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Vrica-Crotone and Montalbano Jonico sections: A potential unit-stratotype of the Calabrian Stage

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A unique composite record from the Mediterranean area exposed on land and spanning the entire time interval of the Calabrian Stage is presented. The record is composed of the Vrica-Crotone section (Calabria, southern Italy) and the Montalbano Jonico section (Basilicata, southern Italy). The Vrica-Crotone section contains the proposed Global Stratotype Section and Point (GSSP) of the Calabrian Stage and extends from Marine Isotope Stage (MIS) 65 to 37 for its Calabrian portion. The Montalbano Jonico section extends from MIS 37 to 17-16. Its upper portion contains MIS 19, which is known to occur close to the Matuyama/Brunhes reversal, and may represent a suitable horizon for the definition of the GSSP of the ‘Ionian’ Stage. Both sections are astronomically tuned, thus providing accurate ages for the bioevents. New biostratigraphic results and radiometric data on volcanoclastic layer V3 of the Montalbano Jonico section are presented together with an updated tuning of the section. A comparison with several Mediterranean and north Atlantic deep-sea cores is also shown to verify the consistency and reliability of the biostratigraphic data. The Vrica-Crotone and Montalbano Jonico sections can be considered a suitable composite record for the Calabrian unit-stratotype and support the revaluation of the unit-stratotype concept in addition to the GSSP approach.

Introduction

The Stage is the basic working unit in chronostratigraphy and represents the lowest rank in the standard chronostratigraphic hierarchy recognizable at global scale. It is defined within a boundary-stratotype, by a Global Boundary Stratotype Section and Point (GSSP) (Salvador, 1994). The GSSP concept was introduced in order to avoid the problem of uncertainties both in time correlation (gaps and/or

overlaps) between historical stages and in their continuity, thus emphasizing the role of boundaries rather than the content for the definition of the stage. An exhaustive review of the history and application of the concept of GSSPs can be found in Aubry et al. (1999) and Walsh et al. (2004). The concept of the unit-stratotype (*a continuously exposed section, in facies favourable for time-correlation, extending from the lower boundary-stratotype to an upper boundary-stratotype*), initially introduced by Hedberg (1958), has been recently re-interpreted and advocated by Hilgen et al. (2006) with particular attention to Neogene units in the Mediterranean area, and by Cita and Pillans (2010). Recent progress in integrated high-resolution stratigraphy and astronomical tuning of sedimentary cycles, in fact, offers the opportunity to define the stages in continuous, cyclic and well-tuned successions. These sections may also serve as unit-stratotypes, thus providing precision and accuracy throughout the entire stage. Consequently, the stage should not just be defined by its boundaries (GSSPs) but also by its content (Hilgen et al., 2006). The Capo Rossello composite section, which contains both Zanclean and Piacenzian GSSPs, represents a prime example of the unit-stratotype approach and several other Pliocene and Miocene examples are known and summarized in Hilgen et al. (2006). On the other hand, formalization of Pleistocene stages is still in progress. After a Special Symposium on the Quaternary (chairs M.B. Cita and B. Pillans) during the International Geological Congress of Oslo (2008), the International Union of Geological Sciences (IUGS), on June 30, 2009, ratified the redefinition of the base of the Quaternary System/Period (and top of the Neogene System/Period), and the redefinition of the base of the Pleistocene Series/Epoch (and top of the Pliocene Series/Epoch) following the proposal of Head et al. (2008a). In detail, the base of the Quaternary System/Period and of the Pleistocene Series/Epoch were lowered to the GSSP of the Gelasian Stage formally defined at Monte San Nicola, Sicily, Italy (Gibbard et al., 2010) dated at 2.6 Ma. With these definitions, the Gelasian Stage/Age shifts from the Pliocene Series/Epoch to the Pleistocene. Several controversial positions have been conveyed in the last two years concerning this issue (i.e., Head et al., 2008a; Walsh, 2008; Aubry et al., 2009; McGowran et al., 2009; Rio et al., 2010) revealing the strong significance of Plio-Pleistocene chronostratigraphy for the international scientific community. If the Gelasian represents the first stage of the revisited Pleistocene, a redefinition of the second stage of this Series, the Calabrian Stage, becomes necessary, as recently proposed by Cita et al. (2008). The proposed Calabrian

GSSP corresponds to the GSSP where the Plio/Pleistocene boundary was ratified by IUGS in 1984 in the Vrica section. It was placed at the top of sapropel “e”, with an astronomical age of 1.806 Ma (Lourens et al., 2004), in the latest part of the Olduvai Subchron. The top of the Calabrian Stage is coincident with the successive ‘Ionian’ Stage which still lacks a formal definition. Cita et al. (2008) asserted that a continuous stratigraphical interval representing the entire time interval of the Calabrian Stage is so far known only from deep-sea sequences recovered in the Mediterranean Ocean Drilling Program (ODP) Legs 107, 160, 161.

In this paper, based on new data collected in the Montalbano Jonico section, we present a composite Mediterranean record, exposed on land, spanning the entire time interval of the Calabrian Stage, which may represent a potential unit-stratotype of that stage. We are well aware that only GSSPs are accepted and considered mandatory by IUGS for global stage definition, nevertheless we consider appropriate the reconsideration of the unit-stratotype notion as complementary to the GSSP concept. A stage is, in fact, the sedimentary representation (“time-rock unit” in Chronostratigraphy) of the equivalent time unit (Geochronology): “the best standard for a chronostratigraphic unit is a body of rocks formed between two designated instants of geologic time” (Salvador, 1994, p. 88). Continuous land-based marine records yielding high-resolution stratigraphy and accurate chronology may be valuable reference sections for the entire stage. These records may be the needful basis for the selection of the best GSSP as well as helpful in the geological practice. It is for these reasons that, although no formal definition of the Calabrian and ‘Ionian’ Stages has been ratified yet, and accordingly, their use is still somewhat inappropriate, we consider constructive to illustrate the continuous land-based marine record which describes the “content” of the potential Calabrian Stage and which may accommodate two consecutive potential GSSPs. The record is composed of the Vrica-Crotone and Montalbano Jonico sections (Figure 1), both astronomically tuned and with high resolution integrated biostratigraphy. The on-land records are compared with Mediterranean and extra-Mediterranean deep-sea records, in order to explore the consistency and reliability of the cyclostratigraphic and biostratigraphic data. Finally, a potential GSSP for the ‘Ionian’ Stage is also suggested in the Montalbano Jonico section.

A potential unit-stratotype of the Calabrian Stage

The composite record consisting of the Vrica-Crotone and Montalbano Jonico sections encompasses the entire Calabrian Stage. For the Vrica-Crotone section we summarize the most significant data following the astronomical calibration provided by Lourens et al. (1996; 1998); whereas we present new biostratigraphic and radiometric data for the Montalbano Jonico section.

The Calabrian interval is well documented in several deep-sea sequences; therefore the overall data are compared using Mediterranean and oceanic deep-sea records (ODP Site 967; ODP Site 964; Core KC01B and Deep Sea Drilling Project - DSDP Site 607) (Figure 1; Table 1). For the coeval interval recovered from the Vrica-Crotone section we consider ODP Site 967 (Emeis et al., 1996), representing an Eastern Mediterranean deep-sea sequence, whose

Figure 1. (a) Geographic location map of the sections considered in this study; (b) Lithological sequence of Montalbano Jonico section showing position of main volcanoclastic layers (V); (c) Lithological sequence of B segment of Vrica section showing the sapropel layers: b, c, d, e, f and h, (modified from ICS web site www.stratigraphy.org). The GSSP of the Calabrian Stage is fixed (dashed line) at the top of level “e” according to Cita et al. (2008).

sapropel pattern and biostratigraphic data have been correlated to the Vrica section (Lourens et al., 1998). ODP Site 964 (Emeis et al., 1996) and Core KC01B, both located in the Ionian Basin, have been considered for the interval recovered by the Montalbano Jonico section. The chronology of these sections follows the recent astronomical re-calibration by Lourens (2004). Finally, we consider DSDP Site 607 as a mid-latitude North Atlantic reference deep-sea section. The oxygen isotope chronology adopted for the core follows recalibration to the LR04 timescale of Lisiecki and Raymo (2005).

Vrica-Crotone section

The well known Vrica-Crotone section exposes the lower part of the Calabrian Stage (Figure 2). This section, located in northern

Table 1. Summary of the sections considered in this study and relative references considered in the present paper

SECTION		REFERENCE				
Section or Leg/Site	Location	Biostratigraphy Biochronology	Oxygen isotope stratigraphy	Magneto- stratigraphy	Tephra- chronology	Age Model
Vrica-Crotone	Calabria (Southern Italy)	Lourens et al. (1996, 1998)	Lourens et al. (1996, 1998)	Zijderveld et al. (1991)		Lourens et al. (1996, 1998)
Montalbano Jonico	Basilicata (Southern Italy)	Marino (1996) Maiorano et al. (2004) This study ----- Ciaranfi et al. (2010) This study	Brilli et al. (2000) Ciaranfi et al. (2001) Ciaranfi et al. (2010)	Sagnotti et al. (2010)	Ciaranfi et al. (2010) this study	Ciaranfi et al. (2010) this study
ODP 160/Site 967	Eastern Mediterranean	Lourens et al. (1998) Raffi (2002)	Kroon et al. (1998)			Lourens et al. (1998)
ODP 160/Site 964	Ionian Sea	Maiorano and Marino (2004) This study	Howell et al. (1998) Sprovieri et al. (1998)			Lourens (2004)
Core KC01B	Ionian Sea	Castradori (1992); this study This study	Rossignol-Strick et al. (1998)			Lourens (2004)
DSDP 94/Site 607	North Atlantic	Ruddimann et al. (1989) Raffi (2002) Maiorano and Marino (2004) ----- This study	Ruddimann et al. (1989)			Lisiecki and Raymo (2005)

Calabria (southern Italy) has been intensively investigated in the past (Selli et al., 1977; Colalongo et al., 1980; Pasini and Colalongo, 1982; Tauxe et al., 1983; Backman et al., 1983; Aguirre and Pasini, 1985; Bassett, 1985; Howell et al., 1990; Zijderveld et al., 1991; Azzaroli et al., 1996; Lourens et al., 1996; Rio et al., 1997; Lourens et al., 1998). Recently, new papers on the Vrica-Crotone section (Suc et al., 2010; Roberts et al., 2010) reveal a continuous scientific interest for this section. It is a well exposed composite section (Figure 1), about 240 m thick, consisting of grey to blue-coloured, marly to silty marine clays. Several sapropel layers occur in the section that were mostly labelled “a” to “t” by Selli et al. (1977). Occasionally, ash beds are present. The uppermost part of the section, which accommodates sapropels “u” and “v” (Figure 2), extends into the Crotone section which is cyclostratigraphically correlated to the Vrica section (Zijderveld et al., 1991; Lourens et al., 1996). The Vrica section was formally designated as the reference for the GSSP of the Pleistocene Series as ratified by IUGS in 1984 (Aguirre and Pasini, 1985; Bassett, 1985). Specifically, the Pliocene-Pleistocene boundary was defined at the top of sapropel “e” which was the primary marker for the recognition of the boundary (Figure 1). After the recent redefinition of the base of the Pleistocene Series at the base of the Gelasian Stage (2.6 Ma), the top of sapropel “e” at Vrica section and the GSSP of the Pleistocene were disconnected (Figure 2). Afterwards, the historical Pliocene/Pleistocene boundary of the Vrica section has been proposed as the GSSP of the Calabrian Stage (Cita et al., 2008). Indeed, the ‘Quaternary’ proposal had intended the Calabrian Stage to be defined by the GSSP at the Vrica section (Gibbard and Head 2009; Gibbard and Head, 2010). It is located about 10 meters below the top of the Olduvai magnetozone (Zijderveld et al., 1991), at the transition between MIS 65 and 64 (Lourens et al., 1996; Lourens et al., 1998). From a biostratigraphic point of view, the boundary almost coincides with the Lowest Common Occurrence (LCO) of *Neoglobobulimina pachyderma* left-coiling (Figure 2) and falls

between the Highest Occurrence (HO) of *Discoaster brouweri* and the Lowest Occurrence (LO) of medium-sized *Gephyrocapsa* (Lourens et al., 1996; Lourens et al., 1998). By tuning the sapropel pattern to the summer insolation time series using the astronomical solution of Laskar et al. (1993, 2004), an age of 1.806 Ma has been assigned to the boundary (Lourens et al., 2004). The astronomical calibration available for the Vrica-Crotone section reveals that the Calabrian portion is continuous, spanning the interval from 1.81 to 1.22 Ma, and provides accurate ages of the biostratigraphic events, sapropels and magnetostratigraphic data (Figure 2). Cyclostratigraphy and biochronology of the Vrica-Crotone section was presented by Lourens et al. (1996) and Lourens et al. (1998) to which we refer (Table 2).

Montalbano Jonico section

The Montalbano Jonico section represents a unique and valuable record of the upper portion of the Calabrian Stage exposed on-land. Several integrated stratigraphic studies have been carried out on the Montalbano Jonico section (e.g. Ciaranfi et al., 2001; D’Alessandro et al., 2003; Stefanelli, 2003; Maiorano et al., 2004), located in the Lucania Basin (Balduzzi et al., 1982). The section is about 450 m thick (Figure 3), consists of coarsening-upwards deposits from silty clays to silty sands and includes five “sapropel” layers (Stefanelli, 2004; Stefanelli et al., 2005; Maiorano et al., 2008) and nine volcanoclastic layers (V1–V9).

Based on calcareous nannoplankton (Ciaranfi et al., 1996; Marino, 1996; Maiorano et al., 2004) the section belongs to the small *Gephyrocapsa* and *Pseudoemiliana lacunosa* zones of Rio et al. (1990). New quantitative data have been collected on planktonic foraminifera from the lower part of Montalbano section with special regards to *N. pachyderma* left-coiling and *Globorotalia crassaformis* distribution patterns (Figure 3). The high-resolution sampling of

Figure 2. Astronomical calibration, oxygen isotope chronology and bioevents at Vrica-Crotone section according to the continuous age model of Lourens et al. (1996). Magnetostratigraphy is from Zijdeveld et al. (1991); lithostratigraphy from Selli et al. (1977), Zijdeveld et al. (1991), Lourens et al. (1996). Astronomical Time Scale (ATNTS2004) from Lourens et al. (2004); summer insolation 65°N ($La04_{1.1}$) from Laskar et al. (2004). LO: Lowest Occurrence; LCO: Lowest Common Occurrence; HO: Highest Occurrence; reap.: reappearance; disap.: disappearance.

1-2 ky allowed identification of two additional planktonic foraminiferal bioevents: the reappearance of *N. pachyderma* left-coiling and the influx of *G. crassaformis*. *N. pachyderma* left-coiling is absent or rare in the lowermost part of the section, while distinct peaks are recorded from 17.2 m upwards, where we identify the reappearance of the taxon (Figure 3). The event occurs below sapropel 28 (i-cycle 112) and is correlated to MIS 36 (Figure 3). Upwards, a short influx of *G. crassaformis* has been recognized from 50.15 to 60.55 m, slightly below sapropel 26 (i-cycle 104), within MIS 34 (Figure 3). The calcareous nannofossil bioevents (Figure 3) are represented by Lowest Common Occurrence (LCO) and Highest Common Occurrence (HCO) of *Reticulofenestra asanoi*, Lowest Occurrence (LO) and temporary disappearance interval (td2 interval in Maiorano and Marino, 2004) of *Gephyrocapsa omega* and have been already presented in previous papers (Maiorano et al., 2004; Ciaranfi et al., 2010). The LCO of *R. asanoi* is located just above sapropel 25 (i-cycle 102) and within MIS 31, while the HCO of this species correlates with i-cycle 86 and MIS 23 (Figure 3). The LO of *G. omega* is recorded within sapropel 19 (i-cycle 90) and MIS 25 and the temporary disappearance interval (td2 interval) extends from MIS 21- 20 to 19-

18 (Figure 3). New data on temporal distribution patterns have been obtained on these calcareous events from other Mediterranean deep-sea records and are presented below.

Rigorous magnetostratigraphic investigations have revealed that the magnetic signal in the Montalbano Jonico section is unreliable due to remagnetization of the entire section (Sagnotti et al., 2010). On the other hand, the sapropel pattern, together with the $^{39}\text{Ar}/^{40}\text{Ar}$ age of the volcanoclastic layer V5, the calcareous plankton biostratigraphic constraints, and oxygen isotope records have allowed an astronomical calibration of the section (Ciaranfi et al., 2010). In addition, a new $^{39}\text{Ar}/^{40}\text{Ar}$ age was recently obtained on volcanoclastic layer V3. Full chemical data on glass shards from this volcanoclastic layer could not be obtained, owing to the strong alteration involving the fragments (Ciaranfi et al., 2010), but well preserved sanidine crystal grains were selected and radiometric dating was carried out at the Department of Geology and Geophysics of the University of Wisconsin in Madison. Irradiation, analysis and general interpretive principles are described in detail by Smith et al. (2008). The age of V3 layer is 801.2 ± 19.5 ka (Figure 4). This age is fully consistent with the stratigraphic position of V3 layer, since it crops out 121.9 m

Table 2. List of the age estimation of Calabrian calcareous plankton biohorizons in selected reference sections. Depth in the section and correlation with oxygen isotope stratigraphy are indicated when available

Bioevent	Section	Depth (m)	Age (Ma)	MIS	Reference
LCO <i>N. pachyderma</i> left-coiling	Vrica-Crotone section ODP Site 967 (Mediterranean) Eastern Mediterranean	127 (m) 54.23 (rmcd)	1.799 1.793 1.79	65-64 65-64	Lourens et al. (1996) Lourens et al. (1996) Lourens et al. (2004)
LO medium <i>Gephyrocapsa</i>	Vrica-Crotone section ODP Site 967 (Mediterranean) Eastern Mediterranean Equatorial Atlantic Equatorial Pacific DSDP Site 607	154 (m) 70.16 (mcd)	1.71 1.729 (± 0.003) 1.730 1.689 1.67 1.704	60 61? 60	Lourens et al. (1996) Raffi (2002) Raffi et al. (2006) Raffi et al. (2006) Raffi et al. (2006) Raffi et al. (1993) recalibrated
HO <i>C. macintyreii</i>	Vrica-Crotone section ODP Site 967 (Mediterranean) Eastern Mediterranean Equatorial Atlantic Equatorial Pacific DSDP Site 607	171 (m) 67.67 (mcd)	1.671 1.676 (± 0.005) 1.664 1.607 1.60 1.642	58-57 59-58 57	Lourens et al. (1996) Lourens et al. (1998); Raffi (2002) Raffi et al. (2006) Raffi et al. (2006) Raffi et al. (2006) Raffi et al. (1993) recalibrated
LO large <i>Gephyrocapsa</i>	Vrica-Crotone section ODP Site 967 (Mediterranean) Eastern Mediterranean Equatorial Atlantic Equatorial Pacific (FCO) DSDP Site 607	192 (m) 64.43-64.6 (mcd)	1.608 1.595 (± 0.005) 1.617 1.560 1.46 1.571-1.574	55-56 55-54 55-54	Lourens et al. (1996) Lourens et al. (1998); Raffi (2002) Raffi et al. (2006) Raffi et al. (2006) Raffi et al. (2006) Raffi (2002) recalibrated
disappearance <i>N. pachyderma</i> left-coiling	Vrica-Crotone section ODP Site 967 (Mediterranean) ODP Site 969D (Mediterranean) Eastern Mediterranean DSDP Site 607 (North Atlantic)	258 (m) 44.38 (rmcd) 29.13 (rmcd) 55.77 (mcd)	1.367 1.370 1.371 1.37 1.364	44-43 44-43 44-43	Lourens et al. (1996) Lourens et al. (1998) Lourens et al. (1998) Lourens et al. (2004) this study (data-set of Ruddimann et al.1986)
HO <i>H. sellii</i>	Vrica-Crotone section ODP Site 967 (Mediterranean) Eastern Mediterranean Equatorial Pacific	295 (m) 41.27 (rmcd)	1.24 1.259 1.256 1.34	37 39-38	Lourens et al. (1996) Lourens et al. (1998) Raffi et al. (2006) Raffi et al. (2006)
HO large <i>Gephyrocapsa</i>	Vrica-Crotone section ODP Site 967 (Mediterranean) Eastern Mediterranean Equatorial Atlantic Equatorial Pacific DSDP Site 607 (North Atlantic)	294 (m) 41.22 (rmcd) 50.02 (mcd)	1.238 1.257 (± 0.003) 1.245 1.255 1.24 1.227	37 38-37 37	Lourens et al. (1996) Lourens et al. (1998); Raffi (2002) Raffi et al. (2006) Raffi et al. (2006) Raffi et al. (2006) Raffi et al. (1993) recalibrated
re-appearance <i>N. pachyderma</i> left-coiling	Montalbano Jonico section Vrica-Crotone section 299 (m) ODP Site 967 (Mediterranean) ODP Site 969D (Mediterranean) Eastern Mediterranean DSDP Site 607 (North Atlantic)	17.2 (m) 39.90 (rmcd) 26.01 (rmcd) 49.36 (mcd)	1.206 1.220 1.209 1.203 1.210 1.207	36 37-36 36 36	this study Lourens et al. (1996) Lourens et al. (1998) Lourens et al. (1998) Lourens (2004) this study (data-set of Ruddimann et al.1986)
beginning influx <i>G. crassaformis</i>	Montalbano Jonico section	50.15 (m)	1.148	34	this study
influx <i>G. crassaformis</i>	ODP Site 967 (Mediterranean)	37.76 (rmcd)	1.135		Lourens et al. (1998)
end influx <i>G. crassaformis</i>	Montalbano Jonico section	60.55 (m)	1.119	34	this study
LCO <i>R. asanoi</i>	Montalbano Jonico section ODP Site 964 (Ionian Sea) Core KC01B (Ionian Sea) DSDP Site 607 (North Atlantic) Eastern Mediterranean Equatorial Atlantic	70.95 (m) 37.35 (rmcd) 35.47 (cpd) 44.79 (mcd)	1.086 1.086 1.081 1.101 1.078 1.136	31 31 31 32	Ciaranfi et al. (2010) Maiorano and Marino (2004) recalibrated this study Maiorano and Marino (2004) recalibrated Lourens et al. (2004); Raffi et al. (2006) Lourens et al. (2004); Raffi et al. (2006)
LO <i>G. omega</i> (= re-entrance medium <i>Gephyrocapsa</i>)	Montalbano Jonico section ODP Site 964 (Ionian Sea) Core KC01B (Ionian Sea) Eastern Mediterranean Equatorial Atlantic Equatorial Pacific DSDP Site 607 (North Atlantic)	138.15 (m) 34.31 (rmcd) 32.62 (cpd) 41.32-40.74 (mcd)	0.954 0.957 0.962 0.956-0.985 1.007 1.040 1.018-1.004	25 25 26-25 27	Ciaranfi et al. (2010) Maiorano and Marino (2004) recalibrated Castradori (1992) recalibrated Raffi et al. (2006) Raffi et al. (2006) Raffi et al. (2006) Raffi (2002) recalibrated
HCO <i>R. asanoi</i>	Montalbano Jonico section ODP Site 964 (Ionian Sea) Core KC01B (Ionian Sea) DSDP Site 607 (North Atlantic) Eastern Mediterranean Equatorial Atlantic	162.85 (m) 32.93 (rmcd) 31.335 (cpd) 36.23 (mcd)	0.908 0.902 0.902 0.906 0.901 0.905	23 23 23 23	Ciaranfi et al. (2010) Maiorano and Marino (2004) recalibrated this study Maiorano and Marino (2004) recalibrated Raffi et al. (2006) Raffi et al. (2006)
beginning temp. disap. <i>G. omega</i>	Montalbano Jonico section ODP Site 964 (Ionian Sea) Core KC01B (Ionian Sea) DSDP Site 607 (North Atlantic)	82.65 (m) 30.82 (rmcd) 29.51 (cpd) 33.31 (mcd)	0.828 0.819 0.820 0.821	21-20 21-20 21-20 21-20	this study this study this study (data-set of Castradori, 1992) Maiorano and Marino (2004) recalibrated
end temp. disap. <i>G. omega</i>	Montalbano Jonico section ODP Site 964 (Ionian Sea) Core KC01B (Ionian Sea) DSDP Site 607 (North Atlantic)	155.45 (m) 29.885 (rmcd) 28.505 (cpd) 31.64 (mcd)	0.771 0.782 0.774 0.781	19-18 19-18 19-18 19	Ciaranfi et al. (2010) this study this study (data-set of Castradori, 1992) Maiorano and Marino (2004) recalibrated

Sample #	Material	K/Ca	Total fusion Age (ka) ± 2	N	MSWD	Weighted Mean Age ± 2
V3	sanidine	32.89	803.5 ± 22.6	11 of 11	0.55	801.2 ± 19.5

J value calculated related to 28.4 Ma for the Taylor Creek sanidine
Age in bold is preferred

a

Figure 4. Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating results for the volcanoclastic layer V3 (a). $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra from the V3 volcanoclastic layer (b).

below V5, whose age was determined at 719.5 ± 12.6 ka (Ciaranfi et al., 2010). At around the Lower - Middle Pleistocene boundary interval several volcanic sources were active in Italy (Ventotene-Santo Stefano islands, Vulture volcano, Sabatini volcanoes, Aeolian seamounts, Linosa and Ustica islands – Peccerillo, 2005 and references therein). Unfortunately, the absence of chemical data on the glass composition makes difficult any inference on the source of volcanoclastic layer V3. In fact, a tephra layer of comparable age (802 ± 8 ka), possibly emplaced from an ancient and poorly known activity of Sabatini volcanoes, was found in several drill-holes in the Tiber River coastal alluvial plain (Karner et al., 2001; Florindo et al., 2007). The former authors, however, document a low size pyroclastic fall event for the Tiber River tephra layer, which is not likely compatible with a dispersal from Sabatini volcanoes reaching the Montalbano area.

As discussed in Ciaranfi et al. (2010), the astronomical tuning of the Montalbano Jonico section (Figures 5–6) was achieved using a 3 ky time lag between the midpoints of each individual sapropel and their correlative precession minima, in the lower part of the section, and the visual comparison of the $\delta^{18}\text{O}$ pattern with the record available at the Mediterranean ODP Site 975, and the $^{39}\text{Ar}/^{40}\text{Ar}$ age of V5 layer,

in the upper part of the section. Slight modifications included in this paper follow the new $^{39}\text{Ar}/^{40}\text{Ar}$ age of V3 layer dated at 801.2 ± 19.5 ka. The astronomical calibration of the Montalbano Jonico section shows that it covers an interval from 1.240 Ma to 0.645 Ma (Figure 6) and provides accurate ages for the biostratigraphic data.

Astronomical Age of Calabrian Biostratigraphic data

The chronology of the lower Calabrian biostratigraphic data, widely discussed in several papers (Raffi, 2002; Lourens et al., 2004; Raffi et al., 2006), is summarized in Figure 7 and Table 2. In the present paper we discuss only the new data collected in the Montalbano Jonico section and correlated records in the sedimentary interval corresponding to the upper part of the Calabrian Stage. In addition, we provide a new chronology of bioevents at DSDP Site 607 for the entire Calabrian interval according to the updated age model of Lisiecki and Raymo (2005).

Reappearance of *N. pachyderma* left-coiling

The pattern of *N. pachyderma* left-coiling offers multiple biohorizons through the whole Calabrian Stage as can be observed in Figure 8. The taxon has a first abundance increase associated with MIS 64 followed by several abundance peaks during glacial marine isotope stages from MIS 64 to 44 (Figure 8), as previously observed by Lourens et al. (1996; 1998). Abundance peaks are absent through

Figure 5. Age–depth profile of Montalbano Jonico composite section. The black diamonds represent the tie-points while the white ones are the position of the volcanoclastic layers. For sediment symbols and abbreviations refer to Figure 3.

Figure 6. Abundance patterns of calcareous plankton index species and oxygen isotope stratigraphy of Montalbano Jonico section plotted versus age based on astronomical calibration of Ciaranfi et al. (2010) and this study. Position of biohorizons are also traced for comparison on the oxygen isotope Mediterranean stacked record of Lourens (2004) according to Mediterranean biochronology in Lourens et al. (1998), Lourens et al. (2004), Maiorano and Marino (2004), Raffi et al. (2006), Lourens et al. (2006), Ciaranfi et al. (2010). IG: large Gephyrocapsa; Npl: *N. pachyderma* left-coiling; Gc: *G. crassaformis*; Ra: *R. asanoi*; Go: *G. omega*. For sediment symbols and abbreviations see Figure 3.

MIS 42-38 and i-cycles 132-114 (interval of temporary disappearance in Figure 8) and re-occur (reappearance event) from MIS 36 upwards. The reappearance of *N. pachyderma* left-coiling at Montalbano Jonico section has an astronomical age of 1.206 Ma, in good agreement with that found in other Mediterranean areas (ODP Sites 967 and 969 at 1.209 Ma and 1.203 Ma respectively) (Table 2). The position of this bioevent relative to sapropel 28 (i-112) at Montalbano Jonico and Site 967 is straightforward (Figure 8) and further confirms the astronomical tuning of the section. A slightly older age for the event (1.220 Ma) is known in the Vrica-Crotone section (Lourens et al., 1996). The interval of temporary disappearance of the taxon is not just a Mediterranean feature, as revealed by the Atlantic DSDP Site 607 (Figure 8). Based on the abundance pattern of *N. pachyderma* left-coiling of Ruddiman et al. (1989) and on the time series of Site 607 (Lisiecki and Raymo, 2005), we provide the position and age of disappearance and reappearance of *N. pachyderma* left-coiling at the North Atlantic site (Figure 8; Table 2). An age of 1.207 Ma for the reappearance event recorded in the North Atlantic site, is highly consistent with the age estimate of the event in the Montalbano Jonico section.

Influx of *G. crassaformis*

Various influxes of *G. crassaformis* have been identified in the lower part of the Calabrian Stage (Lourens et al., 1998) in the Mediterranean area, mostly in deep-sea sections (Figure 8), although quantitative patterns are not available. Here we report quantitative distribution of the influx of the species recorded in the Montalbano Jonico section which is the only record exposed on land known so far. The short influx of *G. crassaformis* extends from 1.148 Ma to 1.119 Ma, within MIS 34, in agreement with the results obtained by Lourens et al. (1998) for the ODP Mediterranean Sites 967 and 969

(at 1.135 Ma and 1.140 Ma, respectively). The high sedimentation rate of the section (Figure 5) and the high resolution sampling reveal the temporal extent of the influx (about 30 ky) and a more accurate calibration of the event with respect to previous data.

Highest Occurrence of large Gephyrocapsa (> 5.5 µm)

The absence of large geophyrocapsids (> 5.5 µm) from the bottom of the Montalbano Jonico section is unequivocal, thus indicating a stratigraphic interval younger in age than their disappearance. It is also in agreement with the calibration of the base of the Montalbano Jonico section at 1.240 Ma. The absence of large geophyrocapsids is consistent with the calibration of the HO event at Site 967 (Figure 8; Table 2) where it has an age of 1.257 Ma (Lourens et al., 1998) and is associated with MIS 38/37 (Raffi, 2002). The HO of large geophyrocapsids is considered a reliable event, isochronous in mid- and low-latitude areas (Raffi et al., 1993, 2006; Raffi, 2002). In the Eastern Mediterranean deep-sea sections it has been dated at 1.245 Ma (Lourens et al., 2004; Raffi et al., 2006), while in the Atlantic and Pacific Ocean it has an age of 1.255 Ma and 1.24 Ma, respectively. A slightly younger age (1.227 Ma) is recorded at the Atlantic Site 607 (Table 2) and at the Vrica-Crotone section (1.238 Ma, Table 2).

Lowest Common Occurrence and Highest Common Occurrence of *R. asanoi*

The LCO and HCO of *R. asanoi* have been recorded previously in the Montalbano Jonico section (Maiorano et al., 2004; Ciaranfi et al., 2010). Calibrations and the reliability of these bioevents in Mediterranean and oceanic areas have been discussed in Maiorano and Marino (2004), Raffi et al. (2006) and Ciaranfi et al. (2010). In Core KC01B new data (with sampling resolution of 1 sample per

Figure 7. Oxygen isotope chronologies of the astronomically tuned Vrica-Crotone and Montalbano Jonico sections recovering the entire Calabrian Stage. Position of biohorizons are also traced for comparison on the oxygen isotope Mediterranean stacked record of Lourens (2004) and on Pacific (Mix et al., 1995a,b; Shackleton et al., 1995) and Atlantic (Bickert et al., 1997) $\delta^{18}\text{O}$ benthic records according to biochronology in Lourens et al. (1998), Raffi (2002), Lourens et al. (2004), Maiorano and Marino (2004), Raffi et al. (2006), Lourens et al. (2006), Ciaranfi et al. (2010) as reported in Table 2. Summer insolation 65°N (La04_{1,1}) from Laskar et al. (2004). Npl: *N. pachyderma* left-coiling; mG: medium *Gephyrocapsa*; Cm: *C. macintyreii*; IG: large *Gephyrocapsa*; Hs: *H. sellii*; Gc: *G. crassaformis*; Ra: *R. asanoi*; Go: *G. omega*. LO: Lowest Occurrence; HO: Highest Occurrence; LCO: Lowest Common Occurrence; HCO: Highest Common Occurrence; reap.: reappearance; disap.: disappearance; td: temporary disappearance. For sediment symbols see Figures 2-3.

2-4 ky) are presented on the distribution pattern of calcareous nannofossil *R. asanoi* (Figure 9). This species, in fact, was not previously recorded in this section. The results are plotted against the astronomical age model of the core (Lourens, 2004). The data-set is compared with the temporal distribution at the Montalbano Jonico section, and with the previous results of Maiorano and Marino (2004) at ODP Site 964 and DSDP Site 607 based on the adopted age models. Both the LCO and HCO of *R. asanoi* display a high degree of correlation between the Montalbano Jonico section and the other records, mainly in the Mediterranean area, as it is clear from Figure 9 and Table 2. A slightly older age of the LCO event is obtained at DSDP Site 607 (Table 2), possibly due to lower sampling resolution in this interval (Figure 9); on the other hand, a consistent discrepancy

is observed with the equatorial Atlantic calibration (Table 2). As discussed in Raffi (2002) and Maiorano and Marino (2004), different calibrations of this event may derive from different taxonomic concepts or from the discontinuous occurrences of the species in the lower part of its range. The age of 0.908 Ma detected at the Montalbano Jonico section for the HCO of *R. asanoi* is remarkably in accordance with both Mediterranean and oceanic records (Figures 7, 9; Table 2).

Lowest Occurrence and temporary disappearance of *G. omega*

The LO of *G. omega* (= re-entrance medium *Gephyrocapsa*) in the Montalbano Jonico section has been dated at 0.954 Ma (Ciaranfi

Figure 8. Mediterranean stacked record of Lourens (2004) and summer insolation $65^{\circ}N$ (La04_{1,1}) from Laskar et al. (2004) are compared with the sapropel patterns, temporal distribution of *Neogloboquadrina pachyderma* left-coiling and oxygen isotope time series at ODP Site 967 (Kroon et al., 1998), Lourens et al., 1996; Lourens et al., 1998), Montalbano Jonico section (Ciaranfi et al., 2010 and this study) and DSDP Site 607 (Ruddiman et al., 1989; Lisiecki and Raymo, 2005). Abundances of *N. pachyderma* left-coiling are related to the total of left and right-coiling *neogloboquadrins* at Site 967 and to the total planktonic assemblage at Vrica-Crotone and Montalbano Jonico sections and Site 607. Position of biostratigraphic horizons is from Lourens et al. (1998) and Raffi (2002) at Site 967, from Lourens et al. (1996, 1998) at Vrica-Crotone section, from Ciaranfi et al. (2010) and this study for Montalbano Jonico section and from Raffi (2002), Maiorano and Marino (2004) and this study at Site 607. At Site 967 black intervals indicate sapropels, shaded areas less-distinct sapropels and jagged pattern slumped interval as in Lourens et al. (1998). For abbreviations refer to Figure 7.

Figure 9. Temporal distribution of *R. asanoi* and oxygen isotope time series at Montalbano Jonico section and Core KC01B, ODP Site 964 and DSDP Site 607. Numerical abundance patterns are from Ciaranfi et al. (2010) at Montalbano Jonico section, from this study at Core KC01B and from Maiorano and Marino (2004) at ODP Site 964 and DSDP Site 607. Abundances are plotted versus age according to oxygen isotope time series of Ciaranfi et al. (2010) and this study at Montalbano Jonico, Lourens (2004) at Core KC01B and 964 and Lisiecki and Raymo (2005) at Site 607. Mediterranean $\delta^{18}\text{O}$ planktonic stacked record of Lourens (2004), Pacific (Mix et al., 1995a,b; Shackleton et al., 1995) and Atlantic (Bickert et al., 1997) $\delta^{18}\text{O}$ benthic records are also shown for comparison. For abbreviations refer to Figure 7.

Figure 10. Temporal distribution of *G. omega* and oxygen isotope stratigraphy at Montalbano Jonico on-land section and Core KC01B, ODP Site 964 and DSDP Site 607. Numerical abundance patterns are from Ciaranfi et al. (2010) at Montalbano Jonico section, Castradori (1992) at Core KC01B and Maiorano and Marino (2004) at ODP Site 964 and DSDP Site 607. Abundances are plotted versus age according to oxygen isotope time series of Ciaranfi et al. (2010) and this study at Montalbano Jonico, Lourens (2004) at cores KC01B and 964 and Lisiecki and Raymo (2005) at Site 607.

et al., 2010) and is in accordance with the considered Mediterranean records (Figure 10). However, the event is widely documented both in Mediterranean and oceanic records as a diachronous event (Raffi et al., 1993, 2006; Raffi, 2002) as also detectable from Figure 7. An interval of temporary disappearance of *G. omega* occurs in the Montalbano Jonico section (Ciaranfi et al., 2010) and is correlatable to td2 of Maiorano and Marino (2004). The beginning and end of the temporary disappearance of *G. omega* have been dated at 0.828 and 0.771 Ma, respectively (recalibrated from Ciaranfi et al., 2010). The interval of temporary disappearance of *G. omega* is still poorly documented in deep-sea sections. Reconsideration of the distribution pattern of *G. omega* (against the updated age model at Core KC01B, Site 964 and Site 607), highlights a good correlation of the interval of temporary disappearance among the

selected sections (Figure 10, Table 2), spanning from MIS 21-20 to MIS 19-18. It is noteworthy that the end of the temporary disappearance of *G. omega* represents the only calcareous plankton event which may approximate the Matuyama/Brunhes reversal in the marine records (Figure 7).

The 'Ionian' Stage: Middle Pleistocene

The Early-Middle Pleistocene Subseries boundary and the 'Ionian' Stage still lack a formal ratification. The name Ionian as the Stage representing the Middle Pleistocene was first introduced by Cita and Castradori (1995) and Van Couvering (1995) and its present use basically follows Cita et al. (2006) and Cita et al. (2008). According

Montalbano Jonico section

Figure 11. Oxygen isotope record and paleobathymetric changes from Montalbano Jonico section and correlation with oxygen isotope stratigraphy of Lisiecki and Raymo (2005) through MIS 19 (a). Radiometric and biostratigraphic constraints (Ciaranfi et al., 2010 and this study) and diagnostic fossil paleocommunity (D'Alessandro et al., 2003; Girone and Varola, 2001) are indicated. (b) Detail of lithological sequence of Montalbano Jonico section through the interval including MIS 19, with positions of characteristic marker layers.

to the “Working Group of the Early-Middle Pleistocene Boundary” - Subcommission for Quaternary Stratigraphy (32nd International Geological Congress in Florence in 2004), the Early-Middle Pleistocene boundary should be defined in a marine section exposed on land at a point “close” to the Matuyama/Brunhes reversal (Head et al., 2008b). Several opinions (Richmond, 1996; Pillans, 2003; Head and Gibbard, 2005) concur in considering the Matuyama-Brunhes paleomagnetic Chron boundary as the primary chronostratigraphic guide for establishing the Early-Middle Pleistocene boundary, although it is only one of multiple criteria that will be used for local, global and regional correlation of the boundary (Head et al., 2008b). At present, the selection of a suitable section for the GSSP of Early-Middle Pleistocene boundary has not been made.

The age of Matuyama-Brunhes reversal is known to have no unanimous agreement; it has been recently dated at *ca.* 789 ka by Quidelleur et al. (2003), *ca.* 774 ka by Channell et al. (2004), *ca.* 776 ka by Coe et al. (2004) and Singer et al. (2008). An age of 781 ka has been estimated in the astronomical-tuned time scale (Lourens et al., 2004). The Matuyama-Brunhes boundary is known to be closely correlated to MIS 19 (Shackleton et al., 1990; Lisiecki and Raymo, 2005). With regards to the marine isotope substages associated with MIS 19 (19.3, 19.2, 19.1) recognized in few $\delta^{18}\text{O}$ planktonic records, the Matuyama-Brunhes reversal has been recorded between marine isotope substages 19.3 and 19.2 (Bassinot et al., 1994), between marine isotope substages 19.3 and 18.4 (Channell et al., 2004), or in the middle part of MIS 19, between marine isotope substages 19.3 and 19.1 (Capraro et al., 2005). The lack of magnetostratigraphic record at Montalbano Jonico section does not help to improve the correlation between Matuyama/Brunhes reversal and MIS 19. Furthermore, the substage subdivision of MIS 19 is rarely recognized in the planktonic and benthic $\delta^{18}\text{O}$ reference records and it is not proposed at the Montalbano Jonico section. On the other hand, the shift from heavier to lighter $\delta^{18}\text{O}$ values, associated with the onset of MIS 19, is clearly displayed in the benthic $\delta^{18}\text{O}$ record at Montalbano Jonico section (Figure 11) and it may represent an alternative and suitable horizon for the definition of the GSSP of the ‘Ionian’ Stage. Variations in $\delta^{18}\text{O}$ mainly reflect astronomically controlled glacial cyclicity and are a powerful tool for global, high-resolution chronostratigraphic correlation. Although Marine Isotope Stage boundaries are not formally defined, a benthic $\delta^{18}\text{O}$ “type section” obtained from 57 globally distributed records, the so-called stack record, is available for the last 5.3 Ma (Lisiecki and Raymo, 2005) with the aim to provide a common timescale of the Marine Isotope Stages. The isotopic signals are considered acceptable for the definition of boundary stratotypes (Remane et al., 1996) and, in fact, this practice has been recently adopted for the definition of the GSSP of the Serravallian Stage (Hilgen et al., 2009).

The onset of MIS19 in the Montalbano Jonico section is very close to the radiometrically dated volcanoclastic layer V3 (801.2 ± 19.5 ka) (Figure 11a) and occurs between 799 and 795 ka. This tuning is consistent with the calibration of MIS 19/20 boundary at 790 ka (Lisiecki and Raymo, 2005). In terms of calcareous nannofossils, MIS 19 in the Montalbano Jonico section falls between the beginning and end of the temporary disappearance interval of *G. omega*, dated at 0.828 Ma and 0.771 Ma, respectively. The sedimentary interval containing MIS 19 is represented by outer shelf deposits recording cyclic sea level changes (Figure 11a). A maximum flooding surface, highlighted by the occurrence of *Neopycnodonte* paleocommunity (D’Alessandro et al., 2003), has been documented in considerable

detail and correlates with MIS 19. It is also accompanied by the occurrence of the mesopelagic species *Bonapartia pedaliota* (Girone and Varola, 2001), a tropical-sutropical Atlantic teleostean (otolith-based) species (Figure 11b). Sedimentary evidence of glacio-eustatic sea level rise correlated with MIS 19 and the Matuyama/Brunhes reversal is also clearly recognized in alluvial and shallow-marine depositional systems in widely different geographic areas (e.g. Pillans et al., 1998; Naish et al., 2005; Massari et al., 2007; Florindo et al., 2007), thus supporting the widespread traceability of this marine isotope stage.

Conclusion

The Vrica-Crotone and Montalbano Jonico sections are the only two astronomically-tuned marine records exposed on-land recovering the entire time interval subtended by the proposed Calabrian Stage. The composite record, excluding the Gelasian portion in the Vrica section, extends from the Calabrian GSSP (1.806 Ma) at the top of sapropel “e”, MIS 65-64 transition and i-cycle 176, to the MIS 17-16 transition and i-cycle 60 (0.645 Ma). All the calcareous plankton bioevents occurring through the whole record are accurately tuned and their positions are strongly comparable with the available Mediterranean biochronology and oceanic data set.

The Vrica-Crotone section contains the proposed GSSP of the Calabrian Stage, located at the top of sapropel “e” and astronomically dated at 1.806 Ma (Lourens et al., 2004). The Montalbano Jonico section contains the MIS 19 which closely corresponds to the Matuyama/Brunhes reversal, a guide criterion for the definition of the GSSP of the Early/Middle Pleistocene (Richmond, 1996; Pillans, 2003; Head and Gibbard, 2005). Despite the unreliable magnetostratigraphic record of the Montalbano Jonico section, for which full reasons are given (Sagnotti et al., 2010), we propose that the onset of MIS 19 represents a valuable horizon for the definition of the GSSP of the Middle Pleistocene in the section. Indeed, the sedimentary interval containing MIS 19 is very well exposed (Figure 11), is characterized by diverse and diagnostic fossil record and is chronologically constrained by means of multiple independent age-significant tools. These features suggest that the Vrica-Crotone and Montalbano Jonico sections can be considered a suitable composite record for the Calabrian unit-stratotype.

Acknowledgements

The authors wish to thank Maria Bianca Cita, Philip Gibbard and Martin Head for their careful revision and valuable suggestions which greatly improved the manuscript. Maria Bianca Cita is doubly acknowledged for her good spirits in encouraging the research on Quaternary stratigraphy and her enthusiastic role in leading the proposal for the redefinition of the Calabrian Stage on behalf of the International Subcommission on Quaternary Stratigraphy. We are grateful to all researchers who have been intensively involved in the study of the Vrica section and whose contributions were very helpful for the accomplishment of the present paper. Constructive discussions with Marcello Tropeano have also improved the manuscript. Results on deep-sea cores are based on samples provided by the Deep-Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP). We are also grateful to Gert J. De Lange who made possible the sampling

of Core KC01B at the Department of Earth Sciences – Geochemistry, Utrecht University. Maureen Raymo is greatly acknowledged for sending updated oxygen isotope chronology of Site 607 for the last 2 Ma. This study was financially supported by “Fondi Ateneo” 2009 (University of Bari) granted to R. La Perna. This work is ISMAR-Bologna scientific contribution no.1703.

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