de grès calcaire très fossilifère à *Cyprina islandica*.
1. — Argiles plastiques . . . . . . . . . . . . . . Pliocène ancien.

Sezione delle colline di S. Maria di Catanzaro: area tipo del Calabriano. Da GIGNOUX 1913.

Fig. 47. Section of the Santa Maria di Catanzaro hills: type area of the Calabrian historical stratotype (GIGNOUX 1913).

guests (the bivalve *Artica islandica*) in the Italian Neogene sections and indicative of a climatic deterioration (International Geological Congress of London 1948).

Lately, SPROVIERI et al. (1973), COLALONGO & PASINI (1980) and COLALONGO et al. (1980, 1981) correctly demonstrated that GIGNOUX (1913) erroneously reported the first appearance of *A. islandica* within the G-G1 bed which instead, occurs below the G-G1 bed as well the appearances of *Hyalinea baltica*, *Globorotalia. truncatulinoides excelsa* (Fig. 48) (COLALONGO et al. 1982). According to these data which suggested the G-G1 bed is no more valid as a guiding criterion for the definition of the base of the Calabrian, and to the very poor geologic-stratigraphic setting of the area, S. Maria di Catanzaro section cannot be considered as reference section of the Neogene/Quaternary boundary (COLALONGO et al. 1982).

EMILIANI et al. (1961) described the Le Castella section, located in the Crotone-Spartivento sedimentary basin, spanning the Neogene/Quaternary boundary (Fig. 48). In particular, the 6th INQUA congress (Varsavia 1961) first and finally the 7th INQUA congress (Denver 1965) proposed the Le Castella section as candidate to place the Neogene/Quaternary boundary stratotype. This solution has been accepted by BERGGREN &VAN COUVERING (1974) and HAQ et al. (1977) and the N/Q boundary was here defined in correspondence of the base of a sandy level ("marker bed", EMILIANI et al. 1961 suggested the correlatability between the "marker bed" and the G-G1 bed), where the first occurrence of *Hyalinea baltica* is recorded. A complete biostratigraphic framework of the Le Castella section is reported in VENZO (1975) (Fig. 49).

Lately, Le Castella section was shown as unsuitable for the definition of the the N/Q boundary for the following reasons (COLALONGO et al. 1982): the G-G1 bed is not

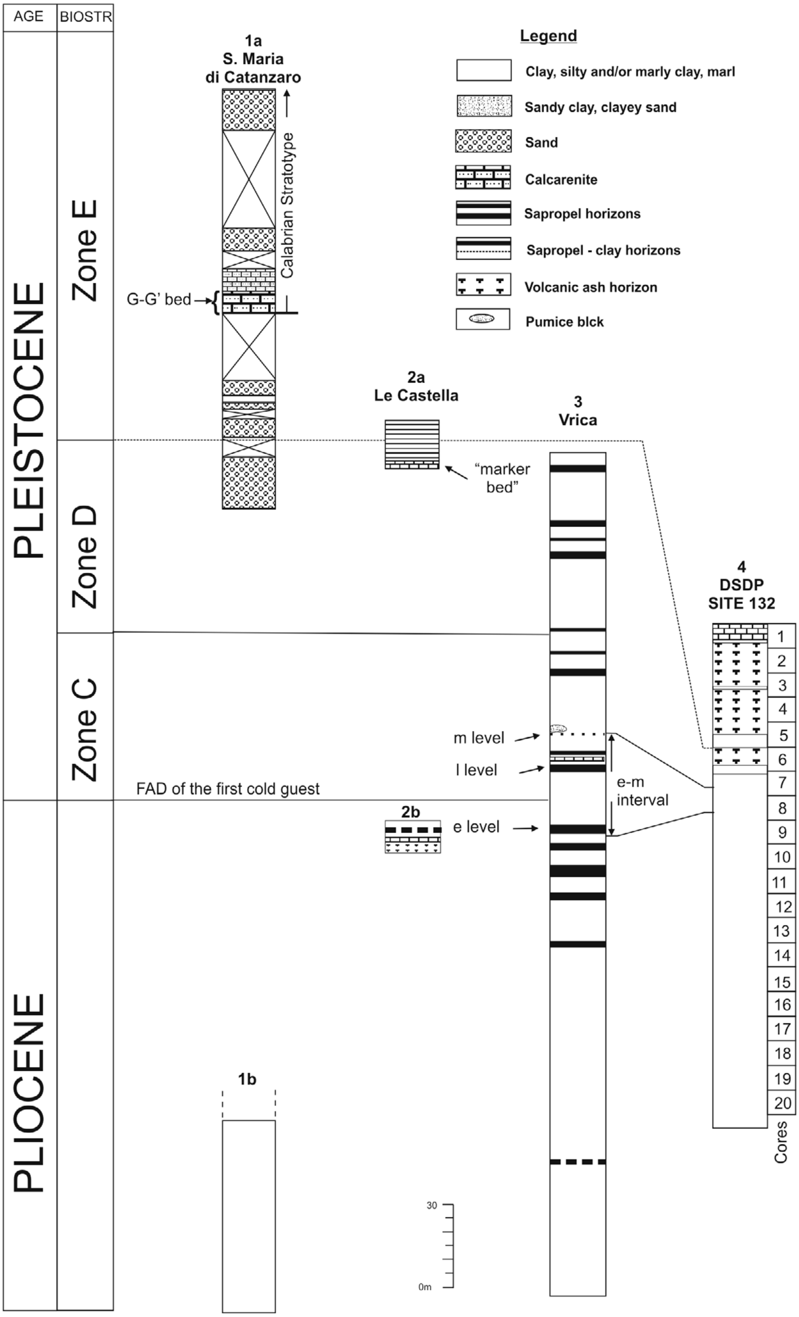



Fig. 48. Biostratigraphic correlation between the designed sections (S. Maria di Catanzaro, Le Castella and Vrica) where is recorded the base of Calabrian (Neogene/Quaternary boundary). After COLALONGO et al. (1982).

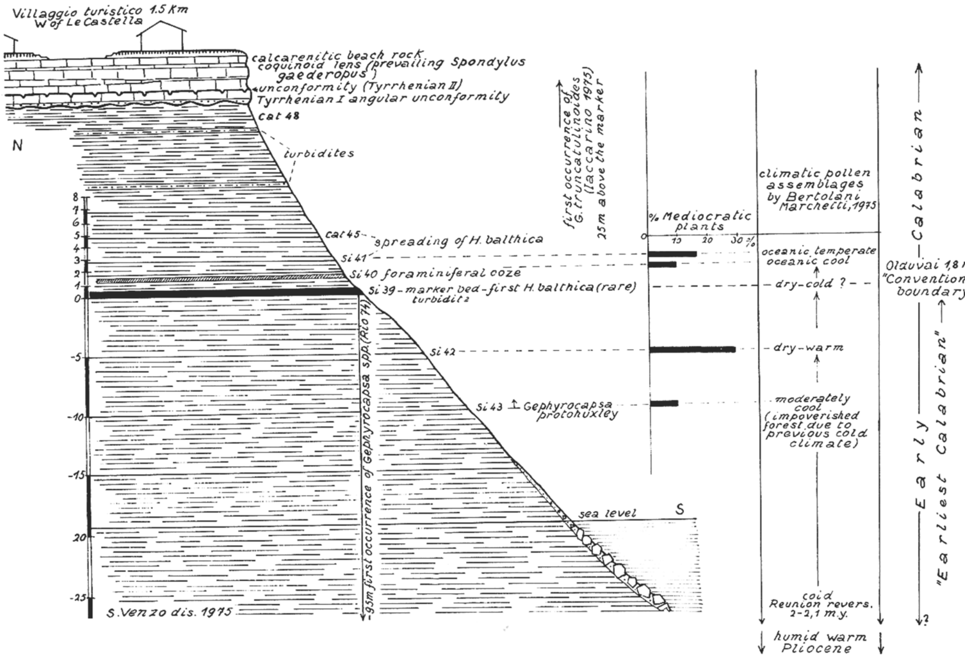



Fig. 49. Integrated stratigraphy of Le Castella section by VENZO (1975).

appropriate for defining the base of the Calabrian (BAYLISS 1969; SPROVIERI et al. 1973; DROOGER 1973; BROLSMA & MEULENKAMP 1973); tectonic disturbance (VENZO 1975; SELLI et al. 1977; PASINI & SELLI 1977; COLALONGO et al. 1980) and the occurrence of a gap just below the marker bed (COLALONGO et al. 1980; RAFFI & RIO 1980).

These conditions prompted the international community to find another section for the base of the Calabrian. SELLI et al. (1977) proposed the Vrica section (located in the Crotone-Spartivento sedimentary basin) as a possible candidate section for the N/Q boundary. In particular, SELLI et al. (1977) proposed to place the base of the Quaternary within a band encompassed between the FO of *Cytheropteron testudo* and the FO of *H. baltica*. On the other hand, COLALONGO & PASINI (1980) and COLONGO et al. (1981) proposed to place the boundary coinciding with the lithological level containing the FO of *C. testudo*. Recently, CITA et al. (2008) proposed a deep review of the definition of the Calabrian stage.

**Pleistocene GSSP (base of the Calabrian and base of the Quaternary) (AGUIRRE & PASINI 1985)**

The GSSP for the base of the Pleistocene Stage (early Quaternary) and base of the Calabrian is located in Vrica section (southern Italy) (Fig. 50) (e.g., VAN COUVERING 1996; VAI 1997). The Vrica section 222 meters-thick, is composed by marly and silty

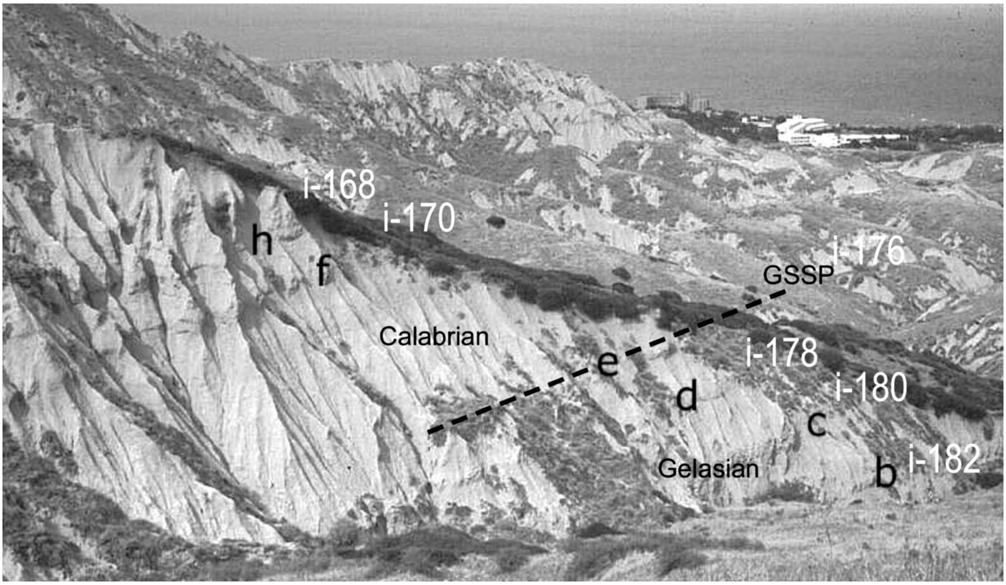



Fig. 50. Vrica section (Calabria): Pleistocene GSSP (Pleistocene/Quaternary boundary). Sapropel "e" corresponds to the GSSP (Aguirre & Pasini 1985)

claystones with interbedded, pink-grey sapropelic marker beds. The GSSP is defined at the base of the homogeneous claystone unit overlying sapropel "e" in the Vrica Section (southern Italy; Aguirre & Pasini 1985) dated astronomically at 1.808 Ma (Fig. 51). The boundary is very close to the Upper Olduvai reversal boundary (Zijderveld et al. 1991; Lourens et al. 1996b).

Calcareous plankton markers used to approximate the base of the Pleistocene (base of the Calabrian) are the LO of *Discoaster brouweri*, the FO of the medium-sized *Gephyrocapsa* and the FCO of *Neogloboquadrina pachyderma* left coiled and the influx of *Globorotalia crassaformis* (Lourens et al. 1996b) (Fig. 51).

After the International Geological Congress of Oslo (2008), during which it has been dedicated a Special Symposium on the Quaternary (chair M.B. Cita), the IUGS on June 2nd, 2009 ratified the redefinition of the base of Quaternary System/Period (and top of the Neogene System/Period), and the redefinition of the base of the Pleistocene Series/Epoch (and top of the Pliocene Series/Epoch). In detail, the base of the Quaternary System/Period, and thus the Neogene/Quaternary boundary, was formally defined by the Monte San Nicola GSSP and thus be coincident with the base of the Pleistocene and Gelasian, at 2.6 Ma (Gibbard et al. 2010). With these definitions, the Gelasian Stage/Age shifts from the Pliocene Series/Epoch to the Pleistocene.

Recently, during the workshop ("The Quaternary time scale: problems and future" organised by Italian Association for the Quaternary (AIQUA) held in Rome (June 2010), the

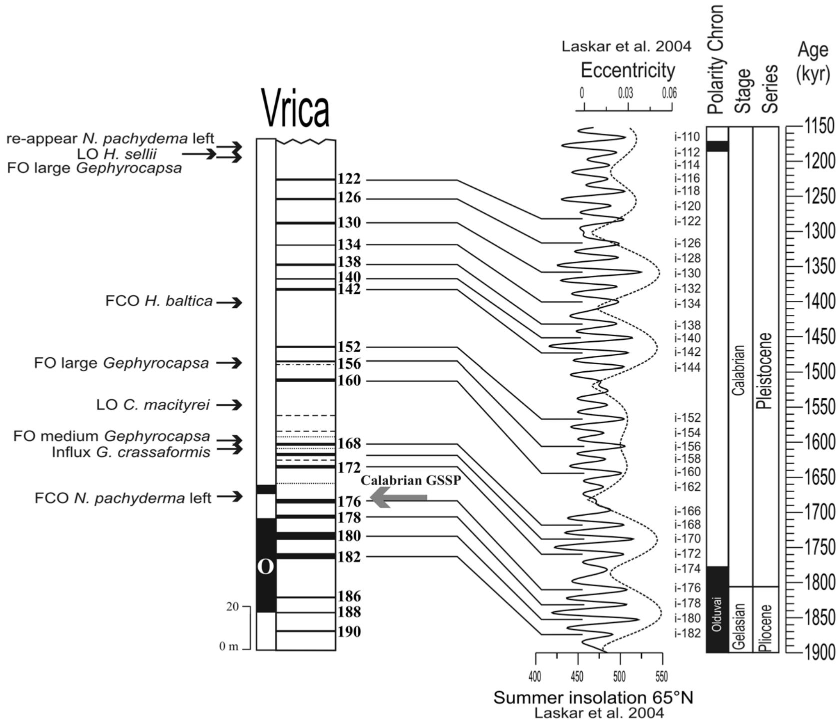



Fig. 51. Bio-magnetostratigraphy and astronomical tuning of Vrica section (Pleistocene GSSP). After LOURENS et al. (1996b) modified.

majority of the Italian stratigraphers expressed their deep disappointment for the IUGS ratification and called for an immediate moratorium (RIO et al. 2010) against the IUGS ratification in favour of a solution that would leave the base of the Pleistocene at 1.8 Ma, in agreement with a long lived and coherent practice in Italy and in the deep sea sediments and consequently the base of Quaternary at 1.8 Ma.

Lately a group of colleagues (e.g.: AUBRY, BERGGREN, HILGEN, MCGOWRAN, STEININGER, VAN COUVERING & LOURENS) tried to prevent the downwards shift of the Pleistocene boundary to the base of the Gelasian and also to keep the Neogene as it was originally defined (HILGEN et al. 2008; AUBRY et al. 2009; MCGOWRAN et al. 2009).

## Conclusion

All the data reported in the astronomically tuned Neogene deep marine records containing the GSSPs allowed the construction of the Astronomical Tuned Neogene Time Scale (ATNTS) of LOURENS et al. (2004). Concerning the future of the last two Miocene GSSPs of the Astronomical Tuned Neogene Time Scale, two deep marine Mediterranean sections (La Vedova in the Conero area and S. Peter Pool section in Malta) are identified as potential candidate to define the base of the Langhian. A suitable GSSP section for the base of tha Burdigalian, however, remains to be found. The alternative option to define this boundary in ODP cores is seriously considered by the Subcommission on Neogene Stratigraphy (SNS). Anyway this option is very far from the main criteria used for defining a GSSP: the accessibility. In fact, the choice of an ODP-Site means that high resolution integrated studies are not repeatable many times. No specific working group has been designed so far for this issue by the SNS.

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