1. INTRODUCTION

The Montalbano Jonico section (MJS) is a candidate for the global boundary stratotype section and point (GSSP) of the Middle Pleistocene Subseries (Ciaranfi et al., 1997) due to the detailed biostratigraphic, climatostratigraphic and chronological constraints arising from multidisciplinary studies conducted over the past twenty years (Ciaranfi et al., 1994; 1996; 1997; 2001; 2010; Marino, 1996; Girone & Varola, 2001; D’Alessandro et al., 2003; Stefanelli, 2003; 2004; Maiorano et al., 2004; 2008; 2010; Stefanelli et al., 2005; Girone et al., 2013a; Sagnotti et al., 2014; Aiello et al., 2015; Bertini et al., 2015; Manno et al., 2015; Petrosino et al., 2015) and meets most of the requirements mentioned in Remane et al. (1996) for the selection of a GSSP. The primary criterion for defining the Lower-Middle Pleistocene boundary was indicated as a point to be selected in a marine succession close to the Matuyama-Brunhes boundary (MBB) (Richmond, 1996; Pillans, 2003; Head & Gibbard, 2005; Cita et al., 2006; Head et al., 2008; Head & Gibbard, 2015a). The MBB is a geomagnetic polarity reversal characterised by different age assignments (see syntheses in Channell et al., 2010; Head & Gibbard, 2015b), polarity transition lasting up to 8 kyr (Channell & Kleiven, 2000; Channell et al., 2004; Leoniardt & Fabian, 2007), associated short-lived precursor(s) (Hyodo et al., 2006, 2011; Wang et al., 2006; Yang et al., 2010; Channell et al., 2010; Sagnotti et al., 2014), and by a slightly diachronous character also depending on latitudinal and longitudinal places (Clement, 2004; Leoniardt & Fabian, 2007). Change in sedimentation rate (and related age-depth model), and the influence of burrowing may produce differences in magnetic recording efficiency and timing (magnetic lock-in depth) of remanence acquisition, possibly introducing uncertainties in the natural magnetization process in marine and continental sediments and age-assignment of the MBB (deMenocal et al., 1990; Channell et al., 2010; Suganuma et al., 2010; Roberts et al., 2013; Snowball et al., 2013; Head & Gibbard, 2015b). When correlated to marine oxygen isotope stratigraphy (MIS 19, Shackleton et al., 1990), in sedimentary successions the MBB may fall at the base, in the middle, or in the upper part of stage 19. On the other hand, climatostratigraphy during MIS 19 is revealed to be a critical means to improve
knowledge on climate evolution during this stage and to enhance correlation between marine and terrestrial realms at the global scale. Moreover, according to some authors, paleointensity minima during MBB seem to have affected change in cosmogenic ray flux and Earth’s climate (Kitaba et al., 2012; Hyodo & Kitaba, 2015). This aspect strengthens the widely accepted importance of climate in Quaternary stratigraphy, the stage boundaries being characterised by biological/physical/geochemical documentation of profound changes in the global climate. Multiple chrono/climatostratigraphic constraints are then necessary in the interval including MIS 19 and the Matuyama-Brunhes transition in order to have helpful and constructive tools aiding local/regional/global (possibly land–marine) correlation, which is a crucial feature for the selection of GSSP (Remane et al., 1996; Gradstein et al., 2003).

The aim of this paper is to provide a synthesis of recent data sets collected throughout MIS 19 at Montal-
bano Jonico and supply preliminary new results which improve the reliability of the numerous chronostratigraphic and clinostratigraphic markers recognized in the section close to the Early-Middle Pleistocene boundary. A synthesis of these results was presented at the “Scientific Days” (Florence, June 18-19, 2015) organized by AIQUA (Italian Association for Quaternary Study).

2. THE MONTALBANO JONICO SECTION

The Lower-Middle Pleistocene composite section of Montalbano Jonico crops out in the Lucania Basin (Balduzzi et al., 1982), a minor basin of the foredeep (Bradano Trough, in Casnadi, 1988) between the Apennines Chain and the Apulia Foreland (Fig. 1). The MJS is about 450 m thick and consists of a coarsening upward succession formed by hemipelagic silty clays and, in its upper part, by sandy clays (Ciaranfi et al., 2010) (Fig. 1). The whole section represents the regressive part of a third-order cycle with several fourth and fifth-order cycles mainly induced by climate changes (Ciaranfi et al., 1997; 2001).

Stable oxygen isotope analyses performed throughout the entire succession on planktonic (Globigerina bulloides) and benthic (Cassidulina carinata) foraminifer tests (Brilli et al., 2000; Ciaranfi et al., 2010), combined with high resolution quantitative calcareous plankton biostratigraphy (Marino, 1996; Maiorano et al., 2004; Ciaranfi et al., 2010; Maiorano et al., 2010; Girone et al., 2013a), 40Ar/39Ar data on volcaniclastic layers V3, V4 and V5 (Ciaranfi et al., 2010; Maiorano et al., 2010; Girone et al., 2013a), for wide-scale correlation and therefore may provide multiple constraints suitable for the selection of the GSSP. Focusing on the MIS19, it is clearly depicted between MIS 20 and MIS18 at the MJS by the planktonic and benthic δ18O records (Ciaranfi et al., 2010; Maiorano et al., 2010). The interval straddling MIS 19 is very well chronologically constrained, bracketed by the 40Ar/39Ar ages of two volcaniclastic layers: V3 (801.2±19.5 ka) in MIS 20, and V4 (773.9±1.3 ka) in MIS 19. The age of V4 is very close to the age of the MBB, referred to 773 ka according to Channell et al. (2010). The beginning and end of the second temporary disappearance of the coccolithophore Gephyrocapsa omega, at 829 ka and 752.76 ka respectively (Fig. 2e), provide valuable bio-events for long distance correlation as they always enclose MIS 19 in Mediterranean Sea and Atlantic Ocean records (Maiorano & Marino, 2004; Maiorano et al., 2004). Additional higher resolution oxygen isotope studies across MIS 19 are in progress at the MJS and support the excellent climate signal in the section (Nomade et al., 2015).

The main chronostratigraphic constraints are shown in Figures 2 and 3 and discussed below.

3. STRATIGRAPHIC AND PALEENVIRONMENTAL CONSTRAINTS THROUGH MIS 21-MIS 18

Recent multidisciplinary studies improved knowledge across the interval from MIS 21 to MIS 18 time (Aiello et al., 2015; Bertini et al., 2015; Marino et al., 2015; Petro sino et al., 2015), based on orbital to millennial scale marine and terrestrial biological data set (pollen, ostracod, benthic micro- and macroinvertebrates), mainly obtained by the analysis of the same samples studied for oxygen isotope stratigraphy (Fig. 2). Some of the taxa recorded from the rich and diverse micro- and macrofossil assemblages at MJS are illustrated in Plates 1 and 2. Chemical studies on juvenile vitric fragments and mineral phases from the volcaniclastic layers allowed these marker levels to be more exhaustively described in terms of their potential source and correlation to other tephra layers in both south-central Italy lacustrine successions and in marine onland and deep-sea cores within a Lower-Middle Pleistocene Mediterranean tephrostratigraphic framework.

The fine chronostratigraphic and paleoenvironmental outline obtained at the MJS makes the section an excellent candidate for the Lower-Middle Pleistocene GSSP in spite of an absent paleomagnetic signal (including the MBB) throughout the section because of remagnetization (Sagnotti et al., 2014). The several events recorded in the Ideale section have high potential for wide-scale correlation and therefore may provide multiple constraints suitable for the selection of the GSSP.
glacial MIS 20. Calcareous plankton data (Maiorano et al., 2016) support the prominent cold climate phase recording the higher abundance of arctic-subarctic Coccolithus pelagicus ssp. pelagicus and Neogloboquadrina pachyderma left-coiling, and the lowest values of the planktonic foraminifera derived Sea Surface Temperature-SST curve (M. Kucera, work in progress) in the uppermost glacial MIS 20. Similar patterns in key calcareous plankton taxa are documented in the Mediterranean Sea at the glacial-interglacial transition during the mid-Brunhes interval (Girone et al., 2013b; Maiorano et al., 2013; Capotondi et al., 2016), demonstrating that the Mediterranean signal of short-lived global climate change may be extended down to MIS 20/MIS 19 deglaciation. Such result, in agreement with the δ18O pattern at the transition MIS 20/MIS 19 (Fig. 2e), could represent the Younger Dryas-like cold and dry event (Giaccio et al., 2015); however the ongoing higher resolution oxygen isotope study (Nomade et al., 2015) and calcarceous plankton and pollen analyses (Maiorano et al., 2016) may give more conclusive detail on climate evolution at this time. A minimum in the benthic foraminifera paleodepth pattern (Stefanelli, 2003, 2004) is also recorded very close to the cold and arid event highlighting a prominent sea level fall (Fig. 2j). The event, combined with the high-amplitude change in benthic foraminifera and ostracod-derived paleodepth curves recorded just above, enables the identification of Termination IX (Figs. 2, 3) which is considered the most prominent marker in the δ18O record before the MBB in MIS 19 (Channell et al., 2010). These results together provide the first documentation in Mediterranean onland marine sediments of Termination IX, a characteristic climate signal in global ocean records (i.e. Lisiecki & Raymo, 2005). The prominent sea level change associated with Termination IX is correlative with the boundary between the third order cycles TB3.8-TB3.9 (Haq et al., 1987) at the major sequence boundary “Lo1” (ca. 0.8 Ma, Hardenbol et al., 1998; ca. 0.78 Ma, Snedden & Liu, 2010) and is recorded in the curve of global sea level of Bintanja & van de Wal (2008) (Fig. 2k). Termination IX may be also recognizable in terrestrial sediments (i.e. Florindo et al., 2007) supporting its value in climatostratigraphy.
3.2. MIS 19.3, Maximum Flooding, Climate Optimum, and Maximum Depth

The $\delta^{18}O$ pattern and all biological proxies clearly record the onset of MIS 19 (Fig. 2) which is also visible in the color sediment change at Termination IX in the Ideale section (Figs 1, 3). The deposition of darker sediments characterizes the MIS 19 interval as may be expected during an interglacial phase and high sea level, when water column stratification could have reduced oxygen levels and thereby increased organic matter preservation on the sea floor. Moreover, the $\delta^{18}O$ pattern distinctively describes substages 19.3, 19.2, and 19.1 (Figs. 1, 3). All biological data from both marine (i.e. Marino et al., 2015) and terrestrial (Bertini et al., 2015; Toti, 2015) realms support the substage subdivision indicating 19.3 as the warmest, based on the elevated values in PTI and AP curves. Increases in the warm-water calcareous plankton taxa confirm the peculiar climate behavior of substage 19.3. In detail, calcareous plankton records the highest abundance of warm water
taxa in the lower portion of substage 19.3 (Maiorano et al., 2016) in correspondence with the lowest δ¹⁸O value (ca. 782 ka), suggesting a climate optimum in the sea surface waters. During the 780.56-777.31 kyr interval, the presence of tropical-subtropical mesopelagic teleostean fish *Bonapartia pedaliota* (Girone & Varola, 2001) (Plate 1, O) suggests warmer conditions deeper in the water column; the highest percentages of *Quercus* (here included among the AP, see Bertini et al., 2015 for detail) and PTI, are recorded contemporaneously (Fig. 2f). Concomitantly, the maximum flooding is indicated by the occurrence of a *Neopycnodonte cochlear* community (D’Alessandro et al., 2003) (Figs. 2e, 3, Plate 1, D-L). It is a deep-water oyster forming encrusting clusters, most probably thriving under conditions of low sedimentation rate, as suggested by the ecological data on a congener species (Wisshak et al., 2009; Gofas et al., 2010). Such environmental conditions are possibly related to the rapid sea level rise after deglaciation.

The maximum depth follows the maximum flooding (ca. 777.3 ka-ca. 773.2 ka), and it is highlighted by the benthic invertebrate communities (D’Alessandro et al., 2003) which record dispersed macrobenthic fauna and the occurrence of benthal taxa such as *Discospirina italica* (Plate 1, A-C), a large miliolid foraminifer from deep waters (Gooday et al., 2013), the mollusks *Dentalium agile*, *Cadulus ovulum*, *Neilonella pusio* and *Delecostephanus vitreus*, typical of Pleistocene bathyal assemblages (Di Geronimo and La Perna, 1997); this phase probably reflects higher sedimentation rate and deeper waters which prevented the development of the *Neopycnodonte* (*N. cochlear*) community. The occurrence of the bathyal ostracod *Krithe compressa* is consistent with deeper environment. Therefore, this paleocommunity indicates a transition to a slope setting (*"Discospirina, Nassarius"* communities in D’Alessandro

et al., 2003) during a sea-level high stand, in good agreement with the major deepening during MIS 19 suggested by benthic foraminifera (Stefanelli, 2003) and ostracod assemblages (Aiello et al., 2015) from ca. 779 ka to 773 ka (Marino et al., 2015), close to the increase in the values of pollen distality index (Bertini et al., 2015) (Fig. 2h).

3.3. End of full interglacial, MIS 19.2-19.1 towards MIS 18

The end of substage 19.3 is marked by the increase of steppe and halophyte elements associated with the slightly higher values in the δ¹⁸O record, during substage 19.2, at about 771.8 ka, just above the V4 layer (Fig. 2e-g). The signal of a decrease in sea-surface temperature is also recorded in the calcareous plankton assemblage (Maiorano et al., 2016), since a distinct drop occurs in the abundance of the warm water taxa. A contemporaneous decrease in the pattern of a synthetic (modeled) reconstruction of Greenland temperature (Barker et al., 2011) is evident (Fig. 2a). Upwards, in MIS 19.1, again warm and humid conditions are inferred by pollen data (increase in arboreal mesothermal taxa, Fig. 2g) (Bertini et al., 2015), according to lighter values in δ¹⁸O (Fig. 2e). An upward decreasing trend in mesothermal arboreal taxa parallels the increase of open vegetation taxa concomitant with heavier δ¹⁸O values, thus marking the beginning of the climate deterioration associated with MIS 18. Distinct fluctuations in isotope curve and biological proxies, and in sediment color as well (Figs. 1-3), are also recorded in MJS during this glacial inception. They are in good agreement with the IRD and oxygen patterns at the North Atlantic Site 980 (Fig. 2c-d), and with the synthetic reconstruction of Greenland temperature variability (Fig. 2a), evidencing global features of suborbital climate variation widely documented in oceanic and lacustrine (i.e. Wright & Flower, 2002; Kleiven et al., 2011; Giaccio et al., 2015), and ice core (i.e. Jouzel et al., 2007; Pol et al., 2010; Barker et al., 2011) records. A better understanding of climate evolution at the end of the full interglacial MIS 19, considered the best analogous of the Holocene (Tzedakis et al., 2012; Yin & Berger, 2012), is crucial for evaluating the temporal extent of the current interglacial and for future climate prediction.

4. CONCLUSIONS

The MJS sedimentary succession provides an exceptional data-set to trace the main paleoenvironmental and climatic changes through MIS 37-MIS 16 in the central Mediterranean, a historical key area for the study of Quaternary stratigraphy and climate. The timing and mode of such changes are examined closely in the interval MIS 20-MIS 18, and correlated with climate fluctuation from globally-distributed records. The integrations of continental (pollen) and marine (ostracods, benthic and planktonic foraminifera, coccolithophores, teleostean fishes, mollusks) proxies allows us to document, up to millennial scale, the nearly contemporaneous response to paleoenvironmental events in the two biological domains, providing an invaluable tool for marine-terrestrial correlation. Multiple chrono- and climato-stratigraphic constraints are recorded and the most important are synthesised in Fig. 3: a) coldest phase in the uppermost MIS 20; b) Termination IX; c) substages 19.3, 19.2, 19.1; d) events of maximum flooding, climate optimum, and maximum depth; e) end of the second temporary disappearance of Gephyrocapsa omega; f) radiometric age of volcanoclastic layers V3 and V4 bracketing MIS 19.

The plethora of data for the MIS 20 to MIS 18 interval collected in the continuous succession (Ideale section) makes it possible to consider the MJS highly suitable for hosting the GSSP of the Middle Pleistocene Subseries and its associated stage. In fact, it meets most of the requirements cited in Remane et al. (1996) for a GSSP:

i) geological, i.e. exposure over an adequate thickness, continuous sedimentation, high sedimentation rate, absence of synsedimentary and tectonic disturbances, absence of metamorphism and strong diagenetic alteration (see Ciaranfi et al., 2010; Maiorano et al., 2010);

ii) biostratigraphic, i.e. abundance and diversity of well preserved fossils, absence of vertical facies changes, favourable facies and numerous biovents for long-range biostratigraphic correlations (see Marino, 1996; Gironi & Varola, 2001; D’Alessandro et al., 2003; Stefanelli, 2003, 2004; Maiorano & Marino, 2004; Maiorano et al., 2004; Joannin et al., 2008; Maiorano et al., 2008; Gironi et al., 2013a; Aiello et al., 2015; Bertini et al., 2015; Marino et al., 2015);

iii) chemostratigraphic and astrochronology (see Brilli et al., 2000; Ciaranfi et al., 2010; Maiorano et al., 2010);

iv) radioisotopic dating (see Ciaranfi et al., 2010; Maiorano et al., 2010; Petrostino et al., 2015);

v) sapropel stratigraphy (see D’Alessandro et al., 2003; Stefanelli, 2003; Stefanelli et al., 2005; Maiorano et al., 2008).

Finally, accessibility, free access, permanent protection of the MJS site are guaranteed by a regional law (L.R. January 27-2011, n.3) by the Basilicata regional administration that established the Special Nature Reserve of the Montalbano Jonico badlands.

Panoramic views of the badlands and some details of the Ideale section are visible at the link: https://youtu.be/PD8AEieZL4M.

The section has been visited by people from many countries during several scientific fieldtrips, the most recent held in Bari (Italy, Field-workshop on the Lower-Middle Pleistocene transition in Italy, October 11-13, 2014) (Fig. 4) organised by the Dipartimento di Scienze della Terra e Geoambientali (University of Bari), and supported by the Italian Association for Quaternary Study (AIQUA) and International Commission on Stratigraphy (ICS) (Ciaranfi et al., 2015).
The MJS is the focus of new investigations even now; supplementary higher temporal resolution analyses on calcareous plankton and pollen, and on mineralogic features of sediments across MIS 19 have been recently performed (Maiorano et al., 2016). Planktonic and benthic oxygen isotope stratigraphy up to the centennial scale is advancing close to MIS 19 in the Ideale section (Nomade et al., 2015) and will provide the best $\delta^{18}O$ record from an onland marine succession known so far. Analyses on the cosmogenic radionuclide $^{10}$Be are in progress; the latter has a distinctive pattern ($^{10}$Be flux anomaly) during the MB transition as documented in the sediments (e.g., Frank et al., 1997; Christ et al., 2003; Suganuma et al., 2010) and ice cores (e.g., Wagner et al., 2000; Raisbeck et al., 2006; Dreyfus et al., 2008). Results of these analyses are promising and will likely be compared with other worldwide records, with the aim to provide reliable information on the timing of the paleomagnetic reversal, avoiding the possible effect of post depositional remanent magnetization lock-in of the geomagnetic signal (Suganuma et al., 2011; Roberts et al., 2013).

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