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ITALIAN GSSPs OF THE QUATERNARY SYSTEM

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ABSTRACT: Italy offers an extraordinarily complete and well exposed record of recent open-marine sediments that have been employed for centuries to establish geological standards of the Neogene and the Quaternary. Over the last decades, the very same successions provided a benchmark for validating ever newer methodologies and techniques in Earth Sciences that contributed dramatically to establishing the modern Geologic Time Scale. The stratigraphic record of Southern Italy and Sicily played a key role in developing the Astronomical Time Scale (ATS) and provided physical reference in the definition of Global Stratotype Sections and Points (GSSPs) for the current Lower Pleistocene Stages (Gelasian and Calabrian). Here, we discuss and summarize the state of the art of the Gelasian and Calabrian Stages, considering the recent advances and ongoing work.

Keywords: Chronostratigraphy, Quaternary System, Pleistocene, GSSPs, Italy.

1. INTRODUCTION

Since the early days of stratigraphy, Earth scientists have felt a compelling need for a precise, practical, and globally accepted subdivision of the geologic time. Establishing a reference time scale is of the essence for chronicling life evolution and past geological events, not unlike a calendar delving into the Earth's deepest past. However, the concept of "deep" geological time extending billions of years beyond the human experience is far from easy to conceive and manage. Not by chance, reasonable estimates of the Earth's age have been attained only recently, after the discovery of radioactivity. The development of increasingly convenient and precise methods for dating rocks during the 19th century was punctuated by major breakthroughs, not only in establishing the order of magnitude of our planet's age, but also in providing means for subdividing the geological record into Units of practical use for Earth scientists. Result of these efforts is the modern Geologic Time Scale (GTS), which is ultimately intended to provide a standard common language for Earth scientists globally. The GTS is based on two strictly intertwined scales, these being an absolute time scale, composed of Geochronologic Units (GCUs) as formalized intervals of the geologic time, and a relative time scale, which classifies rocks into Chronostratigraphic Units (CUs) based on their age (Tab. 1). Construction of the GTS has been hampered over time by several problems, many of which have not been solved so far. They include scientific limits, such as the accuracy and correlation potential of the employable dating tools, and theoretical drawbacks, such as the age-old disagreements on stratigraphic philosophy and procedures in establishing formal units. The GTS is bound to be an endless enterprise, because the improving service ability of stratigraphic tools and the implementation of new methodologies strive in keeping up with the ever-growing need for better age constraints and long-distance correlation. Even the (apparently easy) goal of an international agreement upon rules, procedures, and standards in stratigraphy is far from being accomplished, to great detriment of the whole scientific community.

2. THE GEOLOGICAL TIME SCALE: PAST, PRESENT, FUTURE

The origins of modern chronostratigraphy date back to 1669, when Nicholas Steno, in the attempt of describing the geology of Tuscany, formulated three basic rules - known as Steno's principles - that have since become fundamental to stratigraphy. Following Steno's principles, Italian scholar Giovanni Arduino conceived in 1759 what is acknowledged as the first ever formal classification of the geological time. Based on the study of rocks exposed in northern Italy, he subdivided the Earth's history into four periods: Primary, Secondary, Tertiary, and Quaternary. In 1816, the seminal work "Strata Identified by Organized Fossils" by William Smith introduced the principles of faunal suc-

CHRONOSTRATIGRAPHY (TIME-ROCK)	GEOCHRONOLOGY (TIME)
Eonothem (e.g., Phanerozoic)	**Eon** (e.g., Phanerozoic)
Erathem (e.g., Cenozoic)	**Era** (e.g., Cenozoic)
System (e.g., Quaternary)	**Period** (e.g., Quaternary)
Series (e.g., Pleistocene)	**Epoch** (e.g., Pleistocene)
Subseries (e.g., Lower Pleistocene)	**Subepoch** (e.g., Early Pleistocene)
Stage (e.g., Calabrian)	**Age** (e.g., Calabrian)

Tab. 1 - Hierarchy of Formal Chronostratigraphic and Geochronologic Units.

cession and long-distance correlation and laid the foundations for modern biostratigraphy. During the XIX and early XX centuries, the first "modern" GTS was established by introducing the large-scale chronostratigraphic subdivisions (i.e., Eras and Periods) that are still in use today. Lower-rank CUs (i.e., Stages) were introduced shortly after, although their definitions, boundaries, and use remained for a long time ambiguous. The discovery of radioactivity at the end of the 19th century paved the way for radiometric dating of crystalline rocks. This finally gave the opportunity to establish the order of magnitude of the Earth's age, and laid the foundations for the modern GTS (Holmes, 1960). In the late 1960s, radiometric ages and the history of polarity reversals of the Earth's geomagnetic field obtained from lava successions were eventually merged to create the first Geomagnetic Polarity Time Scale (GPTS; Heitzler et al., 1968). Technologic advances in measuring the magnetic properties of rocks, paralleled by new biostratigraphic scales based on planktonic microfossils retrieved from deep-sea sediment cores, were a game-changer in linking the sedimentary records to the GPTS. Paleomagnetic reversal recognized and dated in volcanic rocks could also be detected in sedimentary successions and calibrated to the bioevents found in the very same records (biomagnetochronology) (Fig. 1). This step promoted a new generation of GTS, where CU boundaries and the geological events within were finally assigned an absolute radiometric age (e.g., Harland et al.,1982; Snelling, 1985; Berggren et al., 1995).

Advancements made in the early 1990s allowed exploiting the pervasive cyclicity preserved within the stratigraphic record for deriving a new stable and extremely precise geochronometer independent of radiometry. This groundbreaking approach relates depositional, geochemical, and palaeontologic cycles in sedimentary rocks to the periodical variations of Earth's orbital parameters, the chronology of which (Fig. 1) has been firmly established by means of mathematical models (e.g., Laskar et al., 2010). Although relatively simple for the most recent part of the geologic record (Miocene to recent), correlation becomes increasingly challenging as we move back in time, due to the chaotic behavior of the solar system (Laskar, 1990). The resultant Astronomical Time Scale (ATS; Shackleton et al., 1990; Bergreen et al., 1995; Hilgen et al., 1997; Lourens et al., 2004), currently in progress, is globally acknowledged as the most reliable and consistent chronology available to date for the last ca. 250 Myr, even if its use is now being extended into the Paleozoic (Gradstein et al., 2020).

3. DEFINITION OF CHRONOSTRATIGRAPHIC UNITS AND BOUNDARIES

The first, yet unsuccessful, formal attempt at establishing a common terminology and philosophical approach in defining stratigraphic ranks and boundaries dates back to the International Geological Congress of Bologna, 1881. Still, it was not until the publication of the International Stratigraphic Guide of Hedberg (1976) that rules and procedures in Stratigraphy were formalized and internationally agreed upon, albeit not universally. One of the key practical procedures proposed by Hedberg was establishing individual stratigraphic Units (of any type, scope, and rank) by means of a formalized Boundary stratotype, namely *"a specific point in a specific sequence of rock strata that serves as the standard for definition and recognition of a stratigraphic boundary"* (Hedberg, 1976). Cowie et al. (1986) emended Hedberg's definition by introducing the concept of Global Stratotype Section and Point (GSSP), a sort of boundary stratotype to be specifically employed for establishing global standard Geochronologic/Chronostratigraphic units of the GTS. In the new edition of the Guide, Salvador (1994) better defined GSSP as *"a specified sequence of rock strata in which a specific point is selected that serves as the standard for definition and recognition of a stratigraphic boundary"*. Although the differences may seem marginal, the GSSP concept of Salvador (1994) as "*a specified sequence of rock strata"* is more practical and functional than the former Hedbergian concept of Boundary stratotype, which made reference to a dimensionless "point" in rocks.

The GSSP-oriented approach has proved effective in establishing many formal CUs over the last decades, with great advantage for the global scientific community. There is an ongoing debate on the most recommendable procedures and strategies to be used in defining future formal CUs and their boundaries, however delving into details is beyond the scope of this paper. Still, it is undisputable that a GTS based on GSSPs only holds several inherent drawbacks. GSSPs define the base of "topless" Stages, as their upward chronostratigraphic extent is only limited by the GSSP of the Stage immediately above, if available. In contrast, the intervening (and most conspicuous) stratigraphy may be completely void of information. In the attempt to address this "empty Stages" problem, Aubry et al. (1999) revived the concept of Unit stratotype, as formerly defined by Hollis Hedberg: *"…the most effective means of providing a chronostratigraphic unit with fixed and uniform limits to*

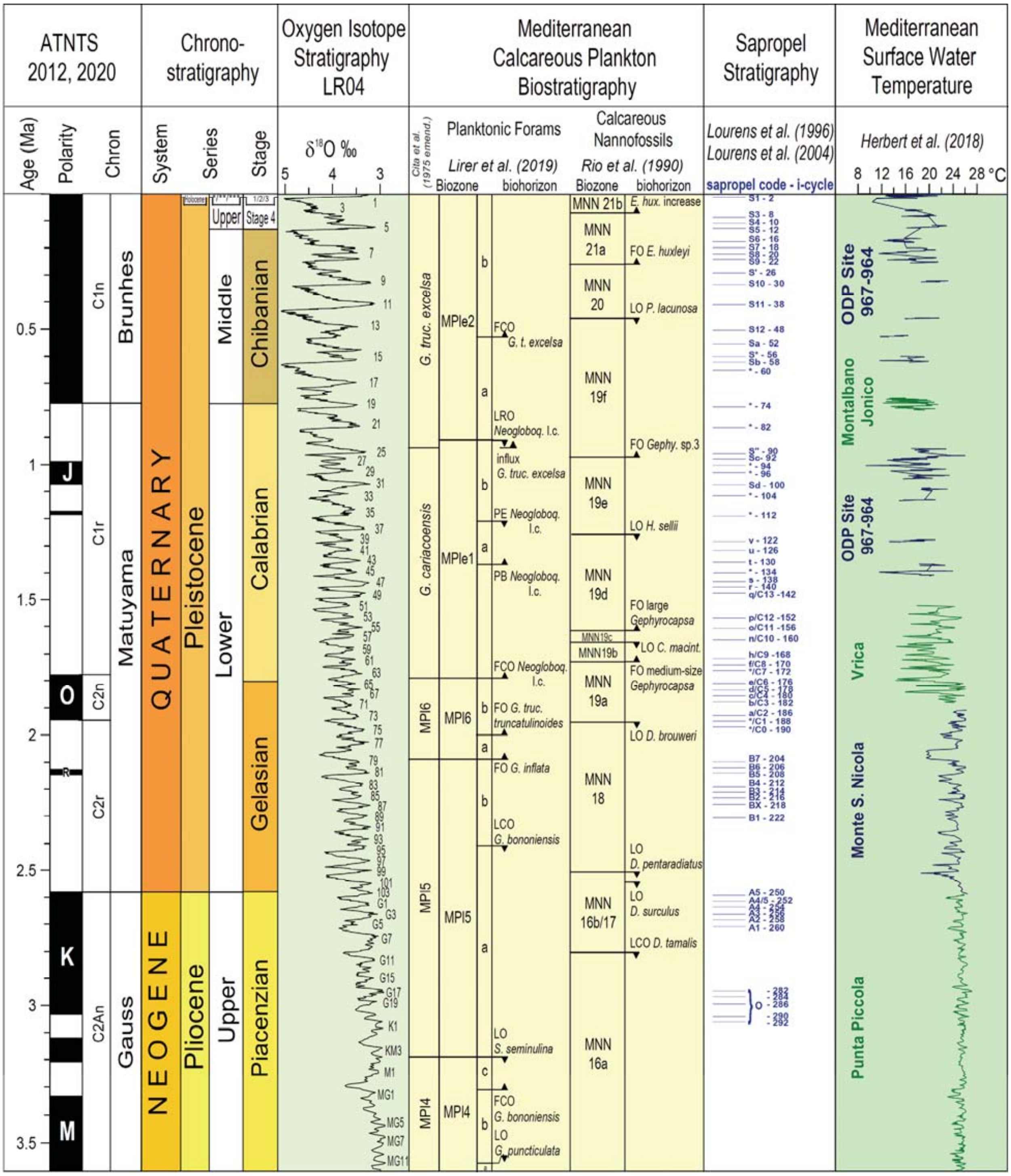


Fig. 1 - Late Neogene/Quaternary chronostratigraphic scheme. Left to right: 1) the Astronomical Time Scale (after Gradstein et al., 2020); 2) Chronostratigraphy of the interval of relevance. Stage 4 corresponds to the Upper Pleistocene Subseries, not yet defined. The Lower, Middle, and Upper Holocene Subseries (*/**/***) and their respective Stages Greenlandian, Northgrippian and Meghalayan (1/2/3) are not shown; 3) the LR04 benthic $\delta^{18}O$ stack of Lisiecki and Raymo (2005); 4) Mediterranean planktonic foraminifera and calcareous nannofossils biostratigraphy. Bioevents have been traced according to the independent biochronology of Lirer et al. (2019) for planktonic foraminifers and Lourens et al. (2004) and Gradstein et al. (2012) for calcareous nannofossils. FO: First Occurrence; LO: Last Occurrence; FCO First Common Occurrence; LCO: Last Common Occurrence; PB: Paracme Beginning; PE: Paracme End; LRO: Last Regular Occurrence; l.c.: left-coiled; 5) sapropel stratigraphy; 6) composite Mediterranean sea-surface water temperature record, integrated with the Montalbano Jonico dataset of Marino et al. (2020).

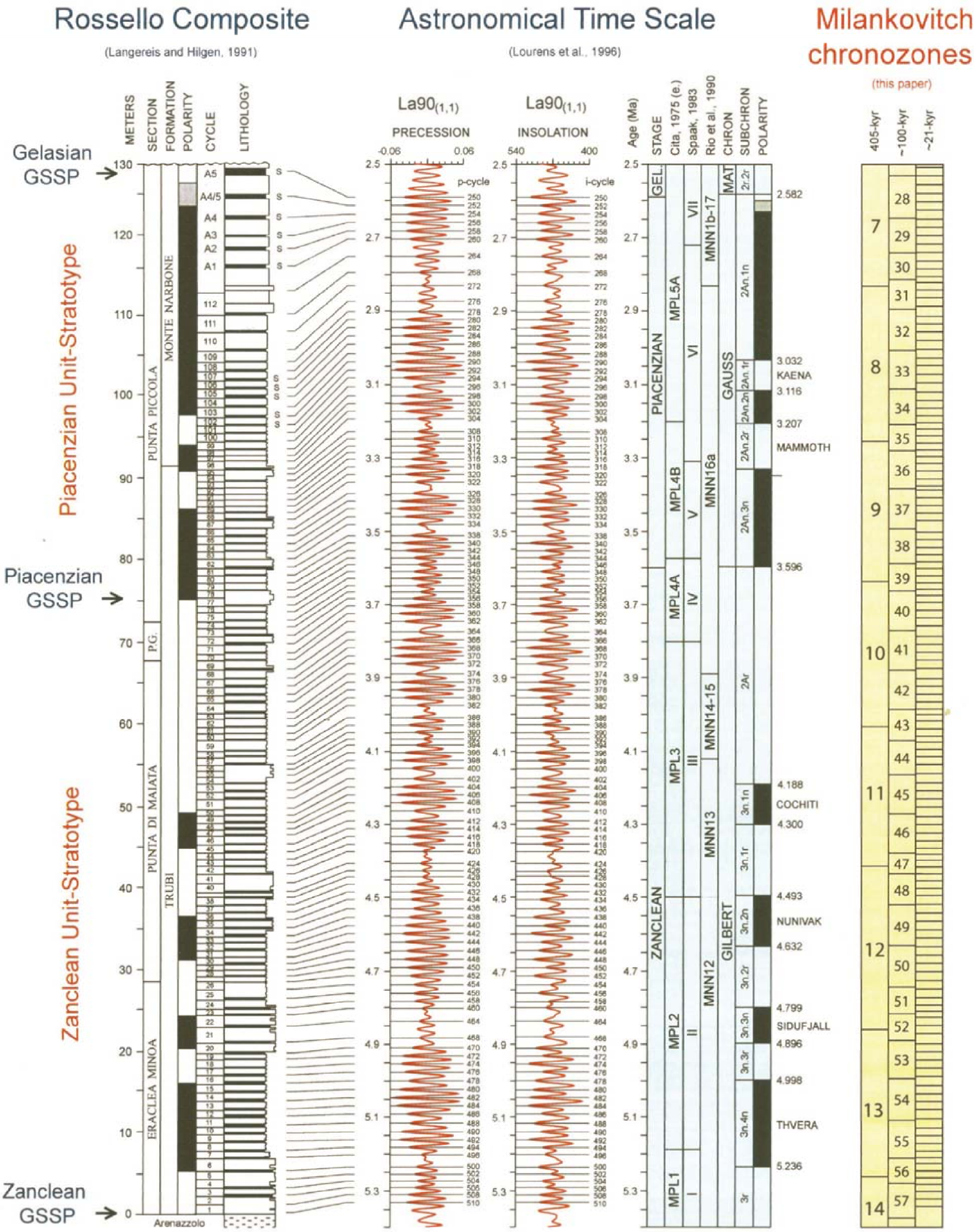
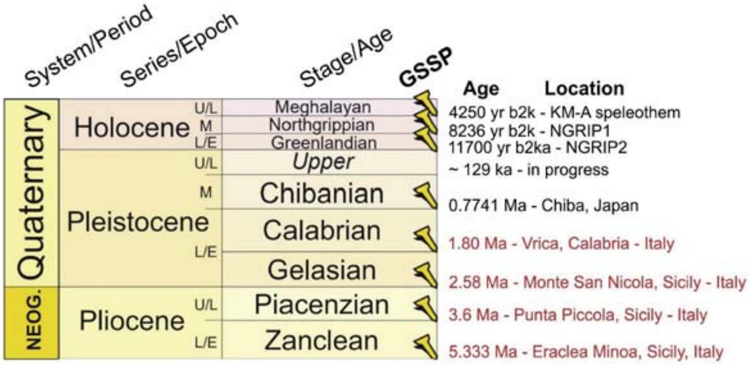


Fig. 2 - The proposed Unit-Stratotype for the Zanclean and Piacenzian Stages at the Rossello Composite Section (Sicily), with biostratigraphy, sedimentary cycles and their astronomical tuning. From Hilgen et al. (2020).

which all workers can return for reference, appears to be the designation of a specifically bounded section of rock strata as the stratotype of this unit. Thus, the scope of a Stage appears to be best defined as the rocks anywhere in the world corresponding in age to the total time-interval represented by the rocks between horizons designated as marking the top and the bottom of that Stage in its type section or stratotype" (Hedberg, 1965). Hilgen et al. (2020) made a further step ahead by introducing the concept of Astronomical Unit Stratotype (Fig. 2), a type of super-CU to be defined in cyclical deep-marine successions amenable to astronomical tuning. This approach would secure accurate age control for each and any of the geological events documented within, thus minimizing the chance of formalizing CU bodies harboring an incomplete or not continuous stratigraphic record. Individual strata could be defined as chronozones, i.e., non-hierarchical chronostratigraphic units to be employed for ultra-high-resolution studies (Hilgen et al., 2006). In this respect, the Mediterranean stratigraphic successions that served for constructing the ATS are perfectly suited as reference sections for defining the Astronomical Unit Stratotypes for the Neogene and Quaternary Stages, as soon as their use will be approved by the competent scientific bodies.



System/Period	Series/Epoch		Stage/Age	GSSP	Age	Location
Quaternary	Holocene	U/L	Meghalayan	✓	4250 yr b2k	KM-A speleothem
		M	Northgrippian	✓	8236 yr b2k	NGRIP1
		L/E	Greenlandian	✓	11700 yr b2ka	NGRIP2
	Pleistocene	U/L	Upper		~ 129 ka	in progress
		M	Chibanian	✓	0.7741 Ma	Chiba, Japan
		L/E	Calabrian	✓	1.80 Ma	Vrica, Calabria - Italy
			Gelasian	✓	2.58 Ma	Monte San Nicola, Sicily - Italy
NEOG.	Pliocene	U/L	Piacenzian	✓	3.6 Ma	Punta Piccola, Sicily - Italy
		L/E	Zanclean	✓	5.333 Ma	Eraclea Minoa, Sicily, Italy

Tab. 2 - Current subdivision of Late Neogene/Quaternary System as approved by the International Commission on Stratigraphy and ratified by the International Union of Geological Sciences, with indication of age and location of the Global Boundary Stratotype Sections and Points (GSSPs) defined so far.

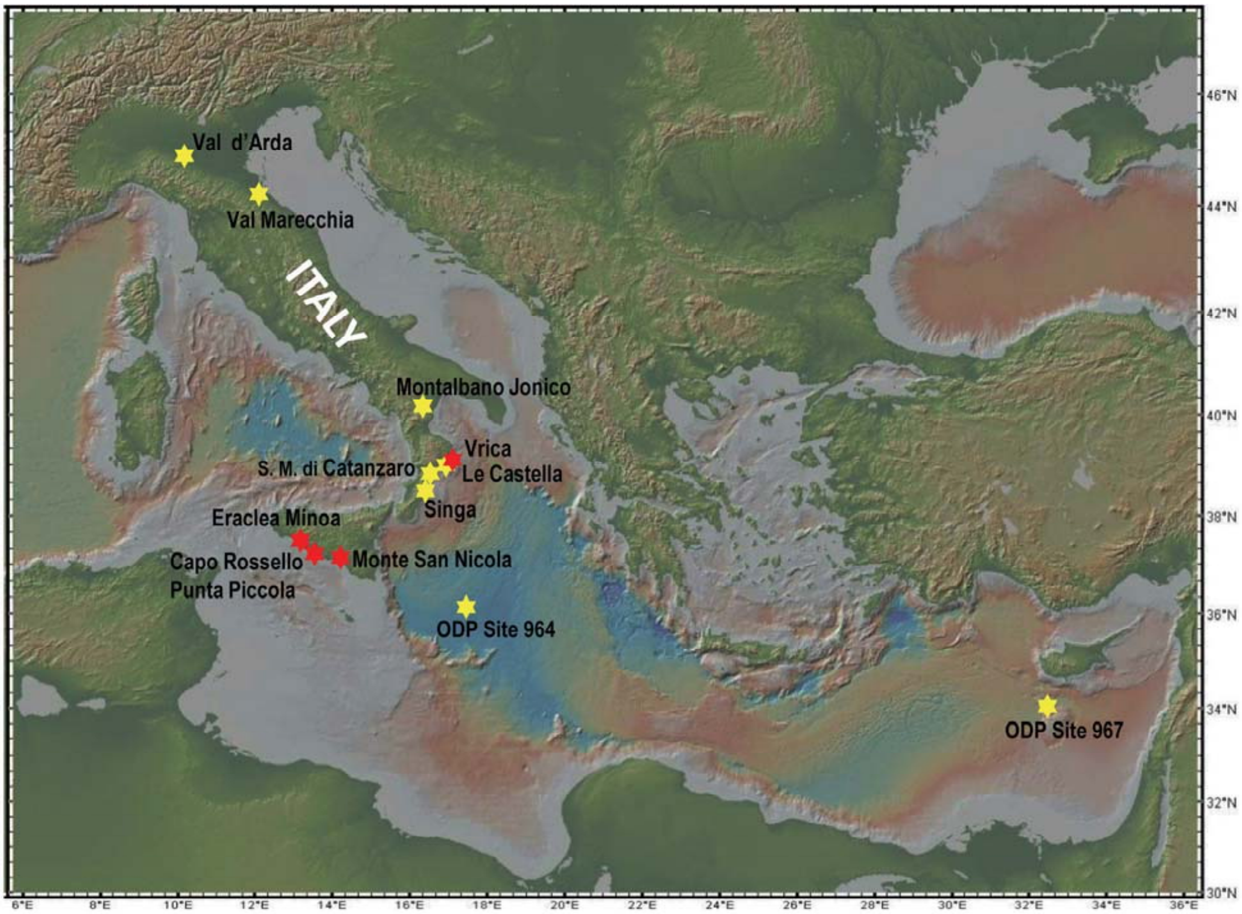
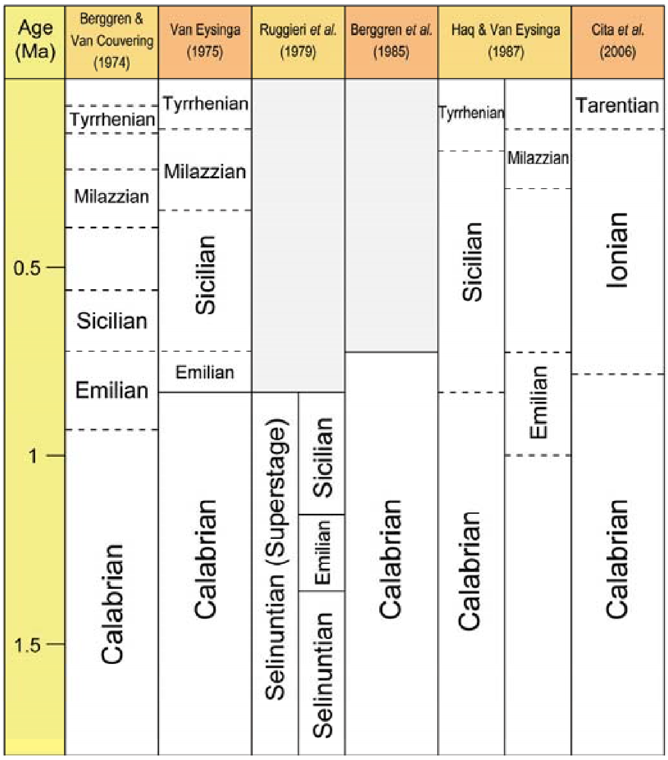


Fig. 3 - Location map of the stratigraphic sections mentioned in the text. In red, location of the Zanclean (Eraclea Minoa), Piacenzian (Punta Piccola), Gelasian (Monte San Nicola) and Calabrian (Vrica) type sections.

4. THE ITALIAN QUATERNARY RECORD

Italy has long been the breeding ground for many geological concepts and models, as well as an exceptional test bench for the definition of chronostratigraphic standards (Krijgsman, 2002; Rio et al., 2004). In particular, the Italian Neogene and Quaternary stratigraphic record played a key role in all the accomplishments listed above (Tab. 2). In subdividing the Tertiary and Quaternary into Stages, Lyell (1833) made reference to Italian sections that even today are of scientific interest. In the current GTS, a vast majority of the formal Stages defined so far for the Pliocene and the Pleistocene (i.e., Zanclean, Piacenzian, Gelasian, and Calabrian) have been established in Southern Italy and Sicily (Fig. 3, Tab. 2). In addition, a plethora of CUs not validated globally, because obsolete, regional in scope, or ambiguous in their definition (e.g., the Astian, Tabianian, Emilian, Santernian, Sicilian, Selinuntian, Ionian, Crotonian, Milazzian, Tyrrhenian, and Tarentian) (Vai, 1996; Rio et al., 1991; Cita & Castradori, 1995; Cita et al., 2006; Lirer & Iaccarino, 2011), are still informally employed today when dealing with Mediterranean successions (Tab. 3). The proliferation of regional Stages was fostered by the plenty of recent marine sediments exposed along the coastlines of Sicily and southern Italy in response to the active geodynamic history of the Mediterranean, which prompted the uplift of a globally unrivalled deep-water Neogene and Quaternary stratigraphy. Furthermore, the elongated Italian peninsula and its submerged extension, the shallow Sicily Strait, form a meridional divide separating the Mediterranean Sea into two (western and eastern) sub-basins, each characterized by peculiar climatic and oceanographic conditions. For this reason, the central Mediterranean borderlands (i.e., Italy and surrounding regions) are a sensitive sounding board for climate changes at both the global and regional scales (Giorgi, 2006). Central Mediterranean open-marine sediments hold a pristine record of the regional biotic and environmental response to climate forcing, such as marine productivity, precipitations and freshwater runoff, zonal and vertical circulation patterns, terrigenous yield, etc. In particular, the stratigraphy exposed along the coasts of Italy and Sicily is usually organized cyclically, and thus amenable to astrocyclostratigraphic investigations. Not surprisingly, the first ATS was established in the early 1990s by merging the Pliocene Rossello composite section (southern Sicily; Langereis and Hilgen, 1991) with the Lower Pleistocene Singa and Vrica sections (Ionian Calabria; Hilgen, 1991a,b; Hilgen et al., 1997). Key tools for validating the astronomical tuning of open-marine Mediterranean records since the Miocene are the notorious dark, organic-rich layers known as sapropels. Mediterranean sapropels formed during periods of maximum insolation (Hilgen, 1991b; Hilgen et al., 1993, 1995, 1999; Lourens et al., 1996, 2001; Rohling, 2015), which is attained under conditions of minimum precession and maximum eccentricity of the Earth's orbit around the Sun, so they are usually found in distinct clusters of 3 to 5 individuals. Their preservation potential and physical traits change accordingly to depositional settings. In the deep (pelagic) domain, where sediment accumulation rates are extremely low, sapropels occur as very thin layers of massive blackish muds. In the predominantly hemipelagic record of Southern Italy, where the terrigenous input is massive, they are usually found as thick, thin-laminated sapropel-equivalent layers, commonly referred to as "laminites".



Tab. 3 - Some of the the chronostratigraphic subdivisions proposed in the past for the Quaternary based on traditional (either formally defined or not) Mediterranean Stages. Modified from Rio et al. (1991). Readers are encouraged to refer to Vai (1996) for further details and discussion on the matter.

5. ITALIAN QUATERNARY GSSPs

Due to the debated 2009 resolution of lowering the base of both the Pleistocene Series/Epoch and the Quaternary System/Period to ca. 2.588 Ma (Gibbard & Head, 2010; Gibbard et al., 2010), the Lower Pleistocene Subseries currently includes two formally defined Stages, these being the Gelasian (ca. 2.588 to 1.806 Ma) and the Calabrian (ca. 1.806 to 0.772 Ma). The first was defined in the Monte San Nicola section (Fig. 4), near the town of Gela (Southern Sicily; Rio et al., 1998), while the second was established in the Vrica section (Fig. 5), Crotone (Ionian Calabria, Southern Italy; Cita et al., 2012), where the former Neogene/Quaternary boundary was defined by Aguirre & Pasini (1985). Both sections have been subjected to astrocyclostratigraphic investigations and contributed as physical reference to

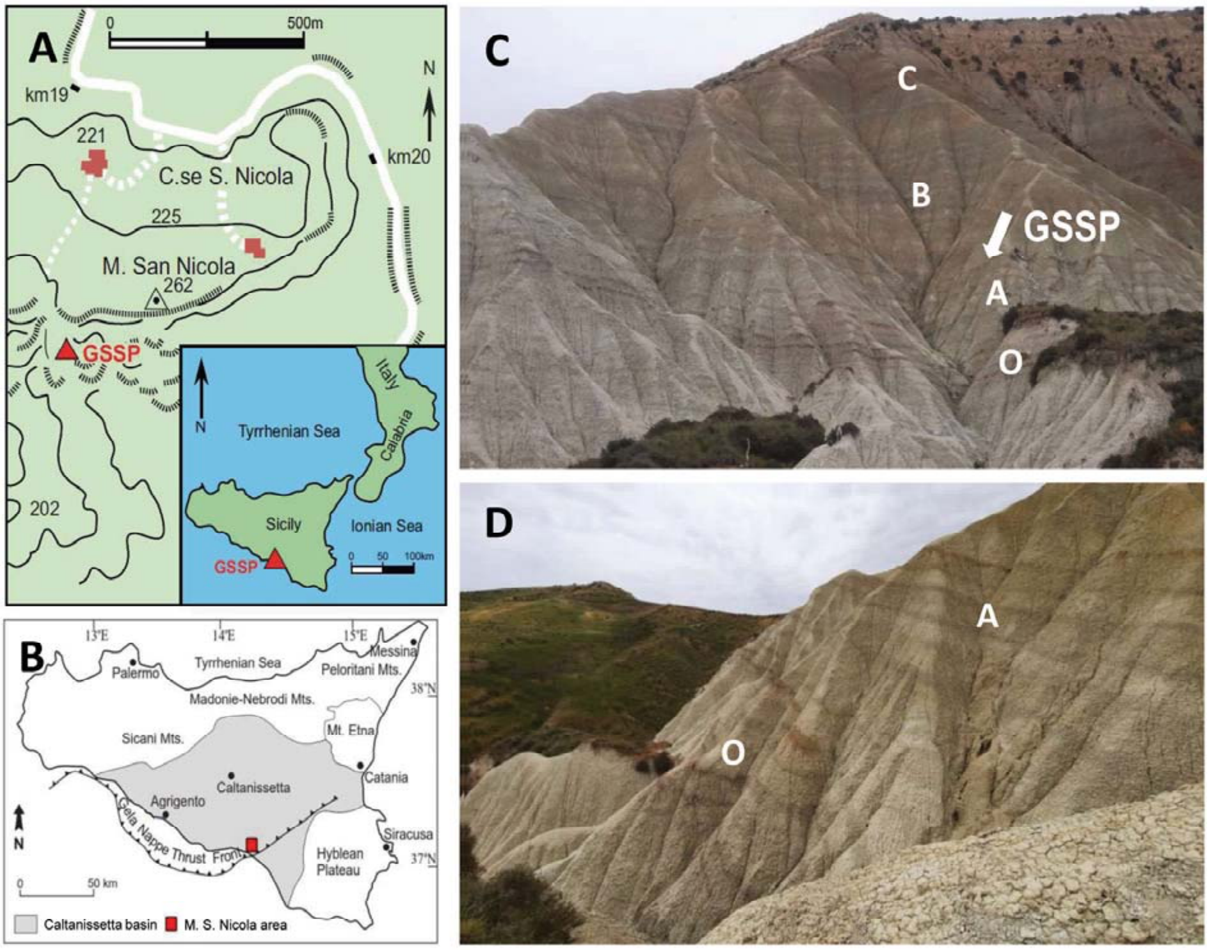


Fig. 4 - The Monte San Nicola section, Sicily, where the GSSP of the Gelasian is located. A) Geographic location of the GSSP (from Gradstein et al., 2020); B) location of the Monte San Nicola area within the Caltanissetta basin (from Capraro et al., 2022); C) profile of the type section and location of the GSSP, with sapropel clusters O-C; D) reddish, thin-laminated layers alternated to brown, non-laminated manganesiferous layers of sapropel clusters O and A.

the construction of the current ATS (Hilgen et al., 1997, 2006). The Vrica and Monte San Nicola sections are represented by slope to outer shelf clayey marls that contain no evidence of erosional surfaces, hiatuses, abrupt variations in sediment composition and/or changes in the sedimentation style, which was persistently dominated by mud settling (Capraro et al., 2022). Clustered sapropel layers occur in both records (Figs. 4C-D, 5D-E) and provide mutual correlation in the interval straddling the Gelasian/Calabrian boundary (Capraro et al., 2022). Unfortunately, the Vrica section does not extend up to the base of the Middle Pleistocene Subseries (Lourens et al., 1996). However, several open-marine records, both from the same Crotone Basin (Capraro et al., 2011) and Southern Italy (Montalbano Jonico section, Basilicata, Southern Italy; Ciaranfi et al., 2010), overlap with the Vrica section and extend seamlessly at least up to MIS 17/MIS 15. Indeed, Maiorano et al. (2010) proposed the spliced Vrica and Montalbano Jonico record as a potential unit-stratotype of the Calabrian Stage.

6. THE GELASIAN STAGE

The Gelasian was formally defined as the third and uppermost Stage of the Pliocene Series (Rio et al., 1998). For decades, the Pliocene had been subdivided into two Stages only, namely the Zanclean (Van Couvering et al., 2000) and the Piacenzian (Castradori et al., 1998). In spite of its current GSSP location in Southern Sicily, the Piacenzian was named after the area in northwestern Italy where the relevant historical type-section is exposed, namely the Arda valley (Piacenza province). The Pliocene to Pleistocene stratigraphy of the Val d'Arda (Fig. 3) was mentioned by Lyell (1833) as the marine "type" of his "Older Pliocene", and later employed by Barbieri (1967) for defining the traditional Piacenzian Stage (Mayer-Eymar, 1858; Pareto, 1865), which was believed to extend up to the base of the Pleistocene. However, Rio *et al.* (1988) and Raffi *et al.* (1989) discovered that the lithological change at the top of the historical Piacenzian stratotype, marked by a transition from open-marine muds to regressive yellow sands (the "Astian" *Auctorum*), occurs close in age to

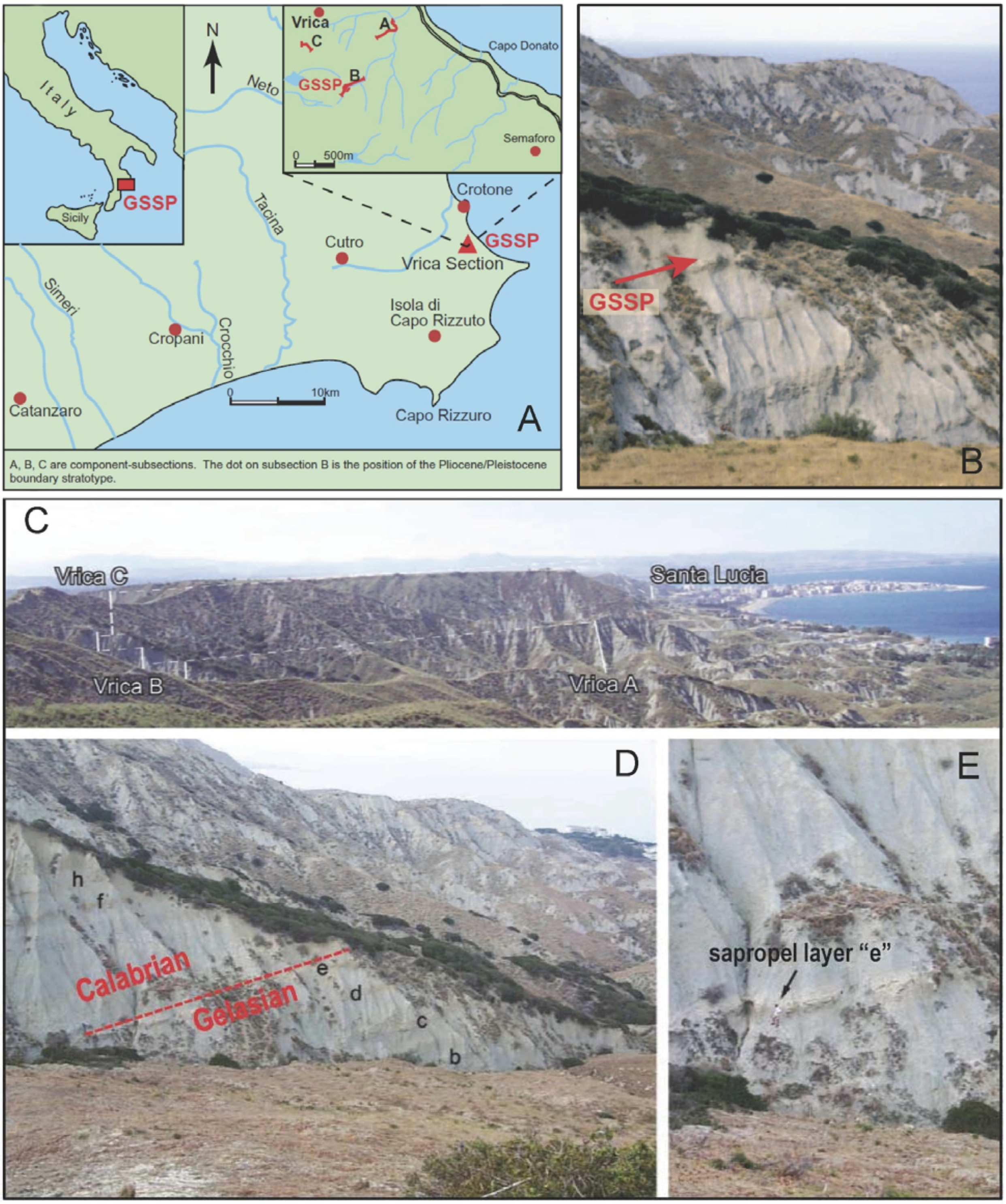


Fig. 5 - The GSSP for the Calabrian Stage in the Vrica section, Calabria. A-B) Outcrops and location of the GSSP (from Gradstein et al., 2020); C) exposure of the A, B and C component segments of the Vrica composite section; D-E) exposure and position of the Calabrian GSSP, with indication of sapropel layers b to e (from Cita et al., 2012).

the global climate cooling at about 2.6 Ma. This event was usually referred to as “the beginning of the ice ages” (e.g., Shackleton *et al.*, 1984). Accordingly, it was demonstrated that the historical Piacenzian stratotype does not provide a continuous open-marine sedimentary record up to the Pliocene/Pleistocene boundary, as defined in the Vrica section (Aguirre & Pasini, 1985). Furthermore, an urgent need was felt within the Quaternary scientific community to acknowledge the importance of the climatic event at 2.6 Ma by emphasizing its visibility in the GTS. In the attempt to address both these issues, Rio *et al.* (1988, 1991) questioned the common practice of extending the Piacenzian up to the base of the Pleistocene (e.g., Barbieri, 1967; Cita, 1973; Berggren *et al.*, 1985), and proposed establishing a new Upper Pliocene Stage corresponding to the “Astian yellow sands” of the Val d’Arda section (Rio *et al.*, 1994). Since the latter consist of shoreface sands inadequate to host a GSSP (Hedberg, 1976; Salvador, 1994), it was agreed to define the new Stage in the open-marine muds of the Monte San Nicola section (southern Sicily), in the very same Caltanissetta sedimentary basin (Fig. 4B) where the Zanclean and Piacenzian GSSPs are also located (Van Couvering et al., 2000; Castradori et al., 1998). The Singa section (Ionian Calabria) was also taken into consideration as a potential GSSP candidate, but Monte San Nicola offers easier access and best exposure conditions (Rio et al., 1998). The name “Gelasian” was after the nearby city of Gela (Rio et al., 1994).

6.1. The Monte San Nicola section

The Monte San Nicola stratigraphy crops out in form of a beautifully exposed suite of badlands (Fig. 4C) few kilometers inland from the coastal city of Gela (southern Sicily). The succession was laid in the south-eastern limb of the Caltanissetta sedimentary Basin (Fig. 4B), a late Neogene structure confined by the front of the Maghrebian-Apennine Chain and the Hyblean Foreland (Catalano *et al.*, 2013; Lentini & Carbone, 2011, 2014). According to Lickorish *et al.* (1999), the Caltanissetta Basin consists of a single thrust sheet containing a train of continuously tightening folds belonging to the “Gela Nappe” of Beneo (1958) and Ogniben (1969). The Gela Nappe includes various sedimentary units, ranging from the Cretaceous-Eocene “Argille Scagliose” (Ogniben, 1969) to the Serravallian-Tortonian “Numidian Flysch” (Gasparo Morticelli *et al.*, 2015; Pinter *et al.*, 2016, 2018). Small piggy-back basins developed within the Caltanissetta Basin in response to complex compressive-translational and rotational movements, and provided accommodation to an expanded upper Neogene and Quaternary stratigraphy (Ogniben, 1969; Catalano *et al.*, 1977; Grasso *et al.*, 1987; Lentini *et al.*, 1991; Vitale, 1996; Lickorish *et al.*, 1999; Ghisetti *et al.*, 2009; Gasparo Morticelli *et al.*, 2015). In keeping with the reference Capo Rossello succession, the open-marine Pliocene and Pleistocene record at Monte San Nicola belongs to the “Trubi” and “Monte Narbone” Formations (Fig. 6). The former (Zanclean-Piacenzian p.p.; Cita & Gartner, 1973; Castradori *et al.*, 1998) consists of cyclically organized, off-white marly limestones and grey/beige marls, void of macrofossils, laid at an estimated depth of ca. 1000 m (Bonaduce & Sprovieri, 1984) in response to the abrupt reprise of deep marine sedimentation after the Messinian salinity crisis (De Visser *et al.*, 1989). Probably due to tectonic obliteration, the entire Messinian to lower Piacenzian stratigraphy is missing at Monte San Nicola, as the Trubi Fm. is only represented by its upper part (ca. 40 m) resting directly on top of the Numidian Flysch (Rio et al., 1994, and references within). The rapid but gradual transition from the Trubi to the overlying Monte Narbone Fm. (Piacenzian p.p.-Calabrian p.p.; Rio *et al.*, 1984; Di Stefano *et al.*, 1993) is associated to a massive increase in terrigenous input. This change is emphasized by sediment colors turning to deep blue/tobacco, decreasing rock competence, an upward increase in the average sediment accumulation rates (Capraro et al., 2022) and the appearance of sapropels, which either occur as reddish, thin-laminated intervals or brown, non-laminated manganesiferous layers (Fig. 4D). The estimated water depth decreases from ca. 1000 m in the basal part of the unit to ca. 500 m at its top (Rio et al., 1994, and references therein). In the Monte San Nicola area, the Monte Narbone Fm. is ca. 125 m thick. However, its original thickness cannot be estimated, because the unit is truncated by a package of richly fossiliferous yellow sands belonging to the shallow-water Agrigento Fm. (Calabrian) documenting the definitive uplift of the area.

6.2. Previous studies on the Monte San Nicola section

The Monte San Nicola section was first studied by Spaak (1983), who investigated the planktonic foraminifer assemblages, and Bonaduce & Sprovieri (1984), who reported on the fossil ostracods record. The sapropel-equivalent layers exposed in the Monte San Nicola badlands were the focus for the work of Sprovieri *et al.* (1986) and Howell *et al.* (1988), who investigated the age and formation mechanisms of laminitic intervals. Driever (1988) analyzed the calcareous nannofossil record, followed by Bertoldi et al. (1989) who employed segments of the Monte San Nicola succession in the attempt to reconstruct the long-term evolution of vegetation and climate across the Pliocene-Pleistocene boundary. Hilgen (1991a) exploited the cyclically organized Monte San Nicola succession for constructing the ATS, while Channell *et al.* (1992) achieved a sharp magnetostratigraphic record of the Gauss/Matuyama geomagnetic reversal close to the Piacenzian-Gelasian boundary (Fig. 6). The same work provided detailed quantitative biostratigraphy based on planktonic foraminifera and calcareous nannofossils (Fig. 6) and demonstrated that the Monte San Nicola open marine stratigraphy extends from the planktonic foraminifera Zone MPl3 to the *Globigerina cariacoensis* Zone (Cita, 1973, 1975, emended by Sprovieri, 1992) (Fig. 6), and from the calcareous nannofossil *Reticulofenestra pseudoumbilicus* (MNN14/15) Zone to the *Calcidiscus macintyrei* (MNN19b) Zone of Rio et al. (1990) (Fig. 6). The section thus extends from the late Zanclean (>4 Ma) to the early Calabrian (ca. 1.6 Ma).

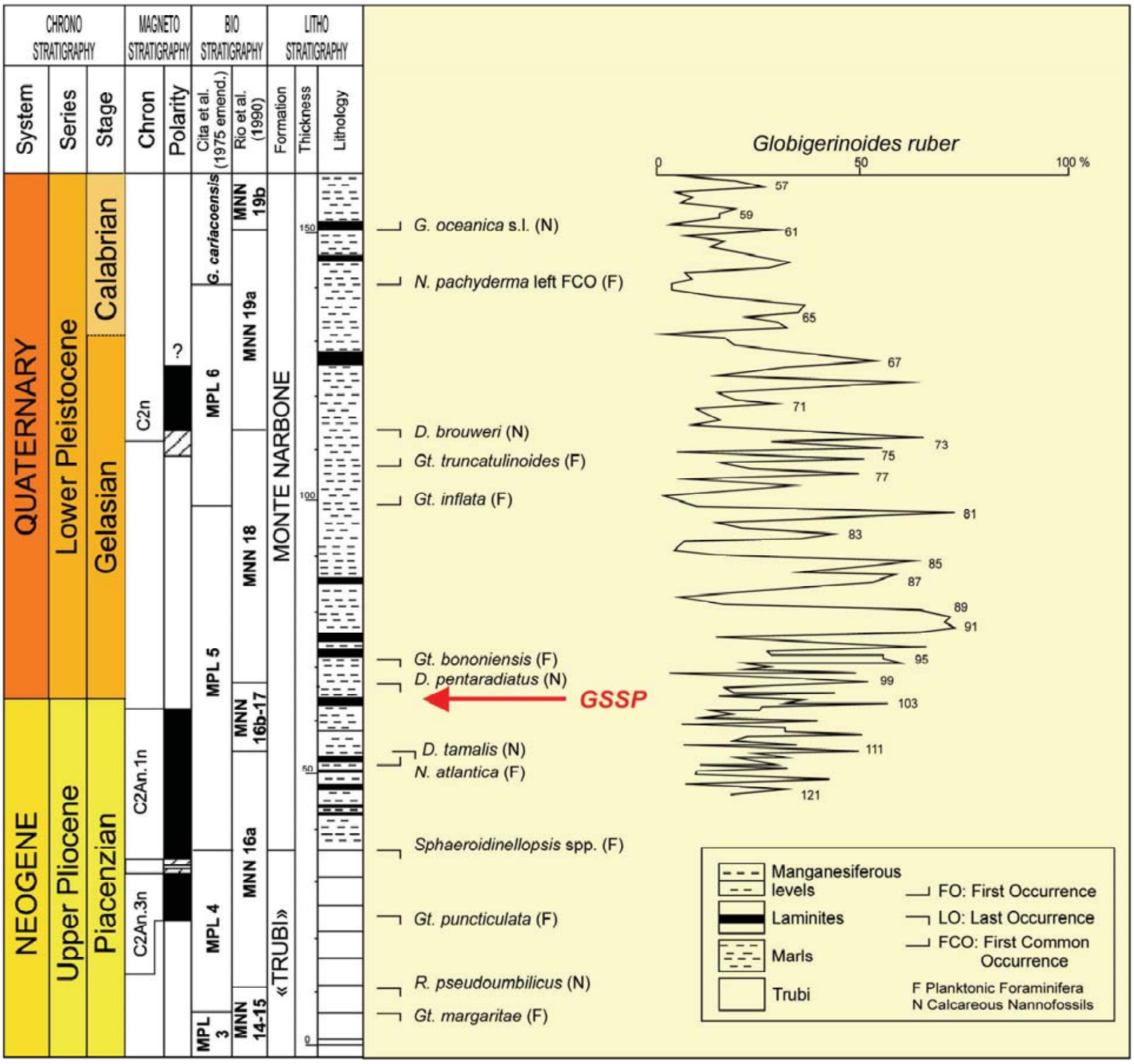


Fig. 6 - Lithostratigraphy, magnetostratigraphy and calcareous plankton biostratigraphy of the Gelasian type section at Monte San Nicola section. Abundance fluctuations of *Globigerinoides ruber* (on the right) are considered by the Authors as a proxy for glacial/interglacial stages. Modified from Rio et al. (1998).

6.3. Definition of the Gelasian GSSP

The Gelasian GSSP was formally ratified (Rio *et al.*, 1998) at the base of the marly unit that overlies a prominent laminitic layer, known as "Nicola bed" (after Monte San Nicola), representing the uppermost Mediterranean Precession-Related Sapropel (MPRS) of cluster A (Verhallen, 1987; Hilgen, 1991b). The "Nicola bed", well exposed regionally (e.g., Castradori et al., 1998), is correlative to MPRS 250 (i-cycle 250) of Lourens *et al.* (1996), in the midst of interglacial Marine Isotopic Stage (MIS) 103 (Figs. 1, 7). The astronomically calibrated age of the boundary is 2.588 Ma (Hilgen, 1991a; Rio *et al.*, 1998). According to the GSSP definition (Rio et al., 1998), the Piacenzian/Gelasian boundary occurs in MIS 103, and predates by ca. 60 kyr the glacial MIS 100 (Fig. 1), which marks the definitive onset of the Northern Hemisphere Glaciation (Lisiecki & Raymo, 2005). The glacial triplet MIS 100-MIS 96, at about 2.5 Ma, is testified globally by ice expansion in northern latitudes (Raymo et al., 1989), changes in vegetation (the "Tiglian"-"Pretiglian" boundary of Zagwijn, 1974, and the"Arquatian" phase of Lona, 1962; Bertini, 2013), beginning of loess sedimentation in continental China (Kukla & An, 1989), and migrations of terrestrial vertebrate faunas (the "elephant-*Equus* event" in Eurasia; Lindsay et al., 1980; Azzaroli et al., 1988, and references therein). The Gauss/Matuyama boundary (Channell et al., 1992) is reported to occur about 1 m above the GSSP, which provides a close approximation of the Piacenzian/Gelasian boundary globally. The

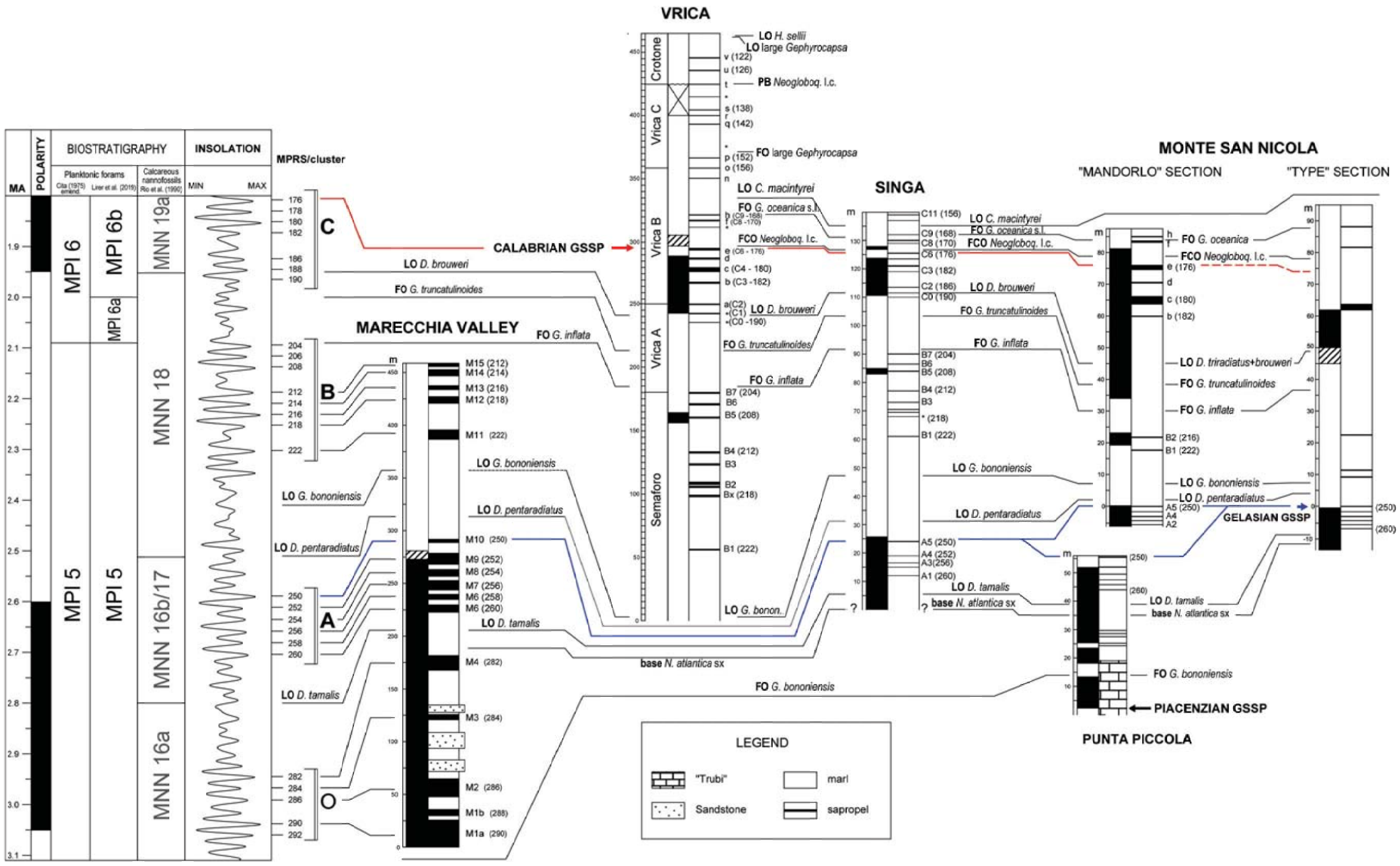


Fig. 7 - Biomagnetostratigraphic correlation between the Gelasian type-section (Rio et al., 1998) and the "Mandorlo" section (Capraro et al., 2022) at Monte San Nicola and other coeval, sapropel-bearing reference sections in northern Italy (Marecchia Valley; Rio et al., 1996), southern Italy (Singa: Lourens et al., 1992; Vrica: Lourens et al., 1996b) and Sicily (Punta Piccola; Castradori et al., 1998). Correlation between the sections is provided by key biohorizons and sapropel layers of clusters O/M, A, B, C. Precession cycles (i-cycles) are also indicated in brackets. Individual sapropel layers are linked to the astronomical target curves (eccentricity, precession, and summer insolation at 65°N) calculated from the La04 orbital solution of Laskar et al. (2004). Acronyms as in Figure 1. Modified from Capraro et al. (2022).

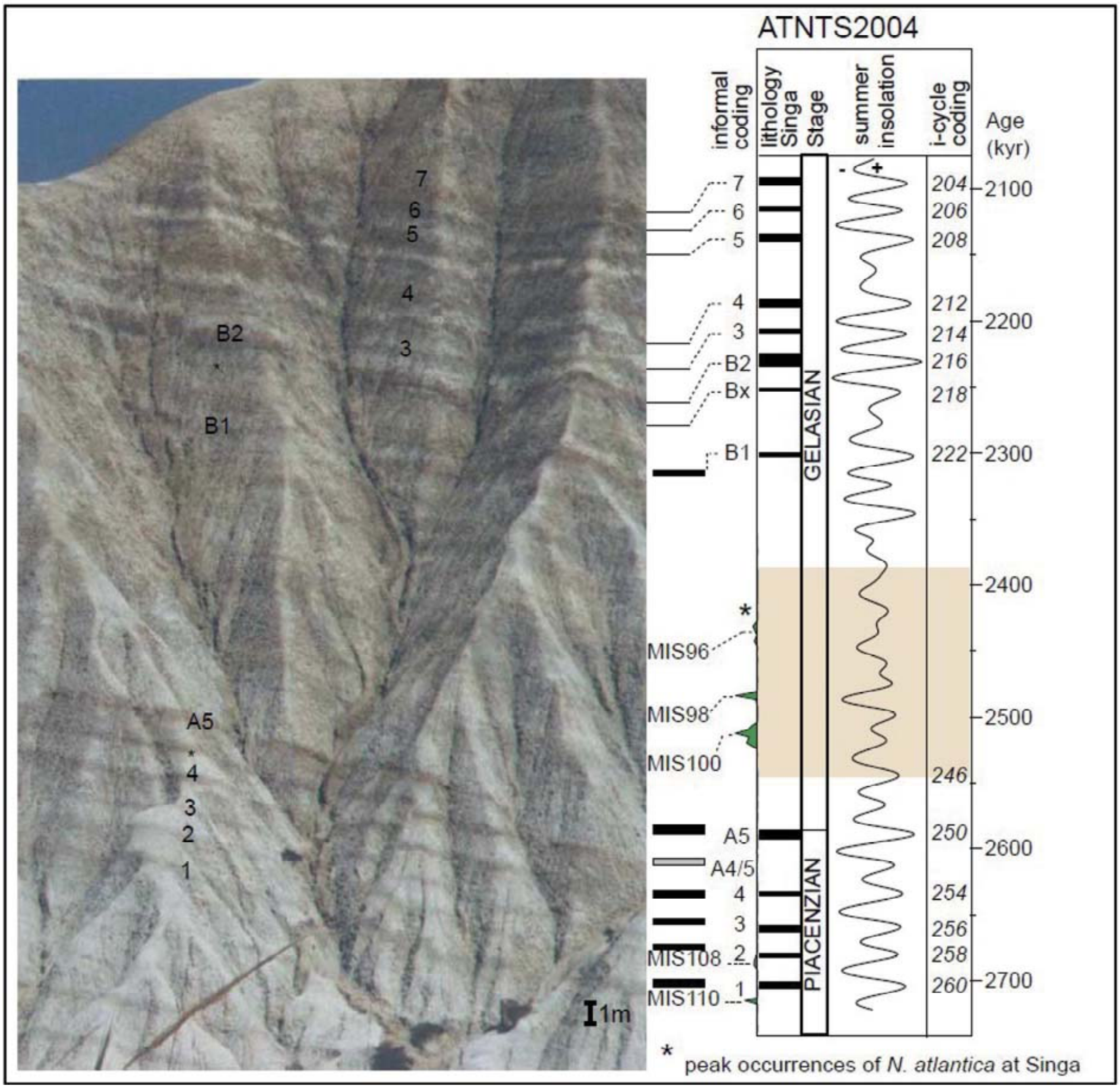


Fig. 8 - The stratigraphy studied by Becker et al. (2005) at Monte San Nicola, with indication of individual sapropels of sapropel clusters A and B. Sapropels are correlated with Singa section and with the La04(1,1) 65°N summer insolation curve. Marine Isotope Stages (MIS) 110, 108 and 100–96 are indicated by peak occurrences of *Neogloboquadrina atlantica* (green shaded) at Singa. The ATNTS2004 shows the sapropel occurrences and stages in relation to the La04(1,1) 65°N summer insolation curve. The shaded area indicates the interval of MIS101-95. The profile of relevance develops close to the “Mandorlo” section of Capraro et al. (2022). Modified form Becker et al. (2005).

boundary is also approximated by the Last Occurrence (LO) of nannofossil species *Discoaster pentaradiatus* and *D. surculus*, which occur in the Mediterranean in coincidence with oxygen isotopic stages 99 and 100, respectively (Sprovieri et al., 1998) (Fig. 1), ~80 k.y. above the base of the Gelasian GSSP (Rio et al., 1998; Sprovieri et al., 1998), by the LO of planktic foraminifer *Globorotalia bononiensis*, which occurs in MIS 96 (Fig. 7), and by the repetitive influxes of *Neogloboquadrina atlantica* in MIS 96, 98 and 100 (Lourens et al., 1992; Becker et al., 2005) (Fig. 8). The LO of the radiolarian species *Stichocorys peregrina* (Sanfilippo et al., 1985), the First Occurrence (FO) of the diatom *Nitzschiajoussaea* in low-latitude regions, and the LO of *Denticulopsis kamtschatica* in the North Pacific (Barron, 1985) also approximate closely the Gauss-Matuyama reversal.

6.4. Recent advancements

Becker *et al.* (2005) performed a high-resolution characterization of the glacial MIS 100 at Monte San Nicola, although they employed a different stratigraphic section than the classical GSSP profile. Their results demonstrate that MIS 100 was characterized by a high-frequency climatic variability in the sub-milankovian time domain of 5-8 kyr/cycle, reminiscent of the Heinrich and Dansgaard-Oeschger events of the late Pleistocene (Dansgaard *et al.*, 1993; Heinrich, 1988; Mayewski *et al.*, 1997). Herbert *et al.* (2015: 2018) reconstructed a long alkenone-derived record of past sea-surface temperatures (SSTs) in the central Mediterranean (Fig. 1) across the upper Neogene and Quaternary by splicing together data from the Punta Piccola, Monte San Nicola and Vrica sections and the deep-sea records of ODP Sites 964 and 967 (Fig. 1). Their results indicate that the major and most consistent drop in Central Mediterranean SSTs occurred at ca. 1.84 Ma, very close to the traditional Pliocene/Pleistocene (i.e., Gelasian/Calabrian) boundary. A long and severe cold episode took place in MIS 78 (ca. 2.09 Ma), correlative to the "first deep glaciations" of Rohling *et al.* (2014), while the MIS 100-MIS 96 glacial interval at ca. 2.6 Ma only appears as a short-lived transient cooling event (Herbert *et al.*, 2015; 2018) (Fig. 1). The Monte San Nicola succession was investigated in its entirety by Capraro et al. (2022), who produced an integrated study on physical stratigraphy, magnetostratigraphy, planktic foraminifera, calcareous nannofossils and cyclostratigraphy from a stratigraphic section adjacent to that of Becker et al. (2005). This study better constrained the position of the Gauss/Matuyama geomagnetic reversal above the "Nicola bed" and demonstrated that the Monte San Nicola stratigraphy spans continuously from the top of the Piacenzian Stage to the base of the Calabrian, without significant stratigraphic gaps and tectonic disturbances (Fig. 7). Accordingly, the Monte San Nicola area is deemed suitable to host the Unit Stratotype of the Gelasian, or possibly its Astronomical Unit Stratotype. On the contrary, they report on the presence of major faults and joints in the middle part of the historical "type" section, which do not affect the GSSP itself but prevent achieving a continuous, undisturbed record in the stratigraphy above. Currently, an international scientific program sponsored by INQUA-SACCOM, GELSTRAT (https://www.inqua.nl/QP33.pdf)) is detailing the stratigraphic interval encompassing the Gelasian GSSP in its type locality, in order to achieve an integrated high (centennial to millennial-scale) resolution stratigraphic/paleoclimatic record across the Neogene/Quaternary transition.

7. THE CALABRIAN STAGE

The name "Calabrian" was first introduced in a geological sense by French stratigrapher M. Gignoux in 1910, for indicating the younger part of the Pliocene Series. In his seminal work *"Les formations marines pliocènes et quaternaires de l'Italie du sud et de la Sicile"* (1913), he proposed as reference section for the Calabrian the stratigraphy exposed at Santa Maria di Catanzaro (Ionian Calabria; Fig. 3): *"Au Monte S. Maria, le plateau culminant du point 207 est occupè par des marnes blanches qui recouvrent ce banc à Cyprina islandica: ce fait est intéressant à noter, car il nous montre d'abord que l'apparition de ce banc est due à une modification de la sedimentation et de la population organique et non à une émersion; et ensuite, il nous prouve que le facies argileux a persisté jusqu'après le début du Calabrien: la continuité de sédimentation qui relie le Pliocène ancien au Calabrien est donc ici bien manifeste"*. For a long time, the Santa Maria di Catanzaro section was acknowledged as the type-section of the Calabrian Stage, the base of which was pinned in correspondence to a fossiliferous sand bed rich in the bivalve *Arctica islandica* (the notorious "GG bed") (Banner & Blow, 1965; Selli, 1967; Bayliss, 1969; Smith, 1969; Bandy & Wilcoxon, 1970; Selli, 1970; Berggren, 1971). Sprovieri et al. (1973) demonstrated that the section harbors a major hiatus, as the shallow-water "GG bed" is transgressive on deep-marine Pliocene marls and should instead be referred to the "Sicilian" Stage of Doderlein (1872). Therefore, the Santa Maria di Catanzaro succession was deemed unfit as the type-section for the Pliocene/Pleistocene boundary. As a replacement, (Emiliani et al., 1961) proposed to define the base of the Pleistocene in the Le Castella section (Crotone Basin, Ionian Calabria; Fig. 3), in correspondence to the so-called "marker bed" where the FO of the "cold guest" *Hyalinea baltica* was detected. Although the proposal was recognized by some (e.g., Berggren & Van Couvering, 1974; Haq et al., 1977), others argued that the section was affected by severe stratigraphic problems, above all a major hiatus immediately below the "marker bed" (Ruggieri & Sprovieri, 1977; Colalongo et al., 1980; Raffi & Rio, 1980; Rio et al., 1996a). Later, Ruggieri & Sprovieri (1979) suggested replacing the Calabrian Stage with the Selinuntian, a Superstage including the Santernian (Ruggieri & Sprovieri, 1975), the Emilian (Ruggieri & Selli, 1949) and the Sicilian of Doderlein (1872) (Fig. 6). However, Vai (1996, 1997) objected that these Units could not be employed formally, as none of them had ever been defined following the required ICS procedures (Hedberg, 1976; Cowie et al., 1986; Remane et al., 1996).

Further uncertainty arose from the lack of agreement on the main guiding criterion to be employed for establishing the Neogene/Quaternary boundary. After years of work, the IUGS/UNESCO International Geological Correlation Programme 41 (1974-1984) concurred in defining the boundary close to the top of Olduvai Event (ca. 1.8 Ma), in keeping with the traditional definition of Pliocene/Pleistocene boundary in use globally within the marine stratigraphers community (e.g., Glass et al., 1967; Phillips et al., 1968; Bandy & Wilcoxon, 1970). Selli et al. (1977) suggested to establish the Neogene/Quaternary boundary in the open-marine Vrica composite section (Crotone Basin, Calabria), which met the request by the international scientific community to define the boundary in a marine Italian section in correspondence with the first immigration of "northern guests" in the Mediterranean. The proposal was accepted by INQUA in 1982, approved by ICS in 1983, and finally ratified by IUGS in 1984. Still, the official documents made no mention of the status of the Calabrian Stage, and the most cited papers in the literature (Aguirre & Pasini, 1985, and Bassett, 1985) made reference to the Vrica GSSP as the Pliocene/Pleistocene boundary stratotype only. Despite the numerous studies performed on the Vrica section in the following decades (e.g., Howell et al., 1990; Hilgen, 1991a; Azzaroli et al., 1996; Rio et al., 1996a; Lourens et al., 1996a,b), the Calabrian remained undefined and its use declined, with the exception of stratigraphers working on Italian sections. Cita et al. (2006, 2008) addressed the problem of Quaternary Stages not yet formally established, and proposed pinning the GSSP of the Calabrian Stage at Vrica in correspondence to the traditional Pliocene/ Pleistocene boundary at ca. 1.8 Ma. The proposal was accepted by the competent bodies, and the Calabrian was ratified as the second Stage of the newly established "long" Lower Pleistocene, immediately above the Gelasian (Cita et al., 2012).

7.1. The Vrica section

The Vrica section (Aguirre & Pasini, 1985; Pasini & Colalongo, 1982) is located ca. 4 km south of the city of Crotone (Fig. 5A), not far from the reference sections of Le Castella (ca. 20 km) and Santa Maria di Catanzaro (ca. 50 km) (Fig. 3). It is part of the emerged part of the Crotone sedimentary basin (Roda, 1964), which offers one of the most expanded, complete, and well-exposed Neogene and Quaternary stratigraphic successions available globally. The Crotone basin is a forearc basin of the Ionian arc-trench system, which was generated by eastward rollback of a west-dipping subduction zone associated with extension in the Tyrrhenian back arc basin (e.g., Malinverno & Ryan, 1986; Kastens et al., 1988; Mazzoli & Helman, 1994; Sartori, 1989; Faccenna et al., 2001). It accommodates a sedimentary infill consisting of >3000 m of terrigenous clastics, primarily yielded by crystalline rock sources of the Sila massif. The stratigraphic architecture of the Crotone Basin is very complex, being the result of a strong interplay between sedimentation, tectonics, eustasy and climate (e.g., Rio et al., 1996b; Massari et al., 2007, 2010). In particular, the vibrant geodynamical processes associated to the evolution of the Calabrian Arc triggered the formation of smaller sub-basins within the main Crotone Basin, with the development on very short distances of stratigraphic successions that differ dramatically in age and physical stratigraphy (e.g., Massari et al., 2010).

The Vrica section consists of an expanded succession of blue hemipelagic marly clays that are spectacularly exposed within a suite of steep badlands immediately inland from the Ionian coast (Fig. 5B-E), between the town of Crotone and the Capo Colonna archeological site. The succession belongs to the upper part of the "Argilla Marnosa di Cutro" of Roda (1964), a very thick package of Piacenzian to Calabrian open-marine sediments that, although with variable facies and age, constitutes the most widespread and exposed unit within the Crotone basin. The stratigraphy including the Vrica section was singled out by Emiliani et al. (1961) as "Papanice Formation", being characterized by the occurrence of tripolacean (laminitic) intervals that are absent in the underlying massive marly clays of the "Semaforo Formation". The Vrica composite section was reconstructed by splicing together three segments (Vrica A; Vrica B, housing the Calabrian GSSP; and Vrica C) (Fig. 5C) that can be confidently linked by means of prominent marker beds and biohorizons (Hilgen, 1990). Correlation between the component segments is secured by the lack of tectonic disturbances, as the local succession forms a regular monocline dipping gently (5-15°) westward. As a whole, the Vrica section extends for a total thickness of ca. 300 m (Fig. 9) and allows for extremely high-resolution investigations, being characterized by sediment accumulation rates in the order of 30 cm/kyr (Rio et al., 1996a) that increase to >40 cm/kyr in the lowermost part of the succession (Suc et al., 2010). Faunal constraints suggest that the Vrica sediments were laid in an epibathyal setting at a water depth between 500 and 800 m (Pasini & Colalongo, 1994). In keeping with many of the outcrops exposed along the modern coastline of the Crotone Basin, the open-marine stratigraphy does not extend above the "large" *Gephyrocapsa* Zone of Rio et al. (1990) (Pasini & Colalongo, 1994), being truncated by a flight of Middle to Upper Pleistocene marine terraces. Further inland, the younger part of the "Argilla Marnosa di Cutro" ("small" *Gephyrocapsa* Zone of Rio et al., 1990) is preserved as a stack of unconformity-bounded transgressive-regressive cycles, and locally overlain by regressive Middle Pleistocene outer shelf to fluvial sediments (Rio et al., 1996b; Massari et al., 2010; Capraro et al., 2011, 2015, 2017).

One of the most impressive features of the Vrica section is the number and individual thickness of sapropelic layers preserved within. They are represented in the field by laminated intervals of organic-rich silts up to 3 m thick (Fig. 5B, E), locally rich in fossil fish remains, that stand out in the local stratigraphy because of their orange color and different competence with respect to the embedding clays (Raffi & Thunell, 1996). In the Vrica record, 14 MPRS layers have been identified that allowed for an astronomical calibration of the section, demonstrating that the section extends continuously from 1.81 to 1.21 Ma (Lourens et al., 1996b, 1998). Sparse thin sandy layers and three widely traceable tephra can be also employed as marker beds for intrabasinal correlation. In terms of calcareous plankton biostratigraphy, the composite section ranges from the uppermost planktonic foraminifera Zone MPl5b to the *G. truncatulinoides excelsa* Zone (Cita, 1975, emended), and from calcareous nannofossil Zone MNN 18 (pars) to MNN19e of Rio et al. (1990). The Calabrian portion of the section extends from MIS 65 to MIS 37 (Lourens et al., 1996b) (Fig. 10). The local stratigraphy of the section compares very well with that exposed in the coeval Singa section, located further south along the coast of Ionian Calabria (Zijderveld et al., 1991). Likewise, the sapropel record at Vrica is in excellent agreement with that found in the upper part of the Monte San Nicola section, where the Gelasian/Calabrian boundary can be easily identified (Capraro et al., 2022).

7.2. Previous studies

During the 1980s and the 1990s, the Vrica section was subjected to numerous investigations performed by international working groups in the light of both its criti-

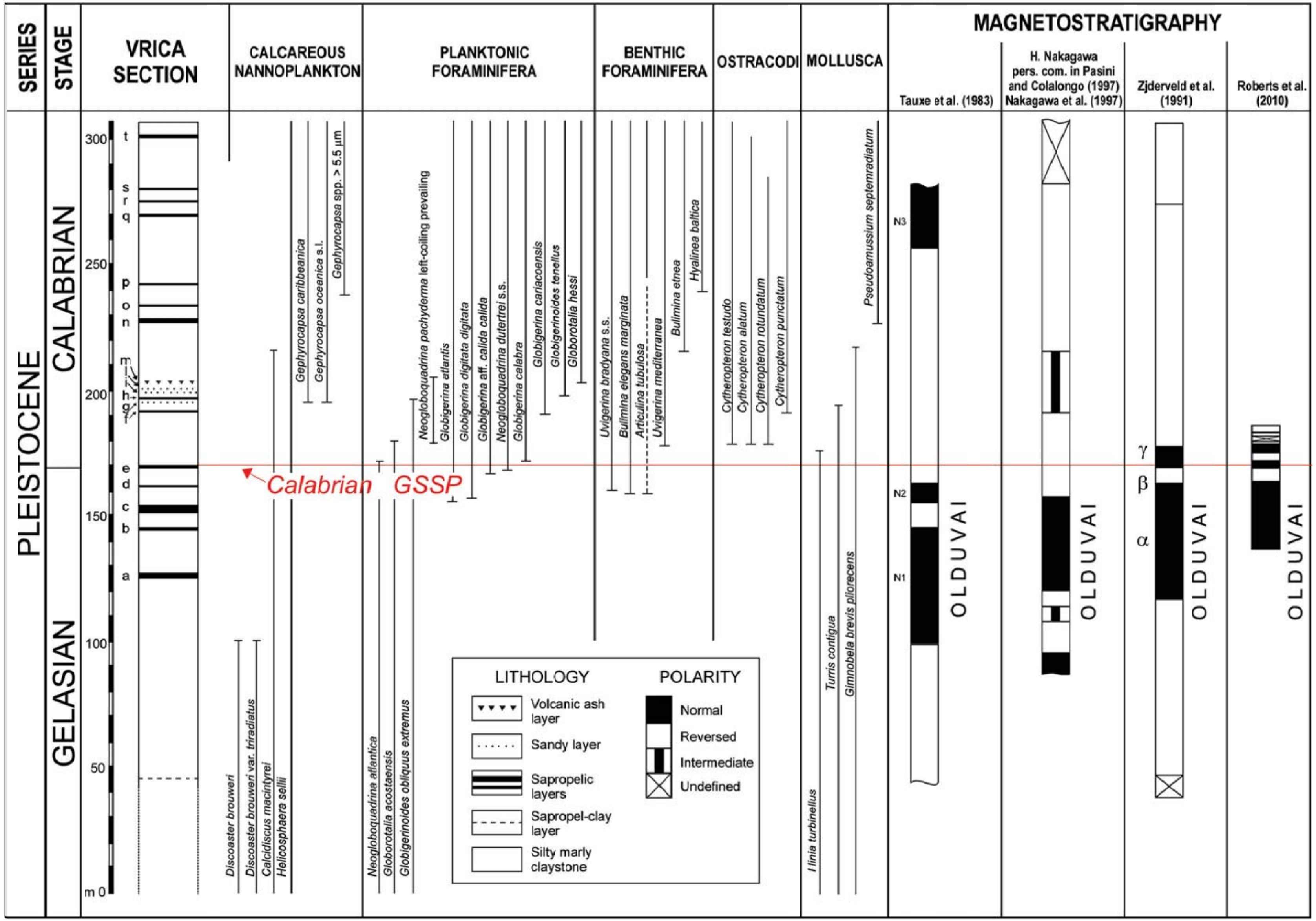


Fig. 9 - Stratigraphy of the "historical" Vrica section, with distribution of significant microfossil taxa and conflicting magnetostratigraphic records. Modified from Pasini and Colalongo (1997) and Cita et al. (2012).

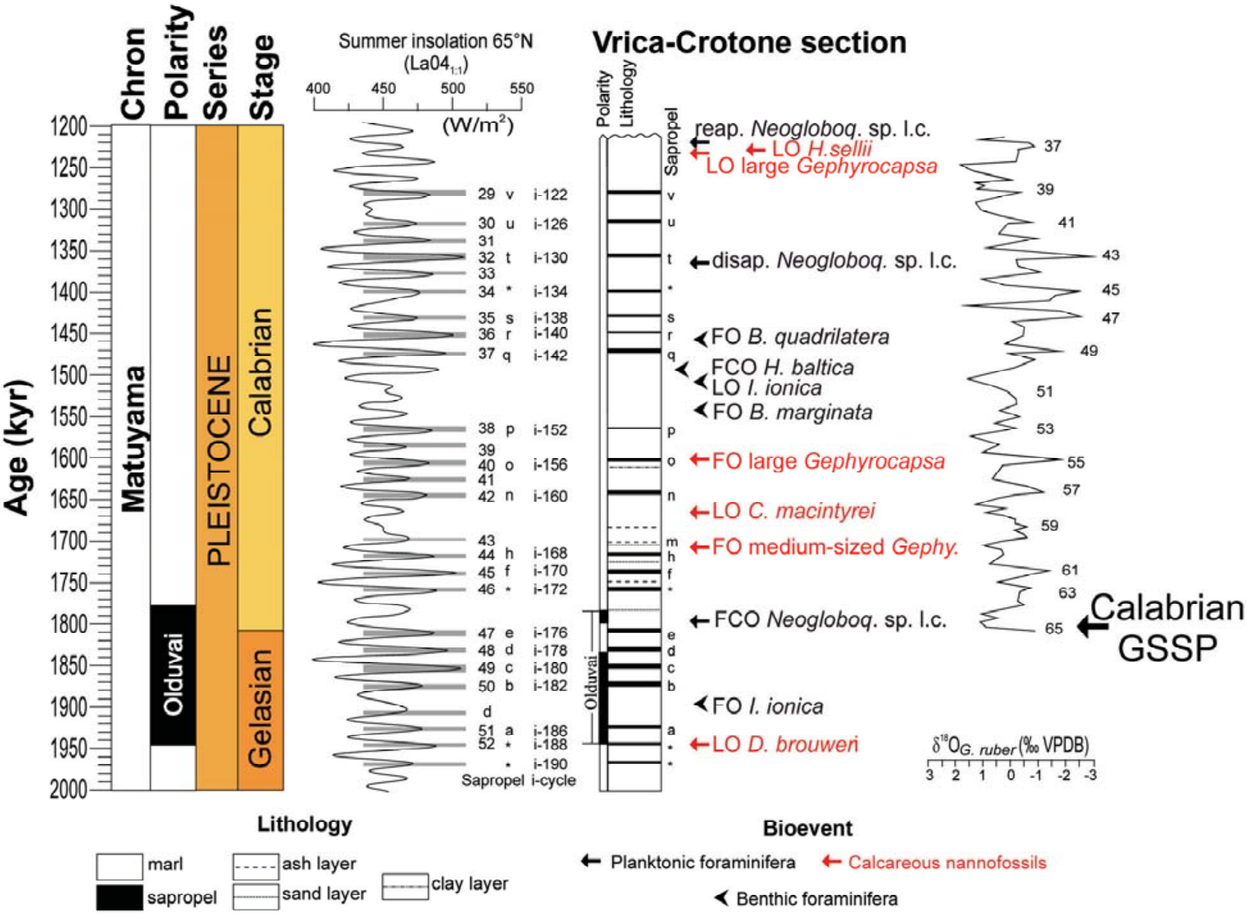
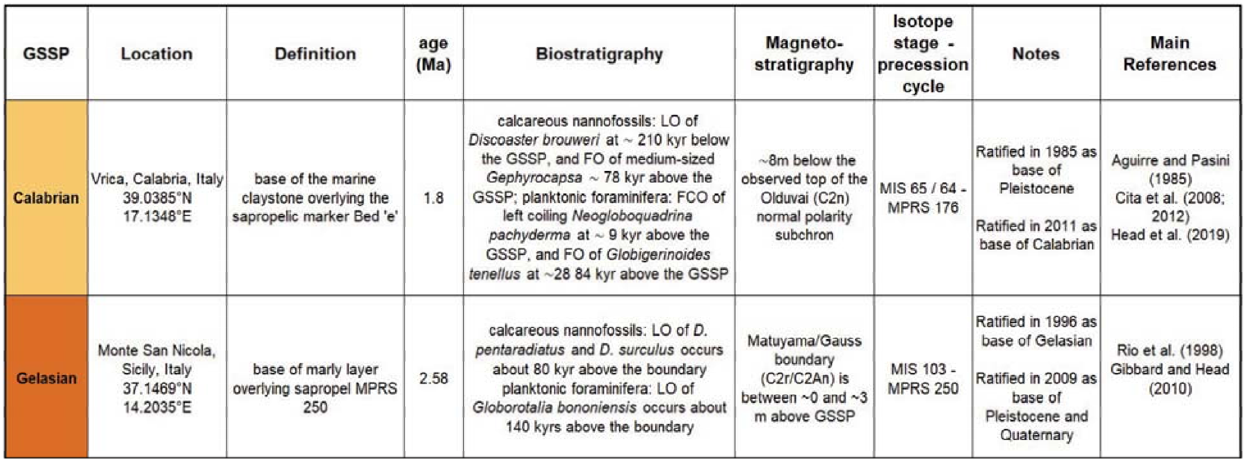


Fig. 10 - Astronomical calibration, oxygen isotope chronology and bioevents at Vrica-Crotone section according to the continuous age model of Lourens et al. (1996a). FO: First Occurrence; LO: Last Occurrence; FCO: First Common Occurrence; reap.: reappearance; disap.: disappearance: l.c.: left coiled. Lithostratigraphy from Selli et al. (1977), Zijderveld et al. (1991), Lourens et al. (1996). Magnetostratigraphy from Zijderveld et al. (1991). Astronomical Time Scale (ATNTS2004) from Lourens et al. (2004). Summer insolation 65°N (La041:1) from Laskar et al. (2004). Modified from Maiorano et al. (2010).

cal role as the reference record for the Neogene/Quaternary boundary and the advances made in astrocyclostratigraphy, which required suitable sections for establishing the new ATS (Hilgen, 1991a; Lourens et al., 1996a, 1998). Tauxe et al. (1983) achieved the first paleomagnetic record of the Olduvai Subchron (Fig. 9), which provided a key criterion for pinning down the Pliocene/Pleistocene boundary. Successive studies (Zijderveld, 1991; Nakagawa, 1997; Roberts, 2010) (Fig. 9) produced conflicting paleomagnetic records, suggesting that the stratigraphy around the Calabrian GSSP, where the top of the Olduvai is expected to occur, is affected by severe remagnetization processes that prevent reconstructing a reliable paleomagnetic record at Vrica. Despite this major concern, the section offers a wide array of integrated biostratigraphic and physical stratigraphic constraints that allow for a safe and easy recognition of the Gelasian/Calabrian boundary, as summarized in the dedicated volume edited by Van Couvering (1996) to which we refer for further information.

7.3. Definition of the Calabrian GSSP

The Calabrian GSSP (Cita et al., 2012) is located at the very base of the marl bed immediately overlying the very prominent sapropel *e* of Aguirre & Pasini (1985), located in the middle part of the component segment B of the Vrica section. The astronomically calibrated age of the boundary is 1.806 Ma (Lourens et al., 1996). According to the original definition for the Neogene/Quaternary boundary, the base-Calabrian is closely approximated by the top of the Olduvai Subchron (Aguirre & Pasini, 1985) (Fig. 1). This event is generally recognized at about 8 m above sapropel *e* (Hilgen, 1991a; Zijderveld et al., 1991; Roberts et al., 2010), although the section is not suitable for detailed paleomagnetic investigations (Roberts et al., 2010). Biostratigraphic markers of the boundary include, for the calcareous nannofossils, the LO of *Discoaster brouweri*, documented at ca. 70 m below the GSSP (~210 kyr prior to the boundary, assuming an average sediment accumulation rates of 30 cm/kyr) (Fig. 10), and more importantly the FO of medium-sized *Gephyrocapsa* (including *G. oceanica*), which occurs ca. 26 m (~78 kyr) above the



GSSP	Location	Definition	age (Ma)	Biostratigraphy	Magneto-stratigraphy	Isotope stage - precession cycle	Notes	Main References
Calabrian	Vrica, Calabria, Italy 39.0385°N 17.1348°E	base of the marine claystone overlying the sapropelic marker Bed 'e'	1.8	calcareous nannofossils: LO of *Discoaster brouweri* at ~ 210 kyr below the GSSP, and FO of medium-sized *Gephyrocapsa* ~ 78 kyr above the GSSP; planktonic foraminifera: FCO of left coiling *Neogloboquadrina pachyderma* at ~ 9 kyr above the GSSP, and FO of *Globigerinoides tenellus* at ~28 84 kyr above the GSSP	~8m below the observed top of the Olduvai (C2n) normal polarity subchron	MIS 65 / 64 - MPRS 176	Ratified in 1985 as base of Pleistocene Ratified in 2011 as base of Calabrian	Aguirre and Pasini (1985) Cita et al. (2008; 2012) Head et al. (2019)
Gelasian	Monte San Nicola, Sicily, Italy 37.1469°N 14.2035°E	base of marly layer overlying sapropel MPRS 250	2.58	calcareous nannofossils: LO of *D. pentaradiatus* and *D. surculus* occurs about 80 kyr above the boundary planktonic foraminifera: LO of *Globorotalia bononiensis* occurs about 140 kyrs above the boundary	Matuyama/Gauss boundary (C2r/C2An) is between ~0 and ~3 m above GSSP	MIS 103 - MPRS 250	Ratified in 1996 as base of Gelasian Ratified in 2009 as base of Pleistocene and Quaternary	Rio et al. (1998) Gibbard and Head (2010)

Tab. 4 - Definitions for the Gelasian and Calabrian GSSPs and relevant chronostratigraphic markers. FO: First Occurrence; LO: Last Occurrence; FCO: First Common Occurrence.

boundary (Fig. 10). Planktonic foraminiferal events include the First Common Occurence (FCO) of left-coiling *Neogloboquadrina pachyderma*, at ca. 3 m (~9 kyr) above the GSSP, and the FO of *Globigerinoides tenellus* (Fig. 9), at ca. 28 m (~84 kyr) above the boundary. These key markers are complemented by numerous less prominent yet sharp biohorizons, as shown in Cita et al. (2008, 2012) and Figures 9-10. A synthesis of the main correlation criteria for the Calabrian GSSP is reported in Table 4.

7.4. Recent advancements

In the last years, the Vrica section has not been a major topic for the geological community. Exceptions are the work of Roberts et al. (2010), who confirmed the poor paleomagnetic properties of the section in the interval straddling the Olduvai Subchron, and that of Herbert et al. (2015), who emphasized that the major and more persistent drop in Mediterranean SSTs after the onset of the Northern Hemisphere Glaciation occurred around the Gelasian/Calabrian boundary (ca. 1.8 Ma) (Fig. 1).

8. SUMMARY

The Italian Neogene and Quaternary marine sedimentary record played a critical role in the development of innovative stratigraphic tools and the definition of chronostratigraphic standards. Among the numerous advancements achieved via the investigation of Mediterranean sections, it is worth mentioning the ATS for the Neogene and the Quaternary, which was largely constructed and validated on sections exposed in peninsular Italy and Sicily. In particular, they include the GSSP sections of the Zanclean and Piacenzian Stages (Lower and Upper Pliocene, respectively) and those of the Gelasian and Calabrian Stages (Lower Pleistocene). The latter two are of particular interest for those working in the Quaternary, as they represent the past and present global reference stratigraphic records for the beginning of the Pleistocene. All these sedimentary records contain multiple biotic and abiotic stratigraphic constraints that allow exporting the relevant GSSPs well beyond their type localities. This further confirms the key contribution given by the Italian sedimentary record in defining chronostratigraphic standards of use at a global scale.

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