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THE GLOBAL STRATOTYPE SECTION AND POINT (GSSP) OF THE TORTONIAN STAGE (UPPER MIOCENE): A PROPOSAL

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1. BACKGROUND AND MOTIVATION

During the last years, much progress has been made in the Neogene by defining Global Stratotype Sections and Points (GSSPs) of the Zanclean (Van Couvering et al., 2000), Piacenzian (Castradori et al., 1998) and Gelasian (Rio et al., 1998) Stages of the Pliocene and the youngest Messinian Stage of the Miocene (Hilgen et al., 2000a). The logical next step is to select and propose the GSSP for the next older stage in the Miocene, the Tortonian (Mayer-Eymar, 1858). This step is greatly facilitated by the progress recently made in establishing orbital-tuned integrated stratigraphic frameworks for the Middle/Upper Miocene both in the Mediterranean (Hilgen et al., 1995, 2000, 2003) and in the open ocean (Shackleton et al., 1997, 1999).

The Monte dei Corvi section located near Ancona on the Adriatic side of Italy is selected as the most suitable section for defining the Tortonian GSSP. The proposed boundary is placed at the mid-point of the sapropel of basic cycle no. 76 in the Monte dei Corvi Beach section of Montanari et al. (1997), close to the last common occurrences (LCOs) of the calcareous nannofossil *Discoaster kugleri* and the planktonic foraminifer *Globigerinoides subquadratus* and associated with the short normal subchron C5r.2n. The GSSP level coincides closely with oxygen isotope event Mi-5 and the associated glacio-eustatic sea-level low-stand of supercycle T3.1 and concurrent deep-sea hiatus NH4 (see Garcés et al., 1997), and is dated astronomically at 11.608 Ma (Hilgen et al., 2000b). The Monte Gibliscemi section is proposed as an auxiliary boundary stratotype because the better preservation of the calcareous microfossils in this section enables quantitative analyses and the construction of a stable isotope record (Turco et al., 2001).

1.1 Tortonian stage: a brief historical review

1.1.1 Original definition of the Tortonian (Mayer-Eymar, 1858)

The Tortonian Stage ("Tortonische Stufe"), named after the town of Tortona in northern Italy, was introduced by Mayer-Eymar in 1858 as "Blaue Mergel mit *Conus canaliculatus* und *Ancillaria glandiformis* von Tortona". In his original definition of the Tortonian, Mayer-Eymar included:

- Marine strata of Tortona (Italy), Baden (Vienna Basin) and Cabrières d'Aigues (Vaucluse, Fr.);

- Continental beds with *Hipparion* at Eppelsheim; beds at Cucurou (Mont-Leberon, Vaucluse, France) and Orignac (Hautes Pyrénées, France) with the same fauna.

It is important to realise that Mayer-Eymar extended the Tortonian up to the base of the Piacenzian considered to be basal Pliocene of age (Fig.1). In 1868, he decapitated his

Tortonian Stage by introducing the term Messinian to indicate the regressive, brackish-water strata above the marine Tortonian (Fig.1). Despite this complex history, the term Tortonian was soon adopted after its introduction partly because of the many influential papers on the subdivision of the Tertiary published by Mayer-Eymar (Fig.1).

1.1.2 Tortonian stratotype section (Gianotti, 1953)

The Rio Mazzapiedi-Castellania section located between the village of Sant'Agata Fossili and the town of Alessandria, some 10 km south of Tortona (Fig. 2), was designated as the Tortonian stratotype by Gianotti (1953) following the geological study of the type area by Gino (1953). Relevant studies in the area have subsequently been carried out by Vervloet (1966), Clari and Ghibaudo (1979) and Ghibaudo et al. (1985) to which the reader is referred for detailed information. The Tortonian stratotype mainly consists of marly sediments (the Sant'Agata Fossili marls of Ghibaudo et al., 1985), which overlie the deltaic sandstones (Mutti E., personal communication) of the Serravalle Formation (Fig.2). Clari and Ghibaudo (1979) subdivided the Sant'Agata marls into two members. The lower member is composed of a 180 m thick succession of bioturbated fine sandstones alternating with clayey siltstones while the upper member consists of an 80 m thick succession of blue-grey hemipelagic silty marls with thin turbidites in its upper part. Biota and lithofacies associations indicate an outer shelf and slope environment respectively.

The Rio Mazzapiedi-Castellania section is unanimously considered as the reference for the nominate time interval. It should be noted however that according to Gianotti (1953) the type Tortonian included the so-called "Marne tabacco a Cerizi" underlying the evaporitic sequence and yielding poor and oligotypical foraminiferal faunas. The younger end of the Tortonian of Gianotti (1953) has been decapitated later by the lowering of the Messinian base (Cita et al., 1965; d'Onofrio et al., 1975).

The Tortonian is consistently reported as a global stage in all the geological time scales (Fig.1). There existed a general consensus that the Tortonian base is approximated by the first occurrence (FO) of the planktonic foraminifer *Neogloboquadrina acostaensis* (see below).

1.1.3 Timing of the base of the Tortonian and top of the Serravallian stratotype

The Serravallian/Tortonian (S/T) boundary is not yet formally defined but is commonly placed at or close to the *N. acostaensis* FO (Cita and Blow, 1969 and Rio et al., 1997 for recent references). This bioevent was first recorded by Cita et al. (1965) from the basal part of the Tortonian historical stratotype section of Rio Mazzapiedi-Castellania (Fig.3) and was coincident with the base of the *G. mayeri*-*G. nepenthes* Zone. Later Cita and Blow (1969), who considered the FO of *N. acostaensis* as the evolutionary appearance from *G. continuosa* (N15/N16 boundary of Blow, 1969), indicated that this event best approximated the base of the Tortonian. 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).

These zonal assignments are conflicting, however, with the common practise to place the N15/N16 boundary at or close to the base of NN8 (see Rio et al., 1997). Recent data from the Monte Gibliscemi section (Sicily) even indicate that the *N. acostaensis* FO actually falls within zone NN7 in the Mediterranean as previously suggested by Foresi et al. (1998). This indicates that the so-called *N. acostaensis* FO at Rio Mazzapiedi-Castellania does not represent the true first occurrence of this taxon, as recently confirmed by the presence of rare *N. acostaensis* in the top part of the Serravalle Sandstones immediately below the base of the Tortonian stratotype (Miculan, 1997; Foresi et al., 1998). Evidently, the base of the Tortonian stratotype postdates the *N. acostaensis* FO.

The base of the Tortonian stratotype is older than the first regular occurrence (FRO) of *N. acostaensis* of Foresi et al. (1998). But the position of the *N. acostaensis* FRO above the *D. hamatus* FO in the Tortonian stratotype (Foresi et al., 1998) conflicts with findings from Monte Gibliscemi which indicate that the *D. hamatus/bellus* entry is delayed in the Mediterranean with respect to low latitudes and postdates the *N. acostaensis* FRO by several 100 kyrs (Hilgen et al., 2000b). Samples from the Tortonian stratotype studied by Foresi et al. (1998) were checked to solve this discrepancy by means of a semi-quatitative analysis and following the taxonomic criteria outlined by Hilgen et al. (2000b), the *N. acostaensis* FRO is positioned lower in the succession near the base of the Tortonian and below the *D. hamatus* FO. Moreover, the dominant right coiling of the neogloboquadrinids from the lower part of the Tortonian and the underlying Serravalle sandstones indicates that there is not a discernable hiatus at the base of the Tortonian stratotype and that the top part of the Serravalle sandstones postdates the first influx of the neogloboquadrinids at Monte Gibliscemi in which the coiling direction is essentially random. These findings further imply that the base of the type Tortonian postdates the last occurrence (LO) of *Paragloborotalia mayeri* (*P. siakensis* of Foresi et al., 1998) and, as a consequence, that all reported occurrences of this taxon in the Tortonian stratotype should be considered reworked. In conclusion, the Tortonian base in the historical stratotype corresponds almost exactly with the *N. acostaensis* FRO as defined at Monte Gibliscemi and dated astronomically at 10.554 Ma (see Hilgen et al., 2000b). This observation is more or less consistent with Müller (1975) who examined the “Serravallian of the Rio Mazzapiedi section" and referred it with certainty to NN7, and probably also to NN8 and the lower part of NN9 (reported only in the abstract of the paper) although the latter could not be confirmed due to the lack of samples from the uppermost part of the Serravalle Sandstone in this section.

The top of the Serravallian stratotype in the Serravalle Scrivia section can be dated at 11.8 Ma by linear extrapolation of the sedimentation rate between the *Sphenolithus heteromorphus* LO (13.5 Ma; Rio et al., 1997) and the last common occurrence (LCO) of *Calcidiscus premacintyrei* (12.3 Ma; Rio et al., 1997). This admittedly rough age estimate indicates that there is no overlap in time between the top of the Serravallian stratotype and the base of the

Tortonian stratotype and that all bioevents in the interval between 11.8 and 10.554 Ma are potentially suitable for delimiting the S/T boundary.

1.2 Selecting the most suitable section and level for defining the Tortonian GSSP

In the Neogene, orbital tuned cyclostratigraphies (Hilgen et al., 1995, 2000; Lourens et al., 1996) play an important role in addition to conventional criteria outlined by the International Commission on Stratigraphy (ICS) in the revised guidelines for establishing global chrono-stratigraphic standards (Remane et al., 1996). This extra criterion is added here because all ratified Neogene GSSPs are defined at lithological marker beds that are astronomically dated. In this way they are tied via first-order calibrations to the standard geological time scale once this time scale is underlain by astronomical tuning as is already the case for the Plio-Pleistocene (Berggren et al., 1995). This implies that other requirements being equal cyclostratigraphy will play a critical role in selecting the most suitable section and level for defining the Tortonian GSSP.

1.2.1 Selecting the guiding criterion for defining the boundary

According to the available biostratigraphic data from the historical stratotype sections (Serravallian and Tortonian), the Tortonian GSSP should be defined somewhere in the interval between the *Calcidiscus praemacintyrei* LCO (= top Serravallian type section, Rio et al., 1997) and the *Neogloboquadrina acostaensis* FRO (= base Tortonian type section, Hilgen et al., 2000b). Three different options were considered for locating the boundary:

1) to place the boundary coincident with the FRO of *N. acostaensis* dated astronomically at 10.544 Ma in the Monte Gibliscemi section. The boundary would closely coincide with the base of the Tortonian in the historical stratotype section and approximately with a major turnover in the calcareous nannofossils marked by the appearance of five-rayed discoasters (*Discoaster bellus* group) in the low latitudes;

2) to place the boundary at or close to the base of the long normal interval of C5n.2n. This reversal has been dated astronomically at 11.043 Ma in the continental section of Orera in Spain (Abdul Aziz et al., 2003). In the open ocean the boundary would be approximated by the *Coccolithus miopelagicus* LCO and the *Catinaster coalitus* FO. And;

3) to place the boundary at or close to the *Discoaster kugleri* and *Globigerinoides subquadratus* LCOs dated at 11.604 and 11.539 Ma in the Monte Gibliscemi section (Hilgen et al., 2000b). These events have similar ages in the Case Pelacani and Tremiti Islands sections (Caruso et al., 2002; Lirer et al., 2002).

The first option is regarded less favourable in view of the relatively low global correlation potential even though the boundary would in that case coincide closely with the Tortonian base in the historical stratotype. The second option was seriously taken into consideration also because it would result in a duration of the Tortonian that deviates less from that of the next younger Messinian stage and, probably, the older Serravallian stage. But this option has not been adopted because calcareous plankton events close to the boundary are less suitable for global recognition of the boundary. The *C. miopelagicus* LCO is diachronous while *C. coalitus* is a less reliable marker in the Mediterranean and its presence/absence in the open ocean is environmentally controlled.

The third option was selected because of the high correlation potential using multiple stratigraphic tools (planktonic foraminifera, calcareous nannoplankton, $\delta^{18}O$, magnetostratigraphy, sequence stratigraphy) which can be applied in widely different settings. The selected calcareous plankton events appear to be synchronous between the Mediterranean and the low-latitude open ocean on the basis of the existing astronomical age models. In addition, the *D. kugleri* LCO is tightly linked to the short normal subchron C5r.2n in the North Atlantic (Olafsson, 1991). Moreover, the event coincides closely with the Mi-5 isotope event and the associated glacio-eustatic sealevel low-stand (TB3.1) and deep-sea hiatus NH4.

The use of *D. kugleri* needs some taxonomic clarification. Our concept of *D. kugleri* fits exactly with the original description of the species (Martini and Bramlette, 1963) and has the same variability in morphology as documented in the original paper with a large and flat central area without a central knob. However, the identification of *D. kugleri* is problematical when preservation is poor because other discoasters (*D. musicus* = *D. sanmiguelensis*, that is a junior synonym) having a similar morphology can be confused with overgrown *D. kugleri*. In addition a higher than average sample resolution is necessary to reliable detect the biohorizon.

1.2.2 Selecting the section to define the boundary

The historical stratotype section of Rio Mazzapiedi-Castellania is considered unsuitable for defining the Tortonian GSSP because the section has not been astronomically tuned and it does not contain the boundary interval selected above. Tuned candidate sections for defining the GSSP are the Monte Gibliscemi and Case Pelacani sections on Sicily (southern Italy: Hilgen et al., 2000b; Caruso et al., 2002), the Monte dei Corvi section in northern Italy (Hilgen et al., 2003) and the San Nicola section on Tremiti islands (Adriatic Sea, Italy: Lirer et al., 2002).

Of all candidate sections Monte dei Corvi (Fig.4,5) is the only section that is demonstrable continuous, shows a lack of tectonic disturbance, is excellently exposed and easily accessible and can be unambiguously tuned in the critical interval across the boundary. The Monte Gibliscemi section is tectonically severely disturbed while the Case Pelacani and San Nicola sections are less well exposed in the boundary interval. Clearly this strengthens the case for Monte dei Corvi to define the Tortonian GSSP as previously suggested by Montanari et al. (1997) and Odin et al. (1997). The section can be cyclostratigraphically correlated in detail to sections on Sicily (Monte Gibliscemi, Case Pelacani) and the Tremiti Islands (San Nicola). Serious short-comings are the moderate to poor preservation of the calcareous plankton and the lack of a reliable magnetostratigraphy in the critical interval. The preservation problem certainly hampers to establish a reliable stable isotope record but detailed biostratigraphic correlations to other Mediterranean sections marked by a better preservation are straightforward. The lack of a reliable magnetostratigraphy in the critical interval can be overcome within the framework of an astronomically tuned integrated stratigraphy because a single tuned section with a reliable magnetostratigraphy suffice. Tuned ages for reversal boundaries are not yet available for this interval from the marine record but may come from a more detailed paleomagnetic investigation of Monte dei Corvi or from retuning of ODP leg 138 sites (Shackleton et al., 1995). However, they have already been obtained from the continental Orera section in Spain (Abdul Aziz et al., 2003).

1.3 Motivations

The Tortonian has been consistently used as a global stage in all recently published standard geological time scales (e.g., Harland et al., 1990; Berggren et al., 1995).

2. THE PROPOSED GSSP OF THE BASE OF THE TORTONIAN

Name of boundary: Base of Tortonian.

Rank of boundary: Stage/Age.

Position of the unit: Lower Stage of the Upper Miocene Subseries, between the Serravallian (below) and Messinian (above) Stages.

Type locality of the Global Stratotype Section and Point: Monte dei Corvi, central Italy, Europe.

Geographic location: The Monte dei Corvi section is exposed in the coastal cliffs of Monte dei Corvi located 5 km SE of Ancona and described in detail by Montanari et al. (1997). See for location also Figure 4.

Latitude: 43°35'12" North; **Longitude:** 13°34'10" East of Greenwich.

Accessibility: The section is very easy to reach from Ancona and is freely and easily accessible to scientists interested in studying the section (Fig.4,5). The section can best be reached via the trail that starts at La Sardella some 100 m east of Monte dei Corvi (Fig.4).

Conservation: Necessary steps will be undertaken for the conservation of the section.

GSSP definition: The midpoint of the sapropel layer of basic cycle no. 76 in the Monte dei Corvi Beach section (Hilgen et al., 2003) is proposed as the GSSP for the base of the Tortonian Stage (Fig.6). The level coincides almost exactly with the last common occurrences

(LCOs) of the calcareous nannofossil *Discoaster kugleri* and the planktonic foraminifer *Globigerinoides subquadratus* (Fig.7), is located stratigraphically 2 m above the Ancona ash layer in an interval of undetermined polarity (Fig.8). The level has been assigned an astronomical age of 11.608 Ma (Fig.9). We selected the sapropel midpoint instead of sapropel base (as has been common practise in defining GSSPs of Neogene stages up to now) because it is the midpoint that is assigned the age of the correlative peak in the astronomical target curve.

Identification in the field: The midpoint of the sapropel layer of cycle 76 will be marked in the field. Identification of the GSSP and re-sampling of the section are greatly facilitated by the readily identifiable sedimentary cycle pattern.

Completeness of the section: The unambiguous orbital tuning of the sedimentary cycles in the boundary interval cannot be explained other than that the succession is continuous. The tuning provides a highly accurate age of 11.608 Ma for the boundary. The section can further be correlated bed-to-bed to other marine sections in the Mediterranean (Fig.10,11). The cyclostratigraphic correlations are confirmed in detail by the high-resolution calcareous plankton biostratigraphy, thus providing another argument for the continuity of the succession. Sediment accumulation rates can be accurately determined and are in the order of 3-4 cm/kyr in the boundary interval.

Regional correlation potential: Integrated stratigraphic correlations of the Tortonian GSSP to other Mediterranean sections are straightforward and unambiguous. High-resolution cyclostratigraphic correlations are confirmed in detail by the position of calcareous plankton events. This applies both to major bio-events such as the *Discoaster kugleri* FCO and LCO, the *G. subquadratus* LCO, and the *Neogloboquadrina* group FO and to secondary events such as the *G. apertura-G. obliquus* group FRO.

The magnetobiostratigraphic record of continental sections in Spain shows that the GSSP predates the *Hipparion* FO with a minimum age of 11.1 Ma (Garcés et al., 1997) and, thus, the Aragonian/Vallesian stage boundary by some amount of time.

Global correlation potential: The *Discoaster kugleri* LCO in the North Atlantic is associated with the short normal subchron C5r.2n (Olafsson, 1991). We can assume that the GSSP is associated with this subchron as well in view of the synchroneity of the nominate bio-event between the Mediterranean type area and the low-latitude Atlantic. Moreover, the subchron has been astronomically dated between 11.618 and 11.558 Ma in the continental Orera section (Abdul Aziz et al., 2003; Fig.12). This confirms the inferred concurrence between this subchron and the Tortonian GSSP, and allows identification of the boundary in continental settings lacking a direct biostratigraphic control. In the marine realm, the *D. kugleri* and *G. subquadratus* LCOs appear to be synchronous between the Mediterranean type area and the low-latitude open ocean (Backman and Raffi, 1997; Hilgen et al, 2000b; Turco et al., 2002).

Stable isotopes yet provide another useful correlation tool. The boundary slightly predates the Mi-5 isotope event of Miller et al. (1991) dated astronomically at 11.4 Ma in the Monte Gibliscemi section (Turco et al., 2001; Fig.11) and the associated glacio-eustatic sea-level low-stand of supercycle T3.1 (Haq et al., 1987) and concurrent deep-sea hiatus NH4 of Keller and Barron (1983). The boundary further coincides almost exactly with the Barstovian-Clarendonian Mammal Age boundary in North America (Woodburne and Swisher, 1995; Alroy, 2002).

3. SUMMARY OF BACKGROUND STUDIES

The coastal cliff exposures of Monte dei Corvi contain the Middle to Upper Miocene part of the succession exposed along the Cònero Riviera. They were first measured and studied in detail by Sandroni (1985), and subsequently re-measured and sampled by Montanari et al., 1988). The sequence is exposed in three main outcrops (see Montanari et al., 1997 and Figure 4): 1) the Monte dei Corvi Beach section along the beach; 2) the La Sardella - Monte dei Corvi High Cliff composite section high up on the cliff, along the scarp of a large landslide, and; 3) the La Vedova section along the seashore bluffs and cliffs at the locality known as La Vedova.

Integrated stratigraphic data are provided by Montanari et al. (1997) who studied the entire composite section and by Hilgen et al. (2003) who focused their attention exclusively on the excellently exposed Monte dei Corvi Beach section (Fig.5). The latter section contains the proposed Tortonian GSSP (Figs.5,6).

Geological setting.

The Miocene succession of Monte dei Corvi is particularly suitable for integrated stratigraphic studies because it occupied a relative external position with respect to the developing Apenninic orogen at that time (Montanari et al., 1997). For this reason the succession remained pelagic throughout most of the Miocene, being affected by the NE-ward prograding orogenic front of the Apennines and its associated flysch-like sedimentation at a late, post Miocene stage (Montanari et al., 1997).

Stratigraphic succession

The entire succession exposed along the cliffs from Ancona to Porto Nouvo extends from the Aquitanian into the Pliocene and contains the Bisciaro (Aquitanian to Langhian), Schlier (Langhian to Tortonian), Euxinic Shale and Gessoso Solfifera (Messinian) Formations of the northern Apennines (Montanari et al., 1997). In this proposal we concentrate on the Serravallian and Lower Tortonian part of the succession exposed along the eastern slopes and in the coastal cliffs of Monte dei Corvi described in detail by Montanari et al. (1997) and Hilgen et al. (2003). This interval is particularly well exposed in the Monte dei Corvi Beach section of Montanari et al. (1997). This section contains the upper part of the marly Schlier Formation (upper part calcareous member and basal part marly member) 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, named Respighi and Ancona, are present (Fig.6). This part of the succession is underlain by the calcareous marls of the massive member of the middle Schlier exposed in section La Vedova and overlain by marls and euxinic shales of the Euxinic Shale Formation exposed in section La Sardella (Montanari et al., 1997).

Depositional environment

The depositional environment remained (hemi)pelagic throughout the succession exposed in the Monte dei Corvi Beach section. Restricted conditions leading to the deposition of the so-called euxinic shales and eventually evaporites associated with the Messinian salinity crisis start higher up in the succession. Bottom water conditions changed cyclically between oxic (marls) and anoxic or dysoxic (sapropel layers).

Calcareous nannofossil biostratigraphy

Calcareous nannofossils are abundant but their preservation is generally moderate to poor, being better in the sapropel layers. Quantitative biostratigraphic studies of the calcareous nannofossils were carried out by Montanari et al. (1997) and Hilgen et al. (2003; Fig.7). Combining the results of these studies, the following succession of events is recorded (in stratigraphic order): *Cyclicargolithus floridanus* LO, *Calcidiscus macintyrei* FO, *C. premacintyrei* LO, *Discoaster kugleri* FCO and LCO, last regular occurrence (LRO) of *Coccolithus miopelagicus*, *Helicosphaera walbersdorfensis* LO and *H. stalis* FCO, *D. bellus* FO, and *D. hamatus* FO. This order of events is essentially the same as found in other Mediterranean sections such as Monte Gibliscemi (Hilgen et al., 2000b), Case Pelacani (Caruso et al., 2002) and San Nicola (Lirer et al., 2002). The GSSP closely coincides with the *Discoaster kugleri* LCO and thus with the MNN7b-c zonal boundary in terms of the standard Mediterranean zonation (Raffi et al., 2003). It falls within Zone NN7 of the standard low-latitude zonation of Martini (1971) and in Zone CN6 of the Okada and Bukry (1980) zonation.

Planktonic foraminiferal biostratigraphy

Planktonic foraminifera are usually abundant but their preservation is often moderate to poor. The qualitative studies of Coccioni et al. (1992; 1994) of the entire composite section allowed to identify all the events employed in the regional zonal scheme of Iaccarino and Salvatorini (1982) and Iaccarino (1985), whereas only few events of the standard low-latitude zonation of Blow (1969) were recognised. The entire composite section ranges from Zone N8 to N17 (Montanari et al., 1997).

The semi-quantitative biostratigraphic analysis presented in Hilgen et al. (2003) focused on the Monte dei Corvi Beach section and allowed the recognition of some additional events in the boundary interval (Fig.7). The FO of the *Neogloboquadrina* group, including *N. acostaensis,* previously recognised at Monte Gibliscemi and dated at 11.781 Ma, was also found at Monte dei Corvi, dated at 11.762 Ma. The *G. subquadratus* LCO dated at 11.539 Ma in the Monte Gibliscemi section was found at a slightly older level at Monte dei Corvi (at 11.593 Ma). The Tortonian GSSP is defined close to this bioevent. It is preceeded by the *Neogloboquadrina* group FO and the *Paragloborotalia mayeri* (sensu Foresi et al., 1998) LO and succeeded by the *G. apertura*-*G. obliquus* group FRO, the *P. siakensis* (= *P. mayeri* sensu Hilgen et al., 2000b) LO and the large-sized *N. atlantica* FO. The GSSP falls within the *P. siakensis* Zone of Iaccarino (1985), coincides with the boundary between *N. continuosa* and *G. menardii* Zones of Foresi et al. (1998), and the boundary between *N. atlantica praeatlantica* and *P. siakensis* Zones of Sprovieri et al. (2002). Application of the standard low-latitude zonation of Blow (1969) is rather useless in view of the strong diachroneity of some of the zonal marker events. For example the zonal markers for N14/N15 and N15/N16 fall apart at Ceara Rise (equatorial Atlantic) but overlap in the Mediterranean. At Ceara Rise the guiding criteria for the base Tortonian fall slightly above the *G. nepenthes* FO (Turco et al., 2002) which event marks the N13/N14 zonal boundary of Blow (1969). In the Carribean Sea, the boundary also falls in the lower part of N14 (Chaisson and D'Hondt, 2000).

Magnetostratigraphy

A detailed paleomagnetic study of the Monte dei Corvi Beach section has been carried out by Montanari et al. (1997) and Hilgen et al. (2003) with the main purpose to determine the magnetic reversal stratigraphy of the section. Applying standard demagnetisation techniques, Montanari et al. (1997) concluded that the magnetic intensity was too weak to yield useful information on the magnetic polarity and that the natural remanent magnetisation (NRM) was already largely removed at temperatures of 200°C. Most samples revealed southwesterly declinations and negative inclinations, but these directions were considered as an overprint.

A pilot study of a limited number of oriented hand-samples similarly revealed weak to very weak NRM intensities, but also some levels with opposite reversed and normal polarity directions. Subsequent analysis of a more detailed sample set made it possible to isolate a characteristic low-temperature component marked by dual polarities (Hilgen et al., 2003). Plotting the ChRM directions resulted in a magnetostratigraphy for the upper part of the section that could be calibrated to the GPTS of Cande and Kent (1995) and ranges from C5n.2n up to C4r.2r (Fig.8). Unfortunately, the lower part of the section, including the Serravallian-Tortonian boundary interval, did not produce a reliable magnetostratigraphy despite the fact that some short reversed intervals were recorded (Fig.8).

Cyclostratigraphy and astrochronology

The Monte dei Corvi Beach section is composed of a cyclic alternation of marls, marly limestones and organic-rich beds (Montanari et al., 1997). The basic small-scale cycle is a couplet (between 0.3 and 1.0 m thick) which consists of an indurated whitish marly limestone and a softer grey to greenish-grey marl. Brownish to blackish coloured organic-rich beds termed sapropels are frequently but not always intercalated in the limestones. Basic cycles have been labelled from the base of the section upward by assigning consecutive numbers to the limestone beds or the corresponding sapropels (Fig.6).

Larger-scale cycles can be distinguished in addition and comprise both small-scale and large-scale sapropel clusters. Small-scale clusters contain 2 to 4 sapropels (and 5-6 basic cycles); large-scale clusters contain several small-scale clusters (and up to 20 basic cycles). Finally a cycle of intermediate-scale is recognised by repetitive sapropel patterns in every other basic cycle. Previous studies of marine sections of Late Miocene to Pleistocene age in the Mediterranean (Hilgen, 1991; Hilgen et al., 1995; Lourens et al., 1996) showed that similar sapropel patterns reflect the astronomical cycles of precession (basic cycle), obliquity (intermediate cycle) and eccentricity (larger-scale cycles). Using the same phase relations as established for the younger sapropels, the sedimentary cycles in the Monte dei Corvi Beach section were tuned to the precession and insolation time series of the La93 solution (Laskar, 1990; Laskar et al., 1993). This tuning provides astronomical ages for all the sedimentary cycles, calcareous plankton bioevents, magnetic reversals and ash beds recorded in the section (Fig.9). It shows that the entire beach section ranges from 13.4 to 8.5 Ma and that the Tortonian GSSP has an astronomical age of 11.608 Ma (Hilgen et al., 2003). Note that our preferred tuning deviates from the eccentricity tuning proposed by Cleaveland et al. (2002). The latter tuning is based on a high-resolution carbonate record and is consistent with the previously published ^{40}Ar/^{39}Ar biotite ages from the ash beds, but not with unpublished sanidine ages for the Ancona bed (see below). However, their tuning can easily be modified as to fit the tuning of Hilgen et al. (2003) followed in this proposal.

Ar/Ar chronology

The composite sequence at Monte dei Corvi contains numerous ash layers, most of which are concentrated in a relatively short interval across the Tortonian/Messinian boundary. Two biotite-bearing ash layers, named Respighi and Ancona, are found in the Monte dei Corvi Beach section, the latter one being intercalated only 2 m below the proposed GSSP. Fresh unaltered biotites from both these ash layers have been dated using the incremental-heating ^{40}Ar/^{39}Ar technique (Montanari et al., 1997). For the Respighi layer, the preferred mean isochron age (of 3 out of 4 experiments) arrived at 12.86 ± 0.16 Ma, while a weighted average of two plateau ages (of a single experiment) of 11.43 ± 0.20 Ma was obtained for the Ancona bed. These ages were calculated relative to an age of 27.84 Ma for the Fish Canyon Tuff sanidine monitor dating standard and they arrive at 12.94 and 11.50 Ma if the recently published age of 28.02 Ma for this standard is applied (Renne et al., 1998). These ages are slightly but significantly younger than the astronomical ages of 13.296 and 11.688 Ma for the same ash layers (Hilgen et al., 2003). Recently, however, single fusion experiments on sanidine from the Ancona ash yielded an age of 11.690 ± 0.20 Ma that is virtually identical to the preferred astronomical age (Klaudia Kuiper, unpubl. results).

Sr-isotope stratigraphy

The Sr-isotope composition of whole rock, isolated foraminiferal tests and fish teeth has been analysed in samples from the Monte dei Corvi Beach and La Sardella sections (Montanari et al., 1997). The isotope composition of the whole rock samples from the Monte dei Corvi Beach section are generally consistent with $^{87}Sr/^{86}Sr$ values in pelagic carbonates from the open ocean. On the other hand, samples (of widely different materials) from the La Sardella section exhibit Sr-isotope ratios that are significantly lower than those obtained from the open ocean. This deviation can best be explained by an increasing isolation of the Mediterranean Basin, or partially so, from the world's oceans (Montanari et al., 1997).

Stable isotopes

Unfortunately, a reliable stable isotope record can not be obtained due to the moderate to poor preservation of the foraminiferal tests. The Monte dei Corvi Beach section can be correlated cyclostratigraphically in detail with the Monte Gibliscemi section (Fig.10) from which a planktic and benthic isotope record is available (Turco et al., 2001; Fig.11). This correlation shows that the Tortonian GSSP slightly predates a short interval marked by heavier $\delta^{18}O$ values that corresponds to the Mi-5 isotope event of Miller et al. (1991). This event supposedly reflects a temporary increase in Antarctic ice volume linked to minimum amplitude variations in the 1.2 myr obliquity cycle (Turco et al., 2001).

Auxiliary boundary stratotype

We propose section Gibliscemi, exposed along the southern slopes of Monte Gibliscemi located on Sicily (Italy) as auxiliary boundary stratotype for the Serravallian-Tortonian boundary. This designation is ment to overcome the problem of the poor to moderate preservation of the calcareous microfossils observed at Monte dei Corvi, which also prevents us from establishing a reliable stable isotope record. The Gibliscemi section has been correlated cyclostratigraphically in detail ("bed-to-bed") to the Monte dei Corvi section, the cyclostratigraphic correlations being confirmed by the calcareous plankton biostratigraphy (Fig.10). At Monte Gibliscemi the S/T boundary is placed at the mid-point of the grey marlbed of small-scale cycle -75 in partial section D located at 24.67 m in the Gibliscemi composite of Hilgen et al. (2000b). The marlbed correlates with the sapropel of cycle 76 at Monte dei Corvi (Fig.10) and coincides closely with the *D. kugleri* LCO. In addition, four volcanic ash layers are found in the basal part of section Gibliscemi which contain sanidine in a datable fraction.

The integrated calcareous plankton biostratigraphy and astronomical tuning of the section were presented in Hilgen et al. (2000b) while the quantitative planktonic foraminifer record, and the planktonic and benthic stable isotope records were published in Turco et al. (2001). The planktonic and benthic isotope records are punctuated by two episodes of $\delta^{18}O$ increase (Fig.11) which have been assigned astronomical ages of 11.4 and 10.4 Ma and correspond to the Mi5 and Mi6 events of Miller et al. (1991). The expression of the Mi5 event thus slightly postdates the S/T boundary as proposed here.

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Figure captions

Figure 1. Historical review of Miocene chronostratigraphic subdivision (see Rio et al., 1997).

Figure 2. Geological map of the Tortonian type area and location of the Tortonian stratotype section in the valley of Rio Mazzapiedi and Rio Castellania between the villages of Sant' Agatha Fossili (after Clari and Ghibaudo, 1979). 1 = alluvial deposits; 2 = Lugagnano Clays; 3 = Cassano Spinola Conglomerate; 4 = Gessoso-Solfifera Formation; 5 = Alosio Conglomerate; 6 = S. Agata Fossili Marl (upper member); 7 = S. Agata Fossili Marl (lower member); 8 = Serravalle Sandstone; 9 = Apennine units; and 10 = trace of the Tortonian stratotype section.

Figure 3. Summary of the calcareous plankton biostratigraphic data from the Tortonian stratotype (from Rio et al., 1997). F = Planktonic foraminifer, N = Calcareous nannofossil. The most recent data have not been included (see text).

Figure 4. Location map for the boundary stratotype section of Monte dei Corvi (A) and (B) the auxiliary boundary stratotype section of Monte Gibliscemi (from Hilgen et al., 2003). The partial sections that combined make up the Gibliscemi composite are in stratigraphic order F, D, C, B and A (see Hilgen et al., 1995, 2000b for details).

Figure 5. Photograph of the older part of the Monte dei Corvi Beach section of Montanari et al. (1997) and of the Serravallian/Tortonian boundary interval. The S/T boundary and numbered basic sedimentary cycles are indicated (cycle numbers after Hilgen et al., 2003). The yellow arrow marks the Tortonian GSSP and the (empty) bottle the Ancona ash bed.

Figure 6. Lithological log of the Monte dei Corvi Beach section (from Hilgen et al., 2003). The two ash beds are indicated by a R (Respighi level) and A (Ancona level). I and II refer to two thick intervals in which it is difficult to ascertain the individual basic sedimentary cycles.

Figure 7. Calcareous plankton biostratigraphy of the Monte dei Corvi Beach section (from Hilgen et al., 2003). No useful data indicates that the marker species has not been counted in this interval because the data would have had no biostratigraphic significance.

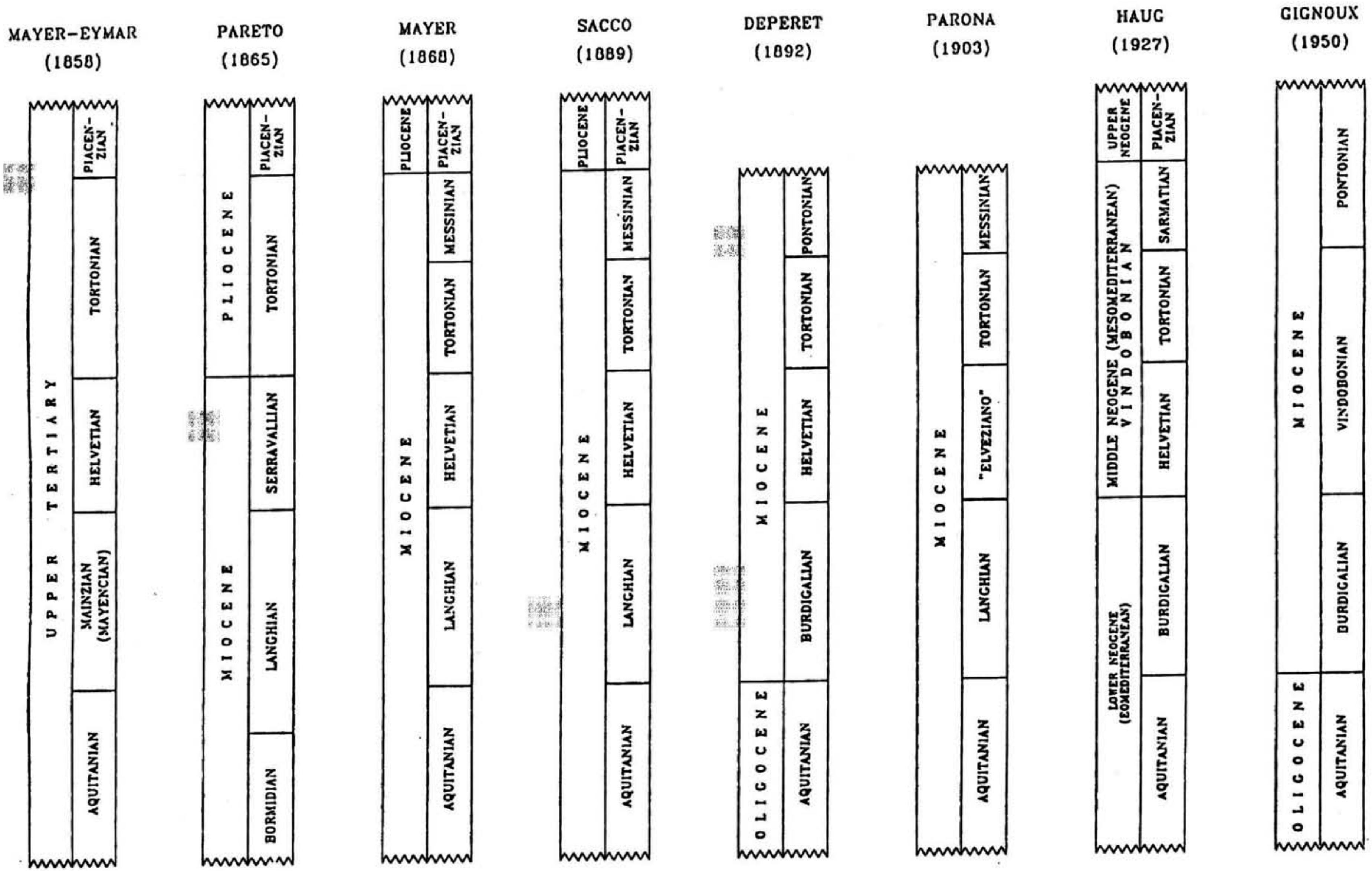
Figure 8. Magnetostratigraphy of the Monte dei Corvi Beach section and calibration to the GPTS of Cande and Kent (1995; based on Hilgen et al., 2003).

Figure 9. Astronomical tuning of the basic sedimentary cycles in the Serravallian/Tortonian boundary interval in the Monte dei Corvi Beach section to precession and insolation (from Hilgen et al., 2003).

Figure 10. Integrated cyclostratigraphic and biostratigraphic correlations between the Monte dei Corvi Beach section and the Monte Gibliscemi section (from Hilgen et al., 2003). The part of the Gibliscemi composite shown here is based on partial sections F, D, C and B (see Hilgen et al., 1995, 2000b for details). Numbered calcareous plankton events refer to: 1) *Neogloboquadrina* group FO, 2) *G. subquadratus* LCO, 3) *P. siakensis* LO, 4) *Neogloboquadrina* group second influx, 5) *N. atlantica* large-sized FO, 6) *N. atlantica* large-sized LO, 7) *Neogloboquadrina* dextral to sinistral coiling shift, 8) *G. partimlabiata* LO, 9) *Neogloboquadrina* sinistral to dextral coiling shift, a) *D. kugleri* FCO, b) *D. kugleri* LCO, and c) *C. miopelagicus* LRO. (Dashed) arrows mark major (minor) influxes of large-size *N. atlantica*.

Figure 11. Benthic and planktonic isotope records of the Monte Gibliscemi section showing the position of event Mi-5 (from Turco et al., 2001). The part of the Gibliscemi composite shown is based on partial sections F and D (see Hilgen et al., 2000b for details).

Figure 12. Cyclostratigraphy and magnetostratigraphy of the continental Orera section in Spain. The succession consists of a cyclic alternation of lacustrine limestones (white beds) and floodplain clays (hatched beds). Also shown are the magnetostratigraphic calibration to the GPTS of Cande and Kent (1995) and the tuning of the small-scale sedimentary cycles.



(a)

Fig. 1. Historical review of the Miocene chronostratigraphic subdivision. (a) Chronostratigraphic proposals before the development of calcareous plankton biostratigraphy.

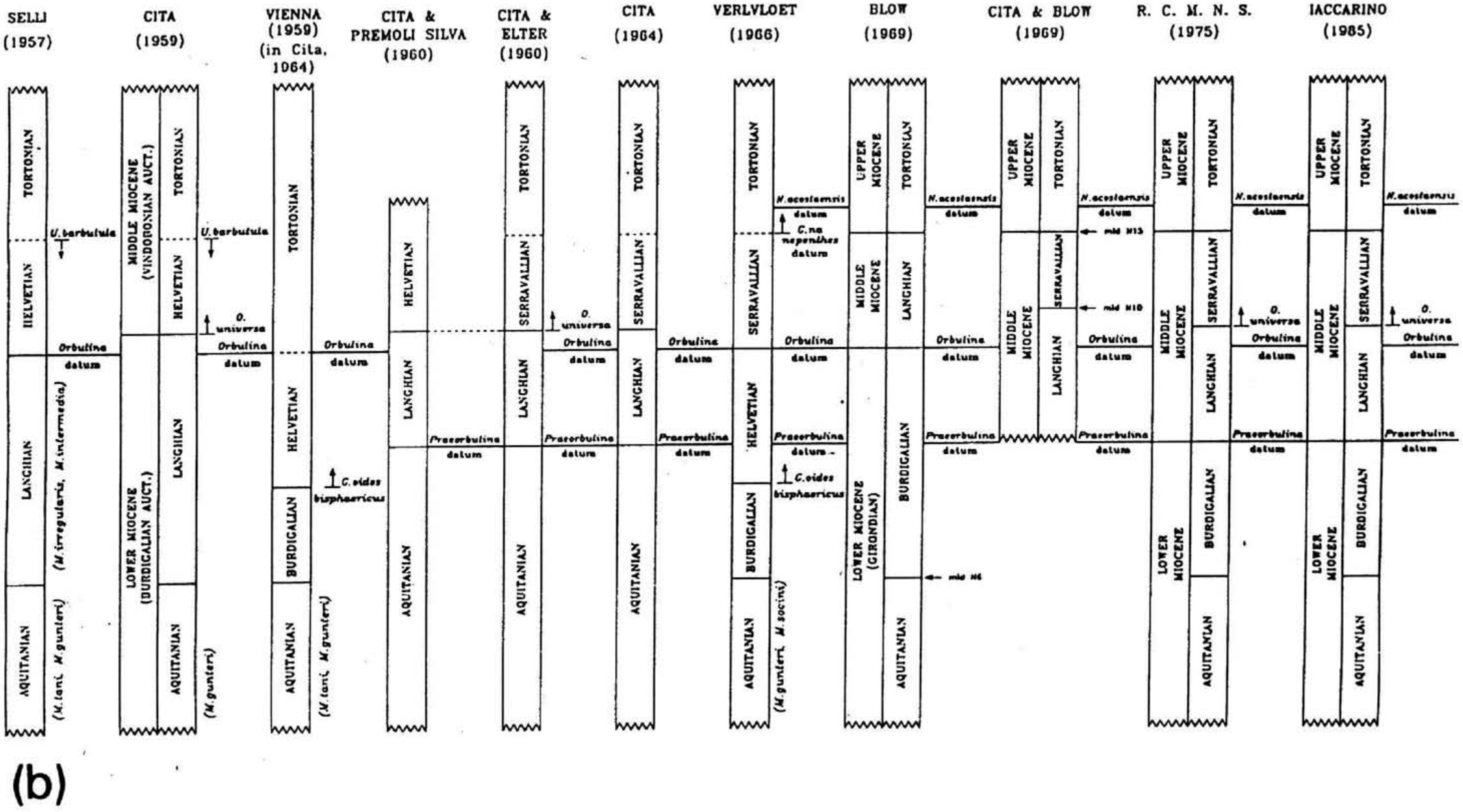
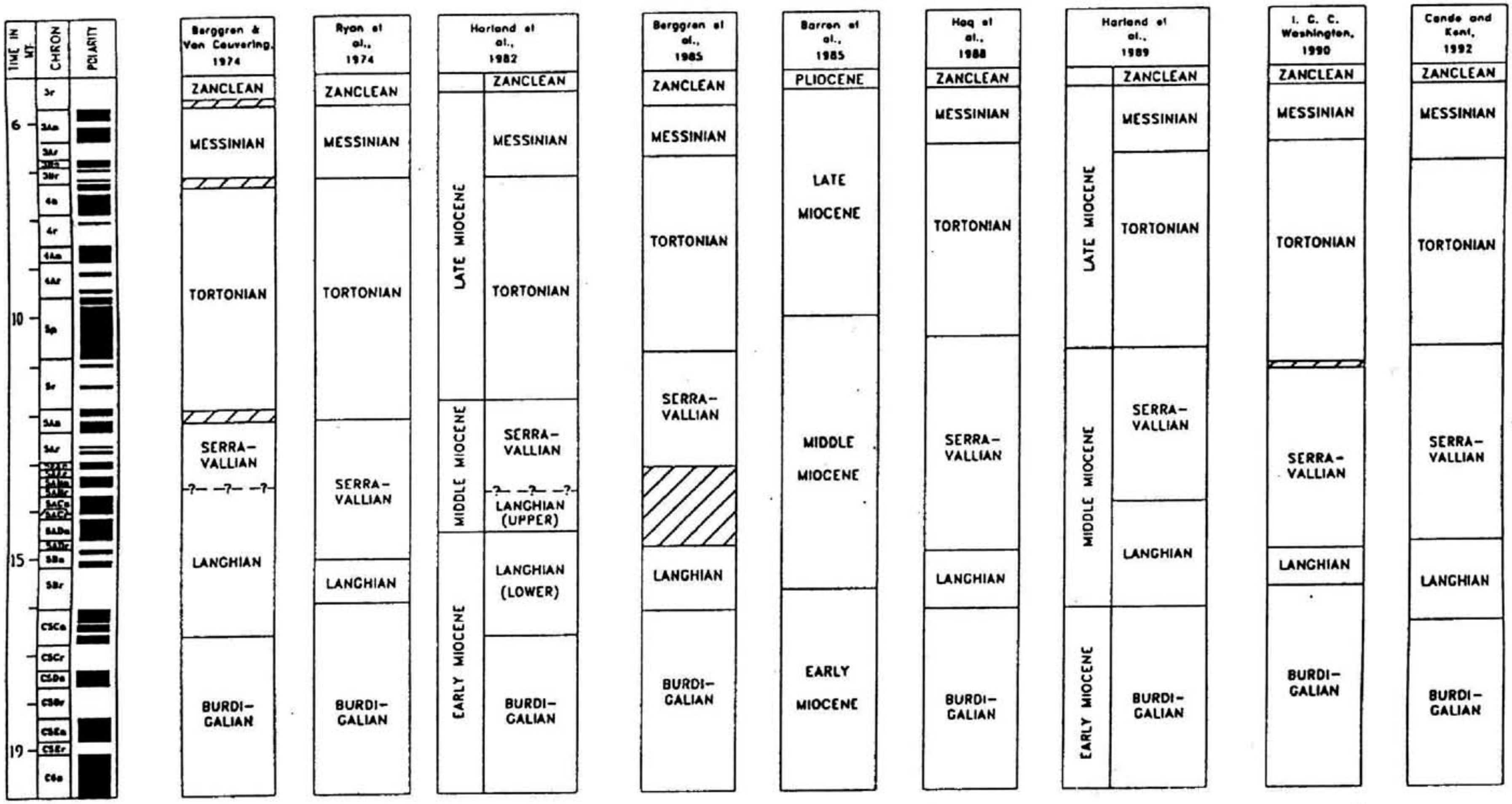


Fig. 1 (continued). (b) Chronostratigraphic proposals using planktonic foraminifer biostratigraphy.



(c)

Fig. 1 (continued). (c) Position of the Miocene stages versus magnetostratigraphy in the most widely used chronostratigraphic schemes proposed in the last 20 years.

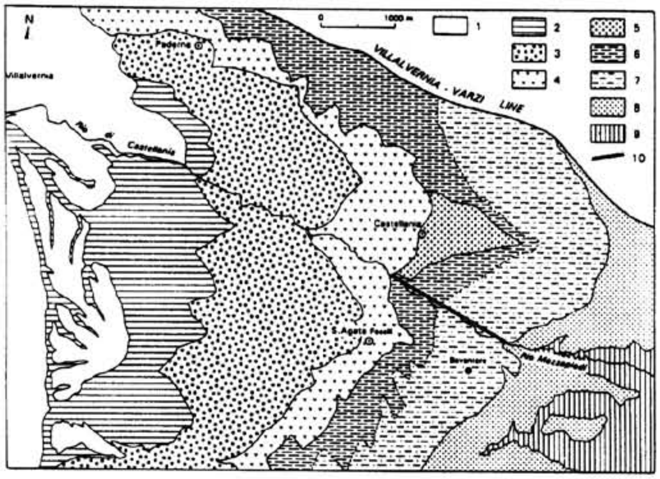


Figure 2

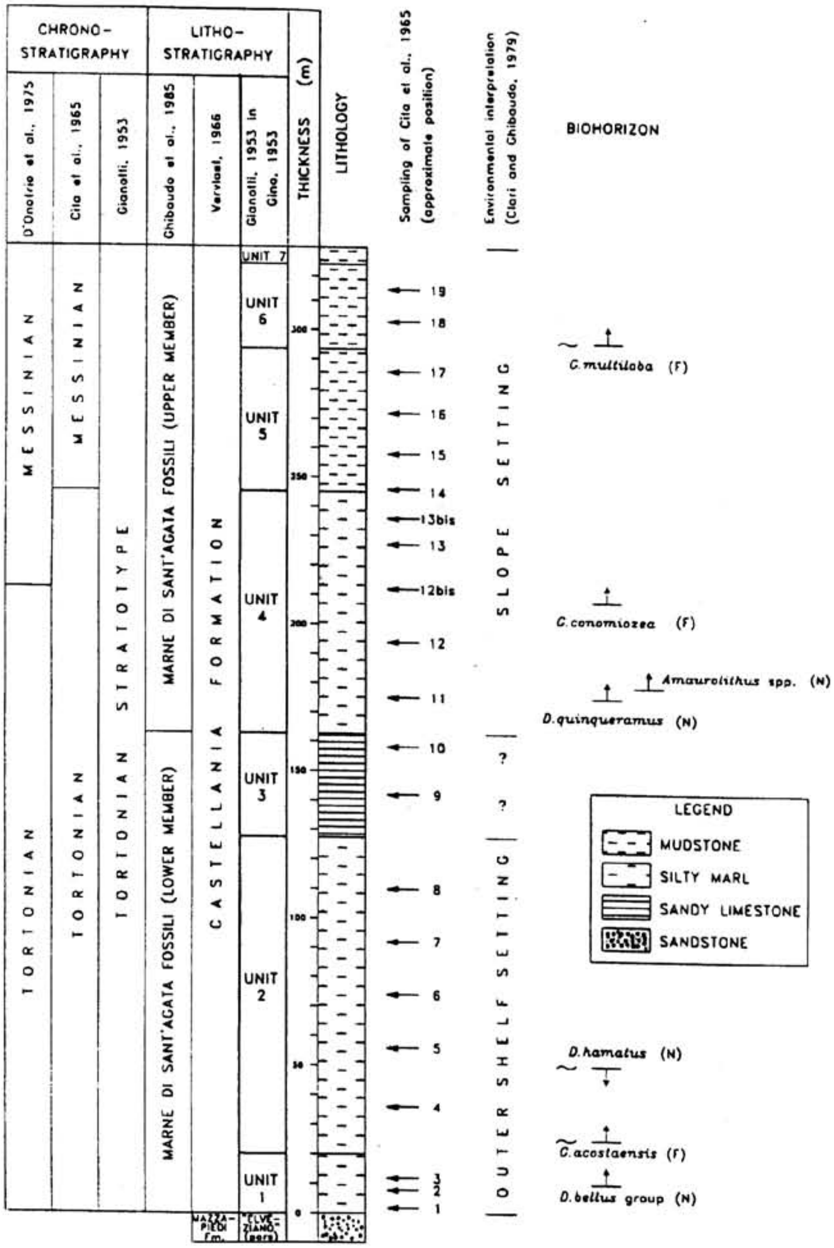
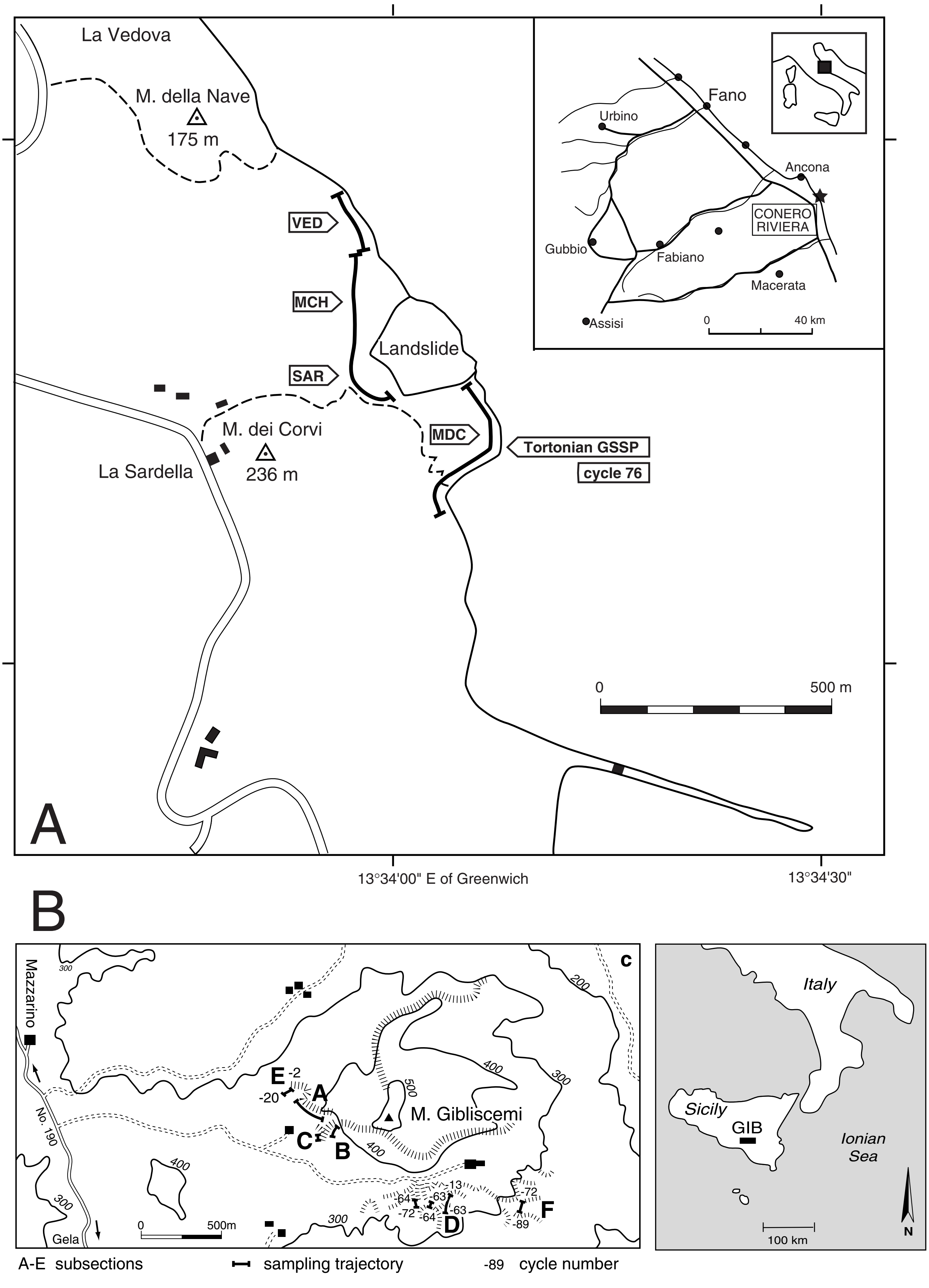


Figure 3


A
La Vedova
M. della Nave
175 m
43°35'30" N
VED
MCH
Landslide
SAR
M. dei Corvi
236 m
La Sardella
MDC
Tortonian GSSP
cycle 76
43°35'00" N
0
500 m
13°34'00" E of Greenwich
13°34'30"
Fano
Urbino
Ancona
CONERO RIVIERA
Gubbio
Fabiano
Macerata
Assisi
0
40 km
B
Mazzarino
No. 190
Gela
300
200
400
500
300
M. Gibliscemi
E
-2
-20
A
C
B
400
13
-64
-63
-72
-64
-63
D
-72
F
-89
0
500m
c
Italy
Sicily
GIB
Ionian Sea
100 km
N
A-E subsections
sampling trajectory
-89 cycle number

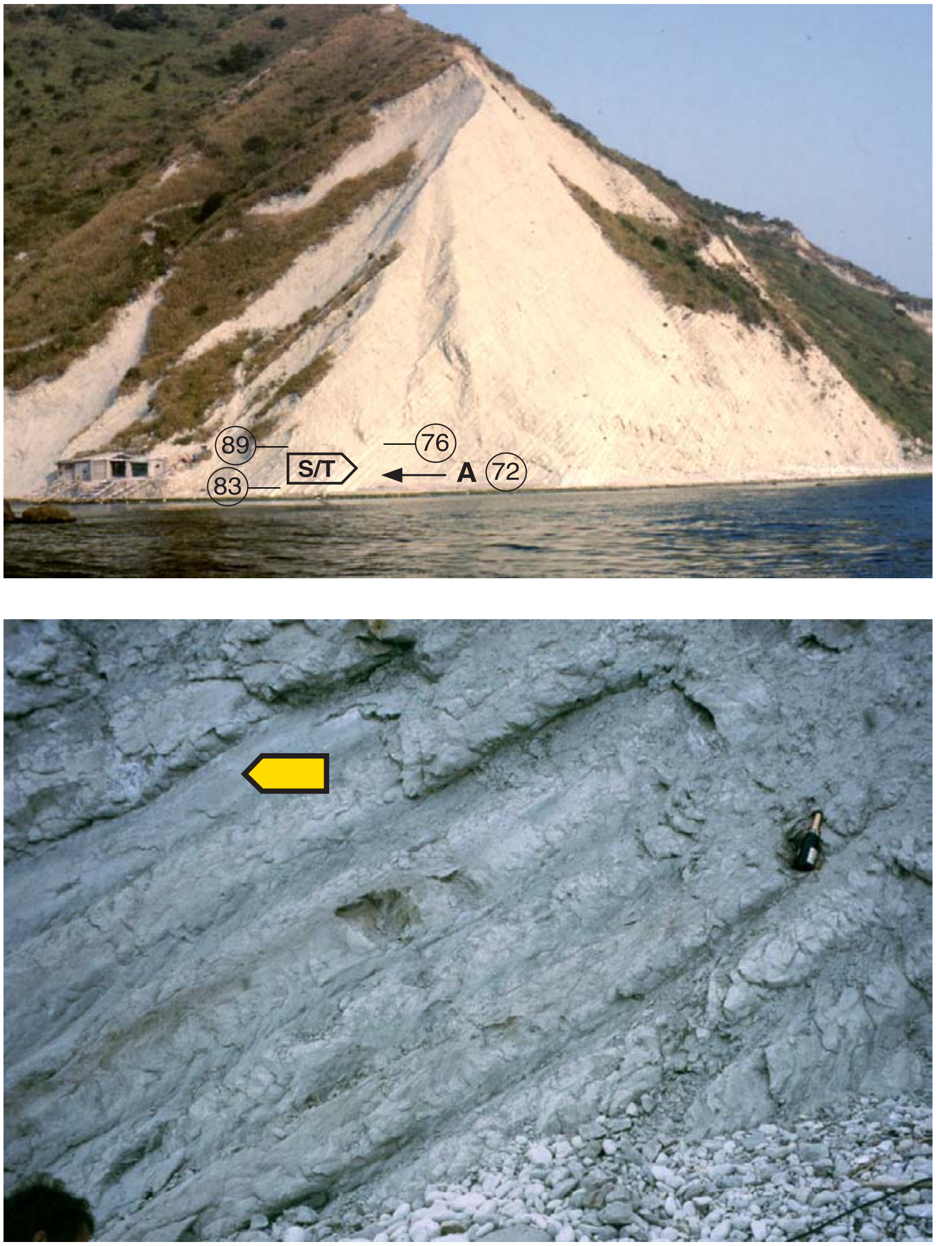


Figure 5

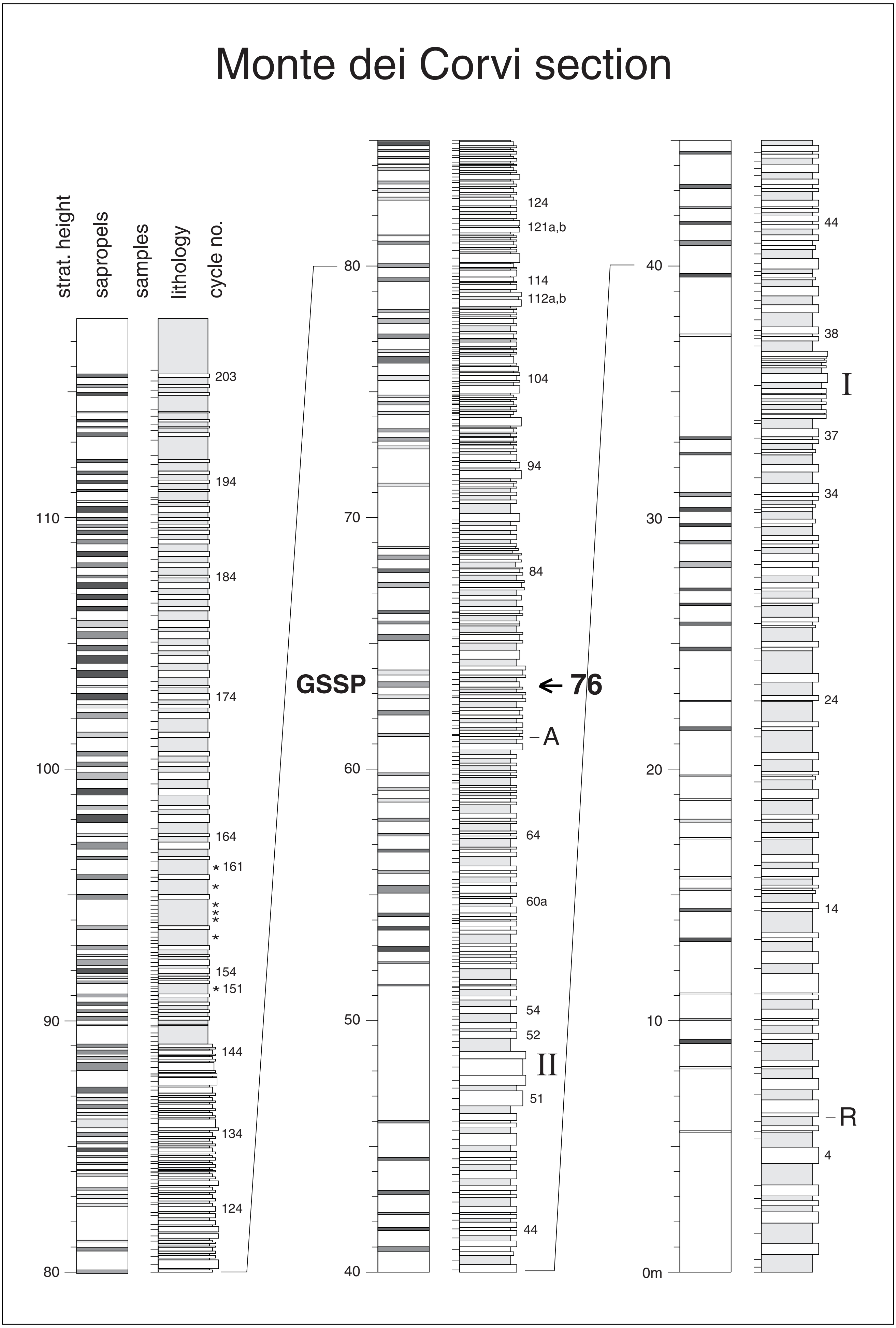

Monte dei Corvi section

Figure 6

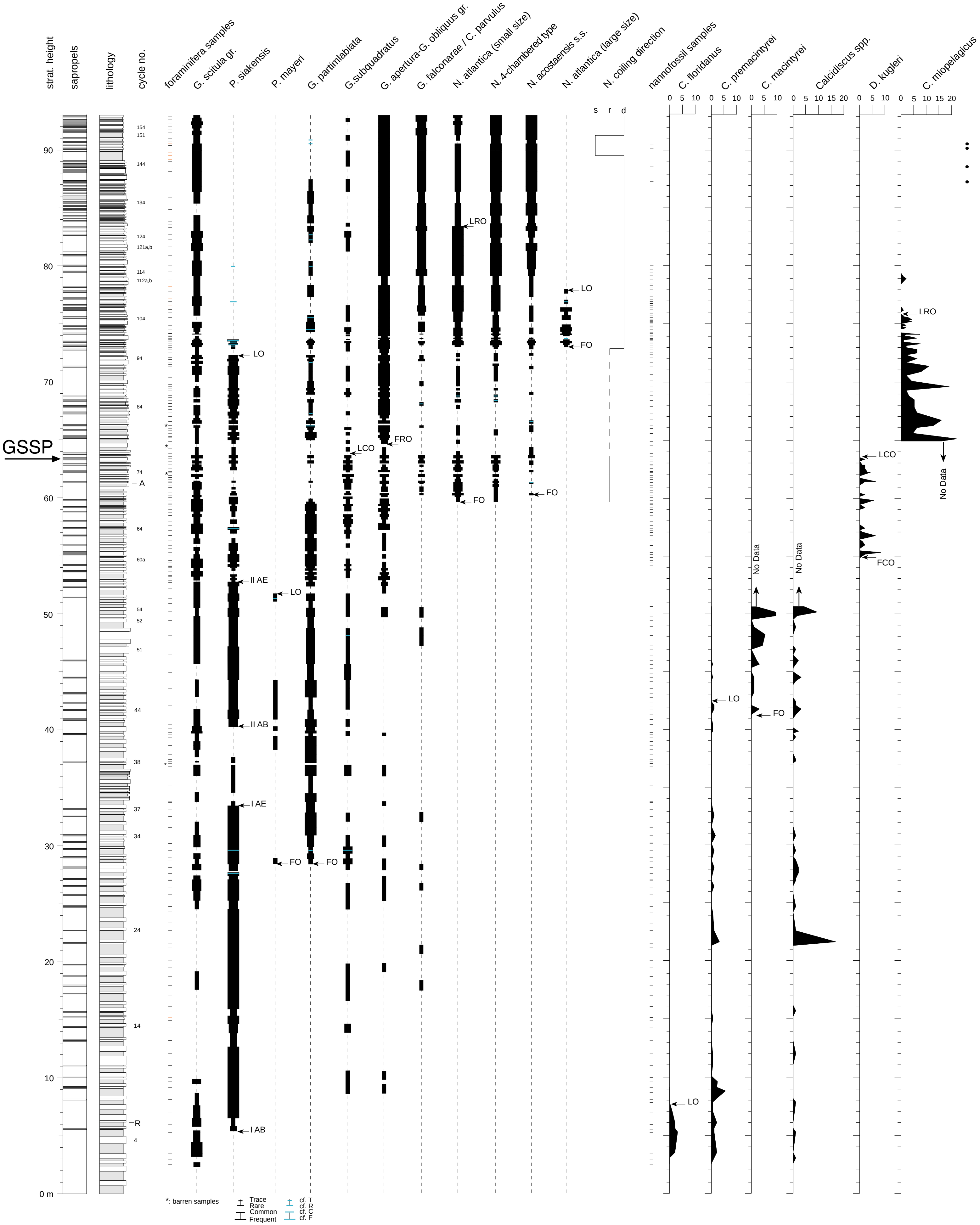

strat. height
sapropels
lithology
cycle no.
foraminifera samples
G. scitula gr.
P. siakensis
P. mayeri
G. partimlabiata
G.subquadratus
G. apertura-G. obliquus gr.
G. falconarae / C. parvulus
N. atlantica (small size)
N. 4-chambered type
N. acostaensis s.s.
N. atlantica (large size)
N. coiling direction
s
r
d
nannofossil samples
C. floridanus
C. premacintyrei
C. macintyrei
Calcidiscus spp.
D. kugleri
C. miopelagicus
0 5 10
0 5 10
0 5 10
0 5 10 15 20
0 5 10
0 5 10 15 20
90
80
70
60
50
40
30
20
10
0 m
154
151
144
134
124
121a,b
114
112a,b
104
94
84
74
A
64
60a
54
52
51
44
38
37
34
24
14
R
4
GSSP
LO
II AE
II AB
I AE
I AB
LO
FO
FO
LCO
FRO
LRO
FO
FO
LO
FO
FO
LO
LO
FO
LO
LCO
FCO
LRO
No Data
No Data
No Data
*: barren samples
Trace
Rare
Common
Frequent
cf. T
cf. R
cf. C
cf. F

Figure 7

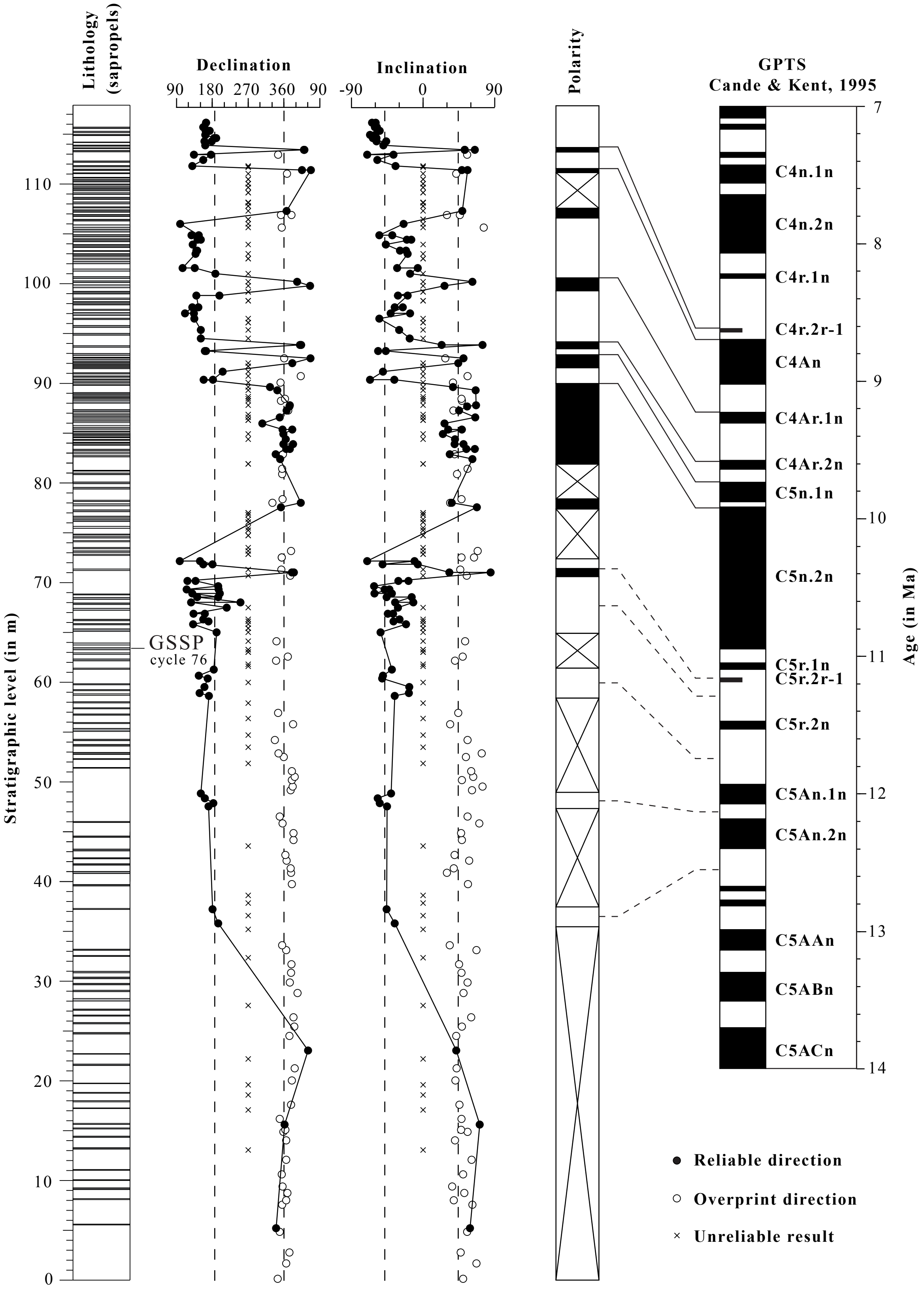

Lithology (sapropels)
Declination
90 180 270 360 90
Inclination
-90 0 90
Polarity
GPTS
Cande & Kent, 1995
Stratigraphic level (in m)
0
10
20
30
40
50
60
70
80
90
100
110
GSSP
cycle 76
C4n.1n
C4n.2n
C4r.1n
C4r.2r-1
C4An
C4Ar.1n
C4Ar.2n
C5n.1n
C5n.2n
C5r.1n
C5r.2r-1
C5r.2n
C5An.1n
C5An.2n
C5AAn
C5ABn
C5ACn
7
8
9
10
11
12
13
14
Age (in Ma)
● Reliable direction
○ Overprint direction
× Unreliable result

Figure 8

Monte dei Corvi section

S/T boundary interval

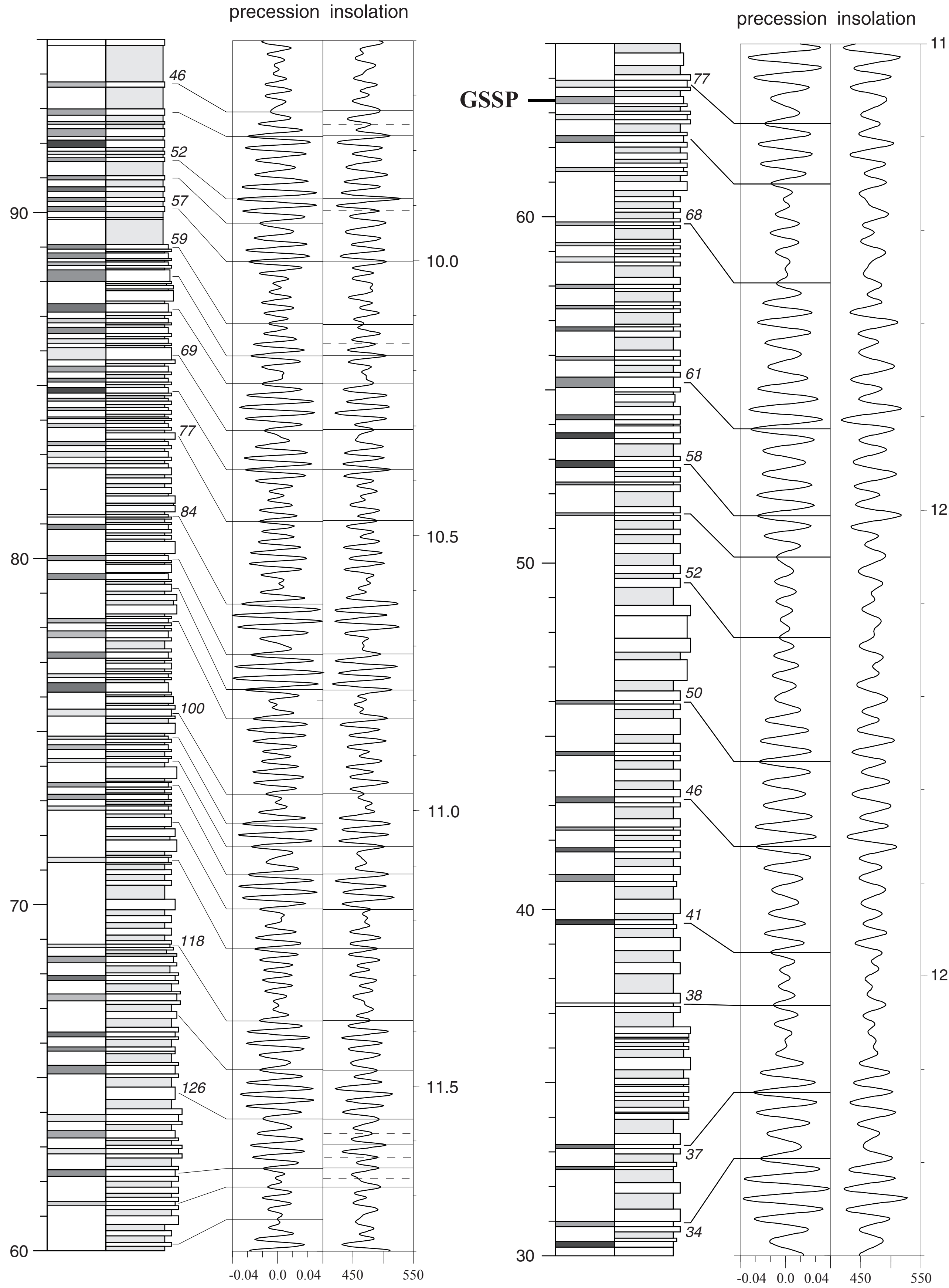
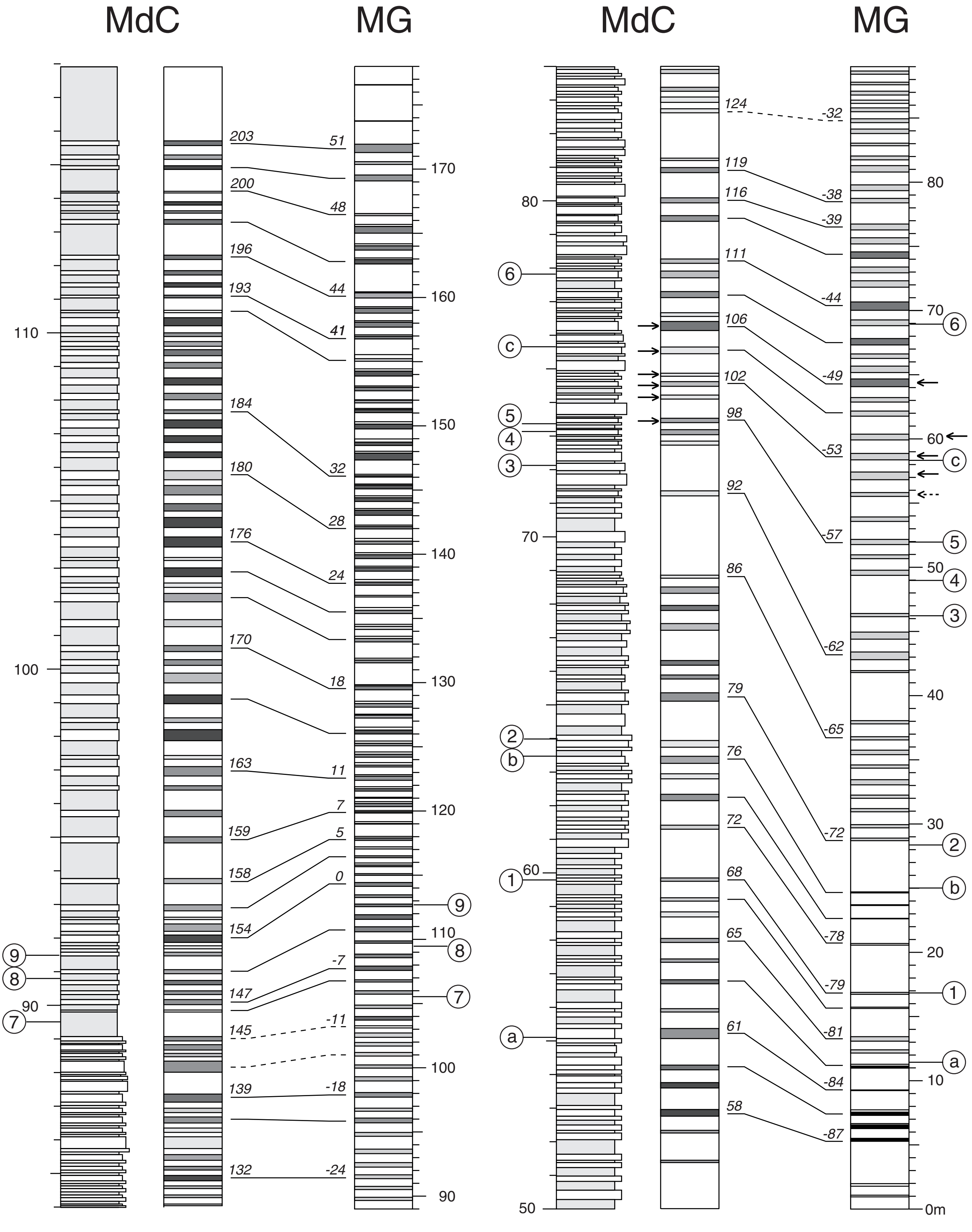


Figure 9

Figure 10

Monte dei Corvi - Gibliscemi

integrated stratigraphic correlations



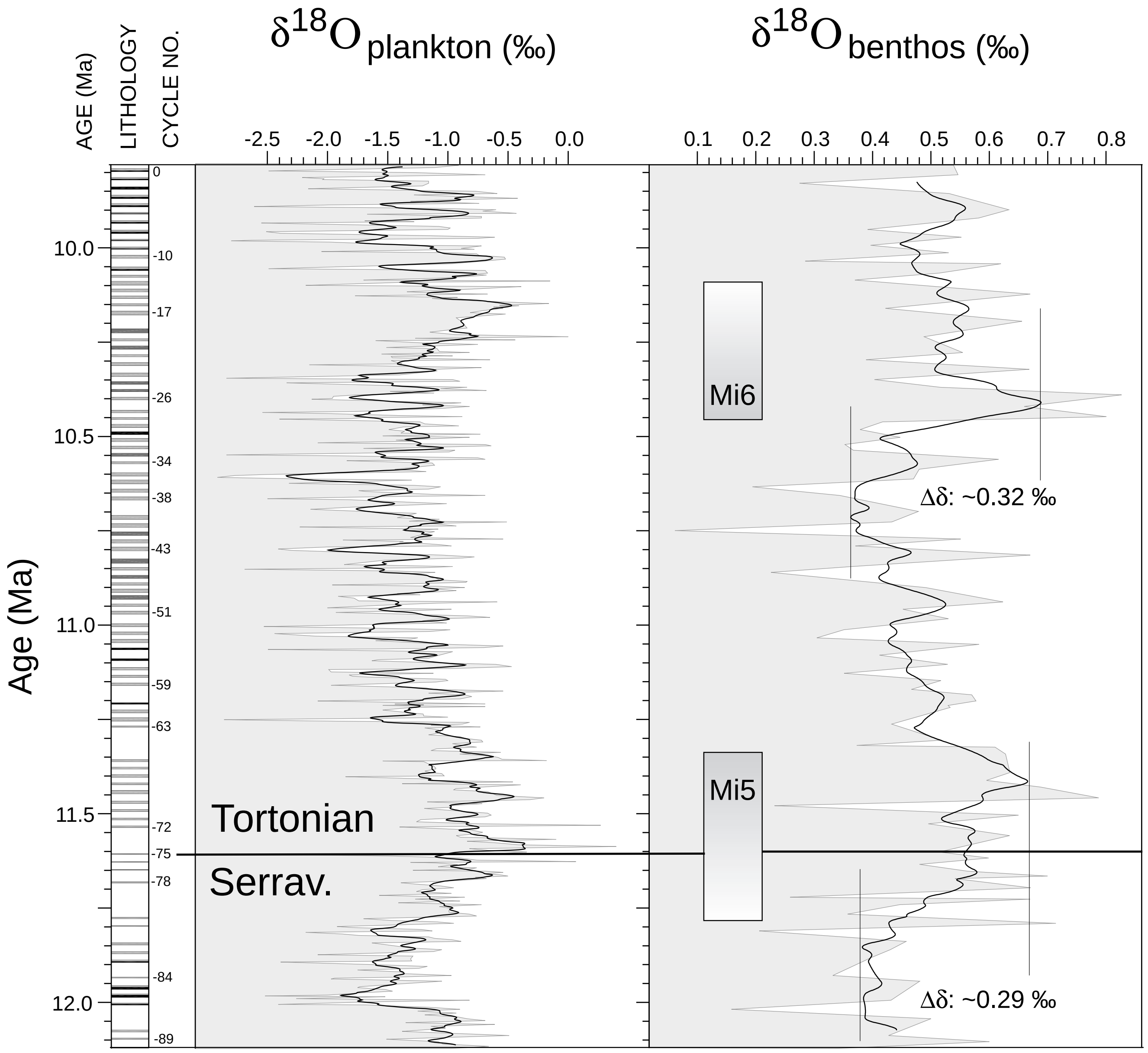

AGE (Ma)
LITHOLOGY
CYCLE NO.
δ18O plankton (‰)
δ18O benthos (‰)
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Age (Ma)
10.0
10.5
11.0
11.5
12.0
0
-10
-17
-26
-34
-38
-43
-51
-59
-63
-72
-75
-78
-84
-89
Tortonian
Serrav.
Mi6
Mi5
Δδ: ~0.32 ‰
Δδ: ~0.29 ‰

Figure 11

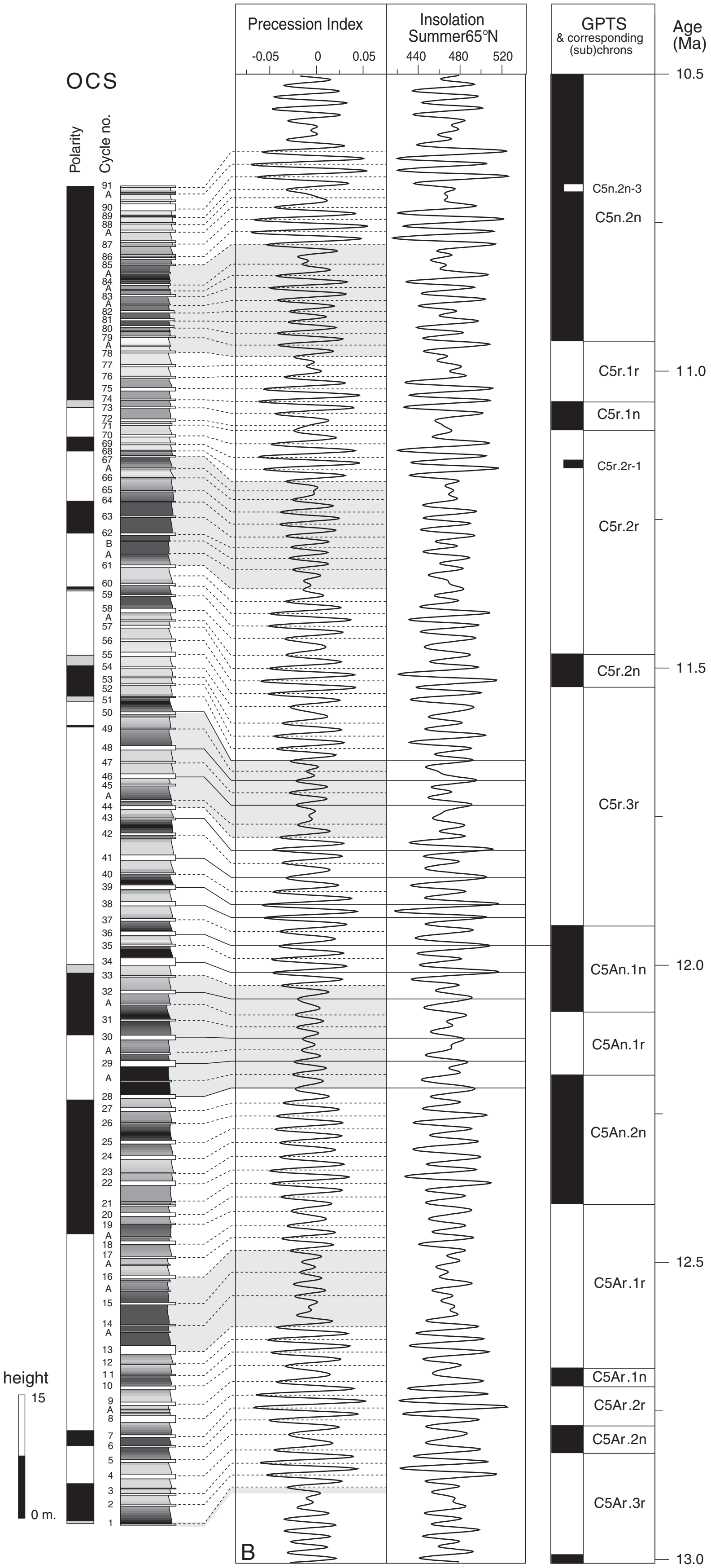

OCS
Polarity
Cycle no.
91 A 90 89 88 A 87 86 85 A 84 A 83 A 82 81 80 79 A 78 77 76 75 74 73 72 71 70 69 68 67 A 66 65 64 63 62 B A 61 60 59 58 A 57 56 55 54 53 52 51 50 49 48 47 46 45 A 44 43 42 41 40 39 38 37 36 35 34 33 32 A 31 30 A 29 A 28 27 26 25 24 23 22 21 20 19 A 18 17 A 16 A 15 14 A 13 12 11 10 9 A 8 7 6 5 4 3 2 1
height
15
0 m.
Precession Index
-0.05
0
0.05
Insolation
Summer65°N
440
480
520
B
GPTS
& corresponding
(sub)chrons
Age
(Ma)
10.5
11.0
11.5
12.0
12.5
13.0
C5n.2n-3
C5n.2n
C5r.1r
C5r.1n
C5r.2r-1
C5r.2r
C5r.2n
C5r.3r
C5An.1n
C5An.1r
C5An.2n
C5Ar.1r
C5Ar.1n
C5Ar.2r
C5Ar.2n
C5Ar.3r

Figure 12