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MAGNETOSTRATIGRAPHIC DATING OF THE MIDDLE AND LATE PLIOCENE SEQUENCE IN THE MARCHEAN APENNINES, CENTRAL ITALY

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ABSTRACT
The Periadriatic Basin of the external Apennines is reported for its Fermo sector, containing a long sequence of pelites interbedding two major conglomerate complexes, in order to calibrate it to the geomagnetic polarity time scale. The studied succession begins with the 283 meters of Mid Pliocene pelites in the Fosso Morignano section, dated from the Mammoth magnetochron (3.3 Ma) to the latest Gauss chron, and calculated by the cyclostratigraphic distribution of its continuous magnetic signal to last until 2.63 Ma. The boundary with the Matuyama chron (2.58 Ma) is placed in the middle of the overlying conglomerate complex of Mt. Ascensione. The shift from the marl to gravel facies suddenly occurs 50 ky before the Gauss/Matuyama boundary and is followed in continuity by a new marly sequence lasting nearly 100 ky in the Rotella section during the earliest reversed Matuyama. A similar depositional cycle, but of shorter duration, is repeated with the Offida profile: the 20 m thick basal pelites exposed in the Fornace section are dated earlier than the beginning of the Olduvai (1.95 Ma), while the upper pelites contain almost fully the Olduvai split end (1.815-1.785 Ma), there included the Pleistocene boundary which was dated 1.796 Ma in the Vrica stratotype. Both profiles focused the calibration of the Late Pliocene and Pleistocene boundaries delineated by the microfaunal content, as the *Globorotalia* gr. *crassaformis* and *G. inflata* zones were always present throughout the Fermo sector, even if their extremes were both missing. This prevented quantifying the stratigraphic relationships between the two sequences, from either the stratimetric or biostratigraphic viewpoints. The present dating revealed a missing time span of roughly 300 ky, including the short normal chron of Reunion (2.15-2.14 Ma), which may be though represented in other portions of the Fermo sector. The correlation of their sequences to one another may be now used as a calibrated signal applied to individual biozones, from the date of nearly 3.3 Ma in the Mid Pliocene through the Pleistocene boundary.

RIASSUNTO
E' stato condotto uno studio magnetostratigrafico sui sedimenti del medio e tardo Pliocene della successione pelitica affiorante nel Settore fermano del Bacino Periadriatico (Marche meridionali). Nella stessa successione già erano state effettuate ricerche stratigrafiche che avevano evidenziato per il suddetto intervallo la presenza delle biozone a Globorotalia *gr.* crassaformis *e a* Globorotalia inflata. *A causa delle microfaune talora povere e prive di forme significative, non era stato possibile porre con precisione i limiti biostratigrafici e di conseguenza quelli cronostratigrafici. Lo studio magnetostratigrafico ha offerto una maggiore risoluzione con la calibrazione alla scala dei tempi delle polarità geomagnetiche, e ha consentito di verificare nell'Appennino centrale quanto evidenziato nello stratotipo della Vrica (sulla costa ionica), cioè la presenza del breve intervallo di polarità inversa nell'Olduvai terminale nel quale è stato fissato il limite Plio-Pleistocene. Detto evento di polarità inversa è stato già messo in evidenza nella successione continentale del versante tirrenico dell'Appennino Settentrionale, sicchè nei due versanti la calibrazione di entrambe le serie data le fasi di sollevamento della catena. In particolare, in questa parte esterna dell'Appennino, la sedimentazione ha registrato gli eventi di polarità magnetiche nell'intervallo da circa 3.3 Ma a 1.7 Ma e le variazioni cicliche del segnale magnetico, secondo i periodi di Milankovitch, nell'intervallo 3.3-2.6 Ma, in base a quanto misurato dalla magnetizzazione residua delle rocce campionate nelle stesse successioni delle analisi biostratigrafiche. Nella porzione inferiore della successione, in cui 283 metri di peliti sono stati campionati nel Fosso Morignano, sono presenti i croni geomagnetici Mammoth (3.33-3.22 Ma) e Kaena (3.11-3.04 Ma) a polarità inversa e quello intermedio (3.22-3.11 Ma), all'interno della polarità normale Gauss che termina all'età di 2.58 Ma. Infatti, dall'analisi ciclostratigrafica e dalla conseguente velocità di sedimentazione che ne è scaturita, si può ritenere che il crono Mammoth sia rappresentato praticamente tutto, mentre superiormente la successione pelitica si arresta circa 50 ka prima del limite Gauss-Matuyama, misurando il numero di cicli presenti nella durata dei 460 ka del crono C2An.1n. Da rilevare che la ciclicità registrata con la maggiore ampiezza ricorre con uno spessore di sedimenti di poco superiore a 40 m che qui è stata interpretata come quella forzata dalle variazioni climatiche legate alla eccentricità breve (100 ka). Dalle peliti del Fosso Morignano si passa con contatto erosivo al complesso conglomeratico del M.te dell'Ascensione, che presenta uno spessore di 400 m ed è costituito da cinque corpi grossolani separati da livelli pelitici di modesto spessore. L'analisi magnetostratigrafica ha messo in evidenza che il passaggio dalla polarità normale Gauss a quella inversa Matuyama, che segna il limite Pliocene medio-Pliocene superiore a 2.58 Ma, avviene nel livello arenaceo-pelitico posto tra il secondo e il terzo corpo conglomeratico. In questo stesso livello si rinviene la prima comparsa di* Bulimina marginata, *la cui calibrazione diretta con il limite Pliocene medio- Pliocene superiore è l'elemento biostratigrafico che caratterizza il limite Piacenziano-Gelasiano. Si può altresì supporre che i primi due corpi del complesso conglomeratico si siano deposti nell'intervallo mancante tra la fine delle peliti e il limite Gauss/Matuyama, cioè negli ultimi 50 ka; la stessa durata può essere valutata per la deposizione della seconda metà circa del complesso conglomeratico, per cui la durata dell'intero complesso è plausibile in 100 ka. Sia la sezione di Fosso Morignano che quella del Monte dell'Ascensione sono state riferite alla biozona a* Globorotalia *gr.* crassaformis. *La sezione delle peliti di Rotella, che segue in continuità i conglomerati di M.te dell'Ascensione è stata misurata per uno spessore di 45 metri, e ha mostrato una magnetizzazione con polarità inversa. Presupponendo anche in questa serie una velocità media di sedimentazione pari a quella calcolata per le peliti della sezione di Fosso Morignano, si può attribuire a tale sezione una durata dell'ordine di 100 ka. La sezione è riferita alla parte superiore della biozona a* Globorotalia *gr.* crassaformis *per la presenza del livello a* Globorotalia puncticulata-inflata, *che nel Bacino Periadriatico marchigiano-abruzzese si rinviene costantemente prima della comparsa di* Globorotalia inflata. *Superiormente, continua la successione pelitica con intercalato il complesso conglomeratico di Offida dello spessore di 200 m, caratterizzato anch'esso, come quello di M.te dell'Ascensione, da cinque corpi conglomeratici. Sia le peliti che il complesso di Offida sono riferiti alla biozona a* Globorotalia inflata. *Quindi, l'analisi magnetostratigrafica ha documentato la presenza del crono Olduvai alla base delle peliti immediatamente sopra il complesso conglomeratico di Offida. E' probabile che il passaggio dalla polarità inversa a quella normale Olduvai avvenga all'interno del complesso conglomeratico, in corrispondenza del quale non si è potuto effettuare misurazioni. Il limite superiore del suddetto crono non è stato raggiunto nella successione esaminata; è stato comunque evidenziato il breve intervallo a polarità inversa, all'interno della parte terminale dell'Olduvai, nel quale è stato fissato il limite P/P nello standard della Vrica.*

Key words: Magnetochronologic Calibration, Gauss Chron, Olduvai Chron, Pleistocene Boundary, Northern Apennines, Central Italy.

Parole chiave: Calibrazione Magnetocronologica, Magnetocrono Gauss, Magnetocrono Olduvai, Limite Plio-Pleistocene, Appennino Settentrionale, Italia Centrale.

1. INTRODUCTION

The magnetostratigraphic study on the Middle and Late Pliocene succession of the external Apennines, central Italy, was carried out in the Fermo sector, one of the three sectors of the Periadriatic Basin in the Marche region, with the aim of calibrating its chronostratigraphic age (Fig. 1). In fact, the reconstructions made so far were based on the biostratigraphic correlation between a number of sections, which revealed an essentially continuous sequence, comparable with the best sections where the Pliocene to Pleistocene stages had been fixed. Those studied in the Apennines and Sicily yielded the last stratigraphic landmarks, formalising the end Pliocene with the Gelasian stage and the "golden spike" for the Pleistocene boundary stratotype by means of their magnetostratigraphic calibrations.

For the present stratigraphic assessments, the numerical dates produced by the geomagnetic polarity time scale (GPTS), as established by the sea-floor magnetic anomalies, was available according to the revision of the Cenozoic and latest Mesozoic chronostratigraphy made by Berggren *et al.* (1995) on the magnetic chronology of Cande and Kent (1992; 1995). Another important aim in dating this series was that the present area is closest to the calibrated continental sequences of Valdarno and Valtiberina of Northern Apennines, thus leading to the correlation of the main geological events in central Italy during some of the most active tectonic phases of their uplift. In particular, this time span, that also witnessed the main climate changes affecting the recent evolution of the geological system and was recognized in the mentioned continental sequences, could be enhanced as a first evidence of the events inferred for the marine sequences by Cantalamessa *et al.* (2002). For this purpose, the magnetic record of the geological time series was processed by cyclostratigraphic treatment, according to the procedures reported elsewhere (Napoleone *et al.*, 2003b), while a discussion of magnetostratigraphic correlations between the continental and marine sequences across the central Apennines will be reported in a coming paper (Napoleone et al., in manuscript).

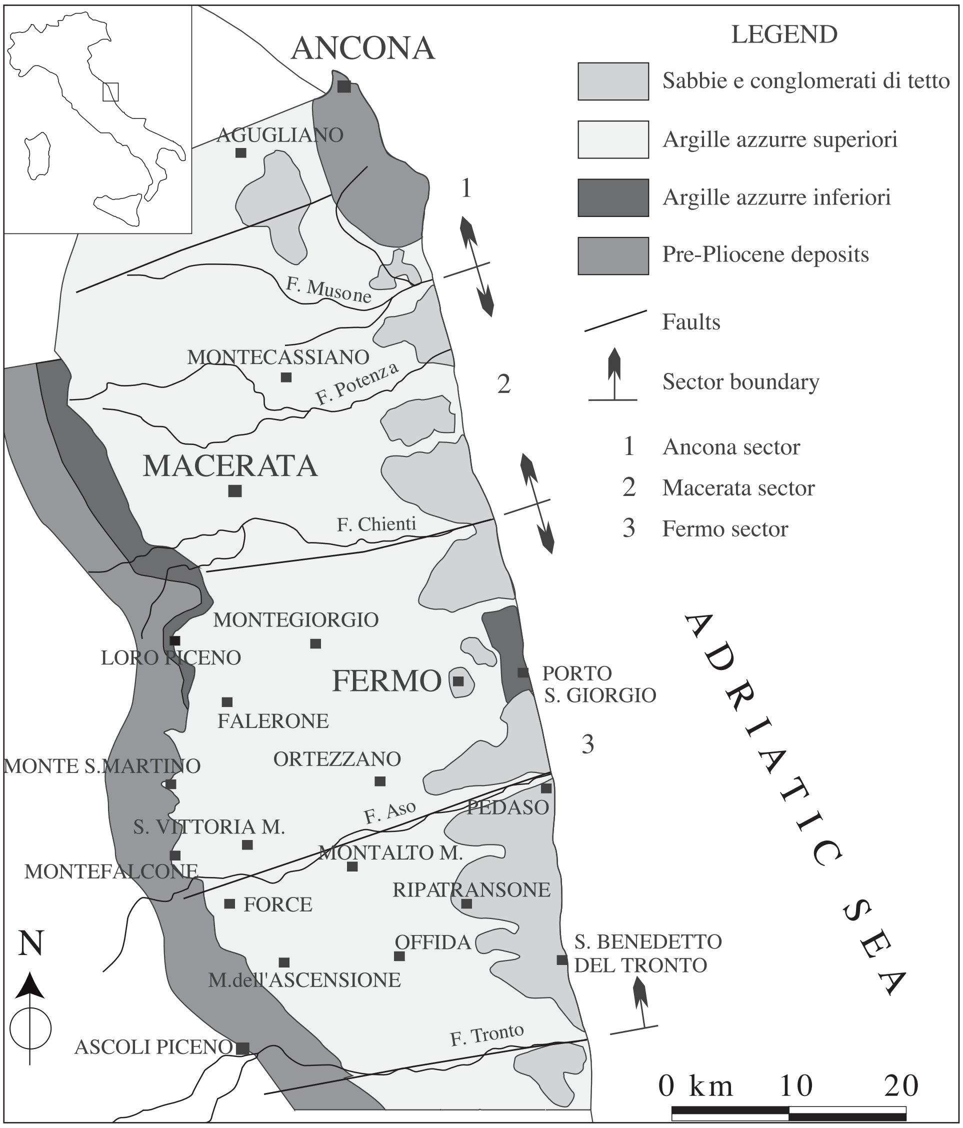

Fig. 1 - Geological sketch-map of the southern Marche district. The Pliocene and Pleistocene deposits outcropping in this portion of the Periadriatic Basin belong to four sectors: 1) Ancona sector 2) Macerata sector 3) Fermo sector, 4) Teramo sector. Their three basic units above the pre-Pliocene basement are: 1. Argille azzurre inferiori; 2. Argille azzurre superiori; 3. Sabbie e conglomerati di tetto. The sequence of the Fermo sector is here investigated.

Schema geologico del Bacino Periadriatico Marchigiano (settori anconetano, maceratese e fermano) e del settore di Teramo. I depositi pliocenici e pleistocenici che affiorano sui terreni pre-pliocenici sono costituiti dalle Argille azzurre inferiori, Argille azzurre superiori e Sabbie e conglomerati di tetto. Lo studio ha interessato la successione nel settore di Fermo.

2. GEOLOGIC SETTING AND BIOSTRATIGRAPHIC AGES

In the external Apennines of central Italy, the Periadriatic Basin was filled by an abundant pile of sediments that concluded the long lasting pelagic deposition. Its continuous record in the Italian peninsula, from the Mesozoic platforms through the pelagic carbonates of the Umbrian-Marchean Series, evolved during the Neogene to the turbiditic sedimentation. It yielded the asset of the Apennine

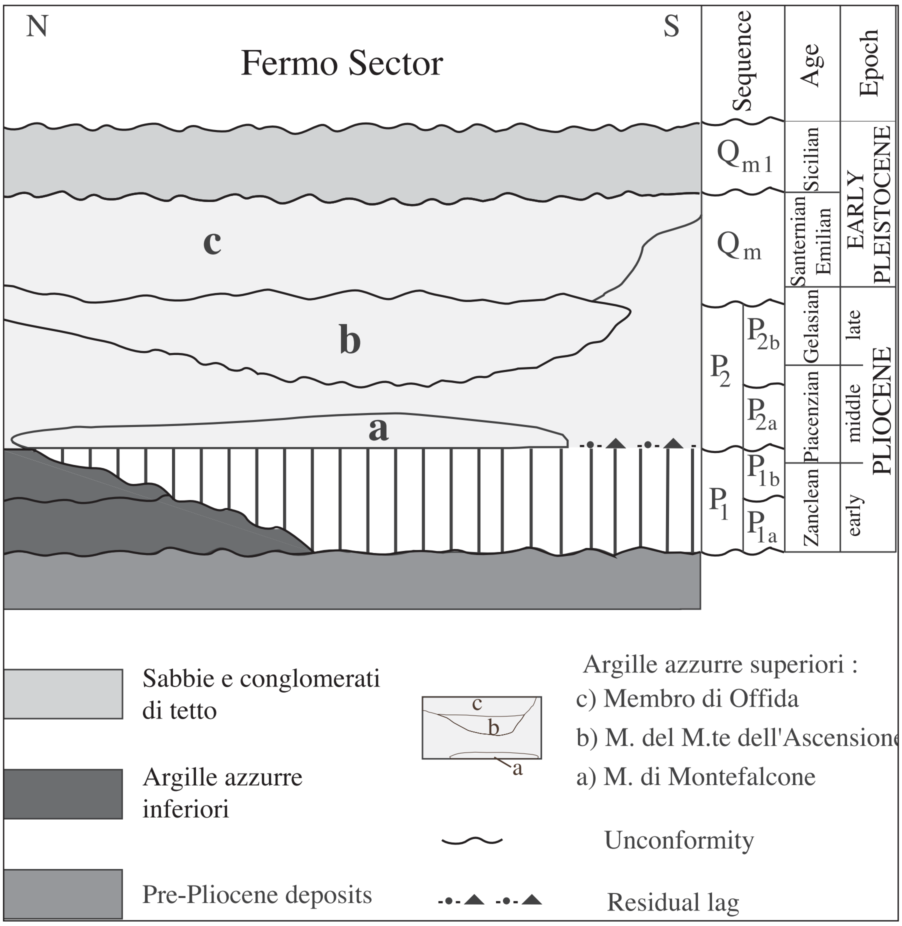

Fig. 2 - Schematic relationships between the Plio-Pleistocene marine units in the external Apennines. The lowermost is Montefalcone (a), whose reduced sequence was not examined, overlain by the Monte dell'Ascensione member (b) and Offida member (c).

Schema dei rapporti stratigrafici tra le unità della successione marina plio-pleistocenica nell'Appennino esterno. L'unità di base è quella di Montefalcone (a) che non è stata investigata, seguita dai membri di Monte dell'Ascensione (b) e di Offida (c).

Ridge, and its evolution relative to the fore-deep complex system, during the Messinian through the Early Pliocene (Bigi *et al*., 1995; 1997; Cantalamessa *et al*., 1986; 1997; 2002). While in the eastern side of the Apennines the Periadriatic Basin was affected by marine sedimentation mostly with pelitic deposits, the late Neogene intramontane basins were developed essentially in the western side with continental sediments. In these basins, a major uplift was recorded by the earliest gravel deposits, dated by magnetostratigraphy to have begun at 3.3 Ma in the Upper Valdarno (Napoleone *et al*., 2003a).

The evidences leading to the identification of the three sectors of the Periadriatic Basin in the Marche, the sectors of Ancona, Macerata, and Fermo are documented in the studies above quoted. These sectors underwent a differentiate evolution related to the effects, even combined, of tectonic changes and eustatic-climatic changes that conditioned the sedimentary environments, as well as depositional modalities and systems. In the Fermo sector the sedimentary sequence is represented, from bottom to top, by the *Argille azzurre inferiori*, *Argille azzurre superiori, Sabbie e conglomerati di tetto* (Fig. 2).

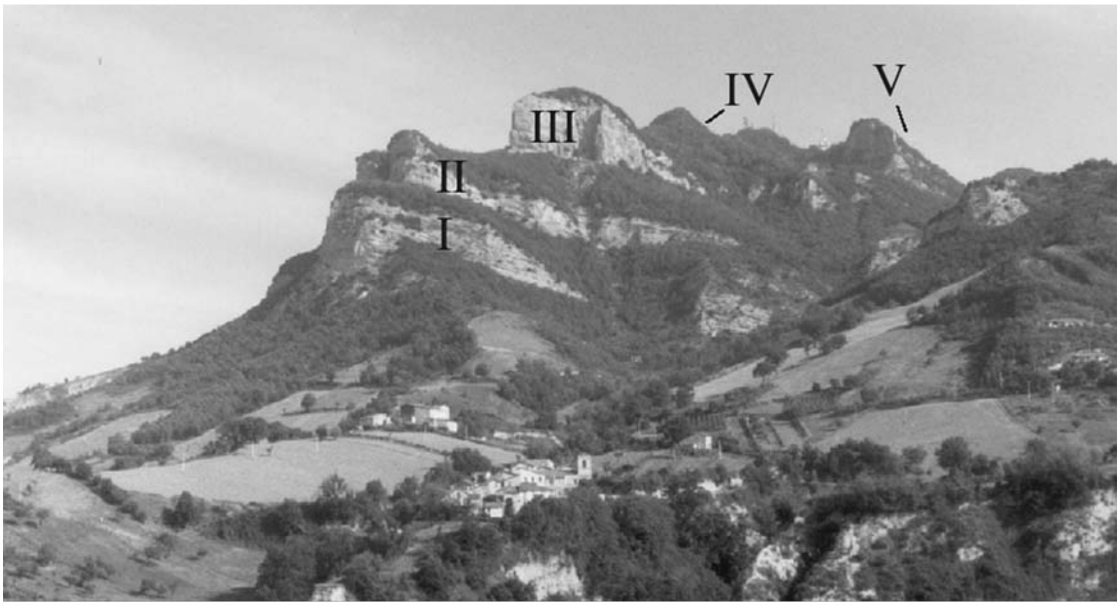

Fig. 3 - View of the Mt. Ascensione gravel complex, exposed for about 400 m above the pelite marl sequence sampled in the Fosso Morignano section. The 5 marked levels of conglomerates overlie the pelite marls with a moderate angular unconformity and both are tilted to the Northeast.

Panoramica del complesso del M.te dell'Ascensione, con circa 400 metri di conglomerati esposti sopra le argille siltose della sezione di Fosso Morignano. Da I a V sono indicati i 5 livelli che insieme alle peliti sono inclinati verso NE e presentano una modesta discontinuità angolare con queste ultime.

The *Argille azzurre superiori,* to which the whole examined sequence belongs, are mainly formed by pelitic deposits interbedded at various levels with complex gravel bodies, as the ones of Mt. Ascensione and Offida. Three members are recognized in the whole formation: from the bottom, Montefalcone, Mt. Ascensione and Offida (Fig. 2). The latter two were sampled. The Mt. Ascensione profile marked the new pelagic deposition after the last turbidites were emplaced in the Early Pliocene; the sampled section exposed in the Fosso Morignano is represented by 283 meters of pelites, overlain with an erosive contact by the 400 m thick conglomerates of Mt. Ascensione which are formed by 5 gravel bodies separated by arenaceous-pelitic thin levels (Fig. 3). The end of this profile is represented by ca. 40 m of pelites measured in the Rotella section. The Offida profile begins with ca. 20 m of pelites sampled in the Fornace section, and is overlain with an erosive contact by the 200 m thick Offida conglomeratic complex (Fig. 4). Various authors (Pieri & Groppi, 1981; Cremonini & Ricci Lucchi, 1982; Cantalamessa *et al.*, 1986; 2002) interpreted this discontinuity as the effect of a further major tectonic pulse, which led to the final asset of the Apennine Range. As for Mt. Ascensione, the 5 gravel bodies forming it are separated by thin arenaceous-pelitic levels, while the pelitic facies overlying in continuity is represented by nearly 60 m, whose uppermost portion was sampled in the Colle Tafone section.

The ends of both profiles resulted of decisive importance for the interpretation of the biostratigraphic reconstruction, in order to reduce the range of incertitude of the *Globorotalia* gr. *crassaformis* and *Globorotalia inflata* biozones which defined the age of the sequence with further details provided by several episodes (Cantalamessa *et al.*, 2002). At the base of the succession, *Globorotalia bononiensis* is associated with *Globorotalia crassaformis*, and upwards the main events are represented by the onset of *Bulimina marginata* followed by the *Globorotalia puncticulata-inflata* bio-horizon. *Globorotalia inflata* was first noticed in the Offida gravel complex, while its absence in the underlying pelites (Fornace section) was possibly related to an ecologic exclusion. This interpretation will be clarified after the magnetostratigraphic results be discussed.

3. PREVIOUS CALIBRATION OF APENNINE SERIES FOR THE MID AND LATE PLIOCENE AGES

The studied Marchean series will represent in Italy the first calibrated one by direct magnetostratigraphic dating after the stratotype at Vrica, southern Italy, established for the Plio-Pleistocene boundary (Van Couvering, 1997), as both related to the GPTS. This tight correlation would add a special relevance to the classical Italian areas where the Neogene and Quaternary ages were investigated since the earliest sedimentologic and biostratigraphic studies, because the asset of the boundary stratotype would be tested throughout a long magnetostratigraphic sequence.

The twofold Pliocene age was used until less than a decade ago, with its late portion identified as the Piacenzian stage. It was fixed in the mid eighteen hundreds in the Piacenza area of the Northern Apennines, on famous sections which still provide detailed evidences of major changes that occurred in proximity of the Plio-Pleistocene boundary (Raffi *et al.*, 1989). Among them, two main points were lately emphasized. The first one deals with the Pliocene warm-water bivalve taxa and fishes which disappeared before the end of the Piacenzian (Monegatti & Raffi, 2001; Sorbini, 1988), as defined by Pareto (1865) and used until the mentioned splitting into the Gelasian new stage. This disappearence was dated within that of *Discoaster tamalis* and D.

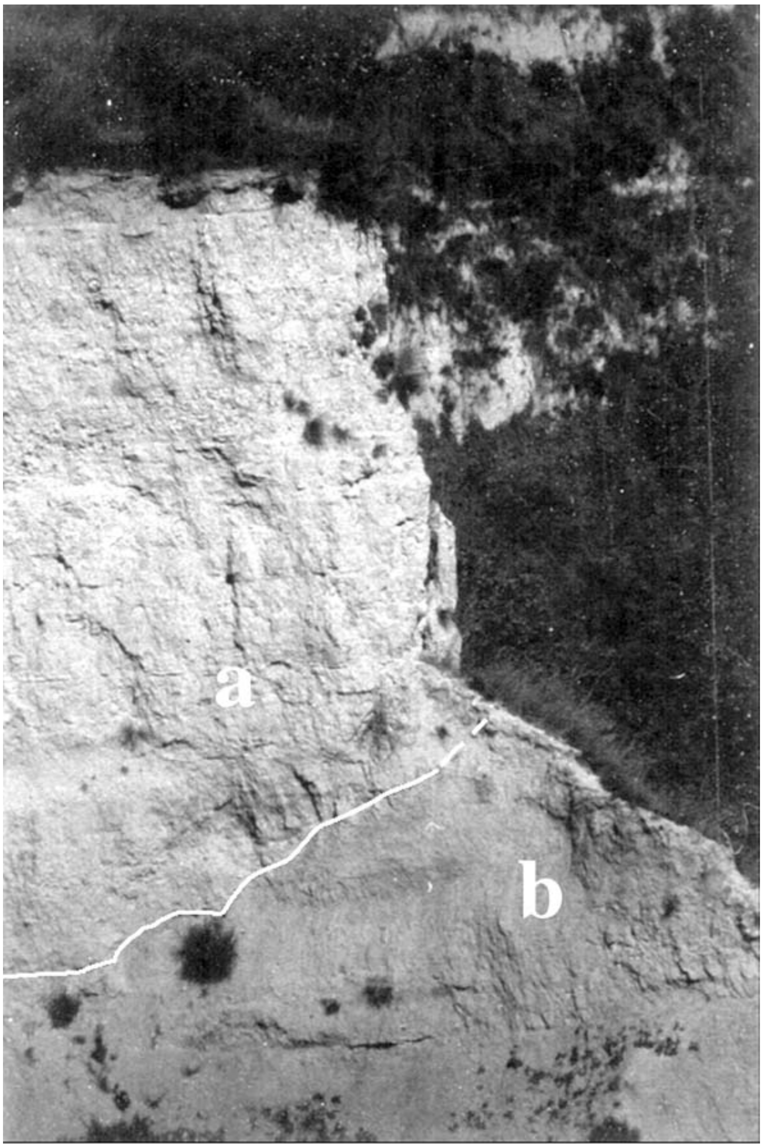

Fig. 4 - An exposure of the erosive contact between the Offida gravel complex (a) and the underlying pelites of the Fornace section (b), in the outskirts of Offida.

Contatto erosivo tra il complesso conglomeratico di Offida (a) e le sottostanti peliti della sezione di Fornace (b), alla periferia di Offida.

surculus confining the nannofossil biozones MNN 16B-17, i.e. close to the onset of the Glacial-Pliocene (Ciaranfi & Cita, 1975; Shackleton *et al.*, 1984; Zagwijn, 1992). The second point was that the sections of the area appeared inadequate to represent the transition from the end of the Piacenzian to the Pleistocene, due to a significant gap. This was fulfilled in the deposits of the Gela sequence, southern Sicily (Cita & Castradori, 1994; Rio *et al.*, 1994; 1997). The Gelasian was there established (Van Couvering, 1995) for the late Pliocene, and thus the best studied series of these critical ages of Piacenzian and Gelasian resulted in the extremes of the Apennine mountain belt.

However, the stratigraphic resolution in the present Marchean sections was until now devoid of a similar accuracy, because of a lesser resolutive biozonation with planctonic foraminifera and poor nannoplankton preservation. On the other hand, magnetostratigraphy actually failed calibrating the P/P boundary in the northern area because of the incomplete extent of the Gelasian stage and the disconformity with the Pleistocene series, for the Santernian stage in the Santerno section (Tric *et al.*, 1991; Mary *et al.*, 1993). During the interval across these ages, tectonics must have been actively uplifting the Northern Apennines, and thus most deposits in the end-Olduvai chron were eroded, while instead yielded at Vrica the key elements to fix the "golden spike" GSSP for the P/P boundary (Van Couvering, 1997).

In central Italy, in contrast, the Pliocene sediments focused special attention since the mid 18 hundreds also on the continental deposits of the intermontane basins (Cocchi, 1856; Pareto, 1865), mainly because their vertebrate faunas contributed to the development of paleontology (Nesti, 1811; 1825; Cocchi, 1867), and of its later use for geochronological meanings (Azzaroli, 1983; Azzaroli *et al.*, 1997). Thence, several marine sequences have been studied in the range of ages between the Late Pliocene and Early Pleistocene, among which are the thick ones bordering the Valdichiana Basin (south of the Upper Valdarno) and farther to the east (beyond the watershed), in the external Apennine Periadriatic Basins. The latter were recently investigated correlating a number of sections (Cantalamessa *et al.*, 2002).

A long Pliocene time span was recognised in the series, as well as its continuation into the Pleistocene, but the P/P boundary was not satisfactorily identified with biostratigraphy. The main aim of the present work is for that reason to date, with the high resolution of the GPTS numerical scale, one of the longest series studied for the Middle and Late Pliocene, and likely correlate its P/P boundary with the stratotype section. Under such conditions, both sides of the Northern Apennines in central Italy would also be correlatable with the highest accuracy, their continental and marine deposits having both been dated with magnetic stratigraphy.

4. MAGNETOSTRATIGRAPHY

The profiles reconstructed from the paleomagnetic measurements were sampled in the same sections studied for biostratigraphy, in order to directly calibrate the ages of the latter to the magnetochronology of the GPTS dates. Biostratigraphic characterization of the series was well established by the previous studies, and yielded a long Mid and Late Pliocene sequence (Cantalamessa *et al.*, 1986; 2002; Bigi *et al.*, 1995; 1997). The magnetic polarity zonation was here established after the rock-magnetic properties had been tested, and the correlations of the biostratigraphy with it represent the main result. Therefore, next chapters will mostly report on the magnetic calibrations with discussion of the results which clarify the chronostratigraphic asset of the series with the magnetic polarity zonation.

4.1 Methods and material

Magnetostratigraphy of the present sequence is in the Fermo sector based on the polarity changes of the paleomagnetic vector reconstructed through the profiles, which will be shown below as the conclusive result after a series of analyses. The measurements were carried out at the Magnetic Laboratory of the ETH in Zurich, on cubic specimens taken from oriented hand-samples. Some specimens were used for the tests on rock-magnetic properties, and most of them to measure the fossil vector of the natural remanent magnetization (NRM), having isolated the primary magnetization. This procedure was used by applying increasing temperatures for cleaning the paleo-vector from possible overprinted magnetizations, and thus recognizing the stable directions carried by a predominantly magnetite composition of the magnetic minerals. For this purpose the magnetic saturation of the samples and its subsequent thermal stepwise demagnetization were applied. Two samples of the Mt. Ascensione unit (Fig. 5A) showed a

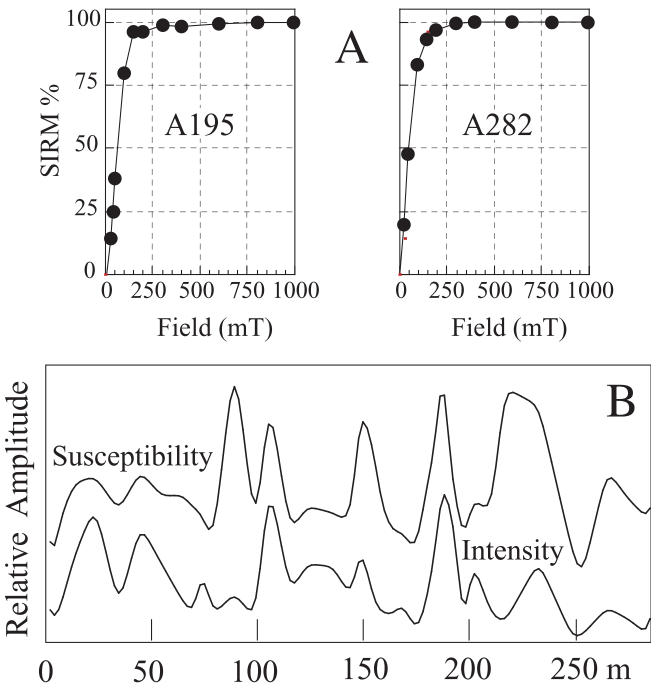

Fig. 5 - (A) Saturation of the isothermal remanent magnetization (IRM) in two samples from the pelite sequence of Fosso Morignano showing the behavior of a low coercivity mineral phase, such as magnetite (B).

(A) Curve di saturazione della magnetizzazione residua isoterma (IRM) di due campioni della serie pelitica di Fosso Morignano che riportano il comportamento di bassa coercitività di una fase mineralogica come quella della magnetite (B).

low coercivity behavior, typical of minerals as magnetite and sulphides. The latter are though very sensitive to temperature and at nearly 300-350 °C produce a new phase of magnetite, while in the present case all samples passed such steps without any deviations disturbing the identification of the virtual geomagnetic pole (VGP) latitudes. These ultimately led to the interpretation of the magnetic polarity zonation through the sequence, which, moreover, showed a remarkable uniformity in its magnetic mineralogy, because of the parallel trends of the NRM and susceptibility curves (Fig. 5B).

An example of the straight direction of the NRM decreasing values toward the origin of the axis after heating is shown in Figure 6, for the representative units. From the top, two samples of reversed and nor-

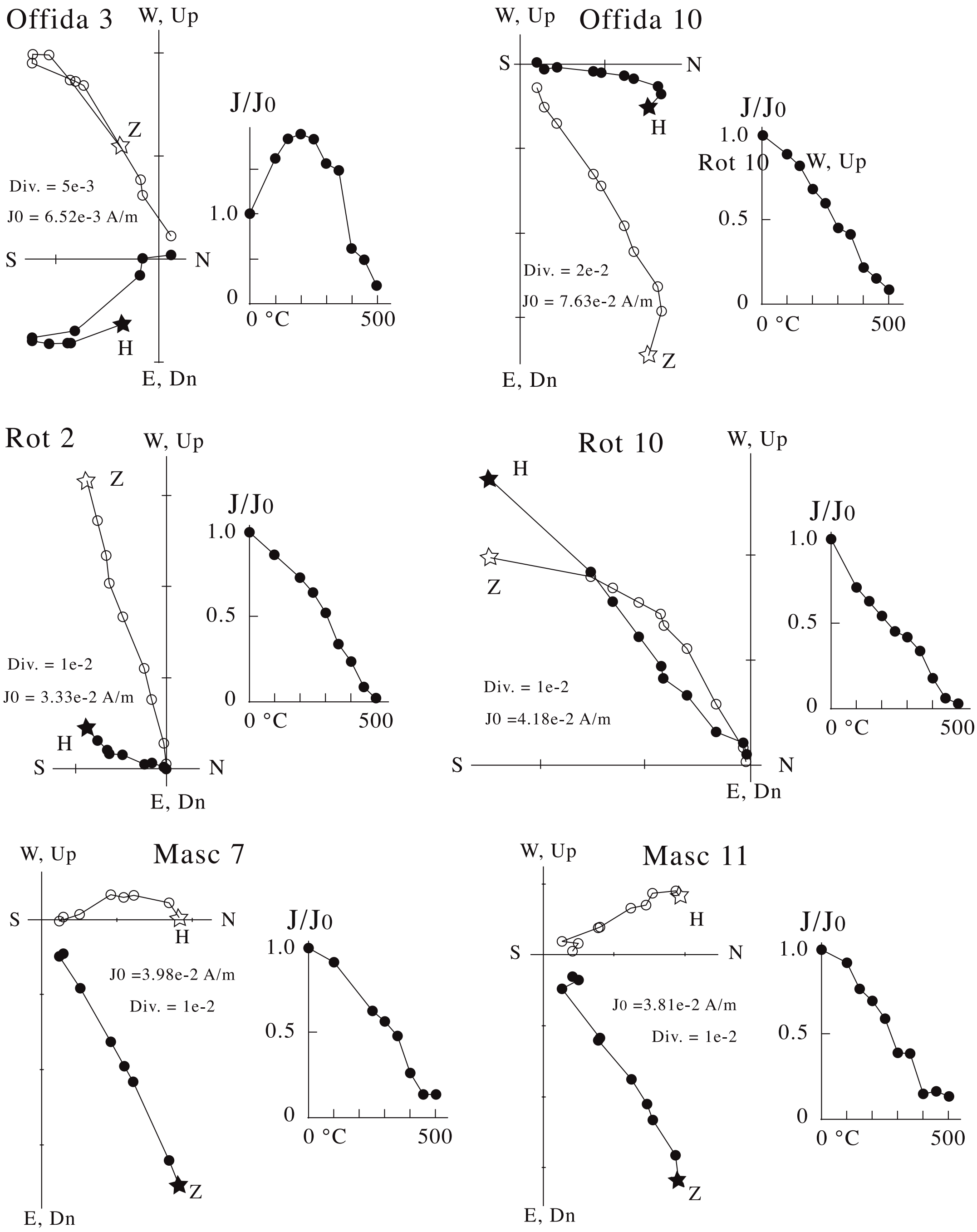

Fig. 6 - The Zijderveld polar diagrams show the directions of the paleomagnetic vector pointing straightforward to the origin, unaffected by secondary magnetizations. Thermal demagnetization by stepwise increasing temperatures did not enhance mineral changes, thus confirming that the primary magnetization was mainly carried by magnetite.

Una serie di diagrammi polari che mostrano le direzioni del vettore paleomagnetico puntare direttamente verso l'origine, senza particolari deviazioni indotte da magnetizzazioni secondarie sovrapposte a quella iniziale durante la deposizione. Le graduali smagnetizzazioni termiche non hanno evidenziato variazioni mineralogiche, confermando perciò la presenza di magnetite come responsabile della magnetizzazione primaria.

mal polarities are shown for the Offida profile. On the left diagram a typical change in both directions, inclination and declination, is shown as a field acquired in the present normal polarity which was removed since the initial steps of demagnetization. In the Rotella section, only one reversed polarity is recorded, while the graphs for the Mt. Ascensione indicate that both signals descend from stable magnetizations of well aligned particles.

Another important analysis, the cyclic stratigraphy of the magnetic signature, was applied to control the magnetic stratigraphy in defining the duration of the long magnetozone at the critical change from the Gauss to Matuyama chron. Its results are illustrated as first, because they relate to the basal sequence for a long time span through the Middle Pliocene and complete the polarity zonation for the magnetostratigraphic interpretation.

4.2 Magnetic cyclostratigraphy of the Piacenzian pelites

The paleomagnetic vector parameters, measured for the basal sequence of Fosso Morignano, revealed, in directions (inclination and declination) and intensities (NRM and susceptibility), a cyclostratigraphic content of the signal in the range of the Milankovitch periods. The duration of the latter was well constrained by the magnetic stratigraphy, whose reliability is marked also by the parallel pattern of the NRM and susceptibility, shown in Figure 5B as an evidence that the magnetic signal was carried only by all aligned fine particles.

In Figure 7A, only the susceptibility curve is shown; the power spectra were processed in the whole time series of 283 m, which enhanced in the diagram by the side the period distribution of the Milankovitch index-forced sedimentation (Fig. 7B). The procedures here applied were used for the coeval series of continental deposits in the intramontane basins, to illustrate the evaluation of the climate changes in the Middle and Late Pliocene and as a further refinement of the magneto-stratigraphic dating (Napoleone *et al.*, 2003a,b).

The results from the present marine series are used straightforward with that aim of better timing the sedimentary events driven by the climate changes, and thus first discussed for the diagram of the bulk time series of the Fosso Morignano section. Its spectrum (Fig. 7B) showed only one prominent peak, the 41.8 m cycle, interpreted as the index-forced sedimentation by the short-eccentricity cycle at 100 ky, as inferred from the following magnetochronologic constraints of the polarity sequence. In the GPTS (Cande & Kent, 1995), the late Gauss chron extends over 460 ky (see also in the next chapter) and would thus contain 4.6 of such eccentricity cycles. In the actual profile, the uppermost magnetozone of normal polarity extends from top of the Kaena, placed at 165 m depth, to the end of the section. At the rate of 41.8 m/100 ky its full time span should extend over a 190 m thick pile, which means that the latest Gauss chron was recorded for only 165 m, from the Kaena to the top, and therefore a 20-25 m slice was missing before reaching the boundary under the steady sedimentary conditions of pelitic deposition. And this also means that, at the rate just said before, a 50 ky duration was not recorded in the pelitic marls. More discussion should be done on the cyclostratigraphic content of the profile regarding the absence of the short period cycles, because the time resolution of the sampling rate was similar to that used for the continental sediments of the Upper Valdarno and Valtiberina (Napoleone *et al.*, 2003a,b) and for the late Albian pelagic carbonates of the Umbrian Series (Napoleone & Ripepe, 1989). The precession and obliquity index-forced sedimentation there produced distinct peaks, in either susceptibility and NRM spectra, or in the directions, also for the shorter periods of obliquity (40 ky) and precession (20 ky).

These short period cycles were searched by processing the present

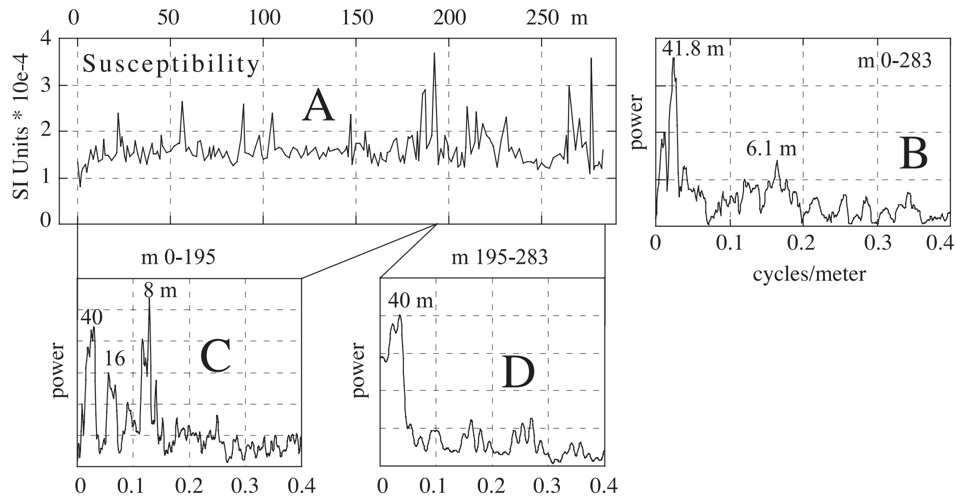

Fig. 7 - Cyclostratigraphic analyses on the Fosso Morignano series. The continuous changes, in the time series of 283 m, of the magnetic signature (A) are processed for the susceptibility signal by the enhancement of the spectra of the period amplitudes. The whole time series evidenced a fundamental period of 41.8 m, as shown in the diagram by the side (B). The split portions, from top to 195 m, to which corresponds a date close to the base of the Kaena chron shown in (C), and the lower series from there to the bottom in (D), provided quite different spectra. That one in (C) showed the same basic period at 40 m and the additional peaks at 16 m and 8 m, which coincide with the obliquity and precession-forced sedimentation of the astronomical parameters driving the climate changes, while in the lower section the cyclicities are all represented by the short-eccentricity cycle.

Analisi ciclostratigrafica della serie di Fosso Morignano. Le variazioni continue del segnale magnetico della suscettività lungo la serie temporale dei 283 m di peliti (A) forniscono gli spettri di ampiezza dei periodi presenti: la serie complessiva contiene un solo periodo dominante, di 41.8 m (B), attribuito all'influsso delle variazioni astronomiche della eccentricità breve sulle condizioni climatiche, mentre, suddivisa in due porzioni, mostra tre picchi ben distinti fino a 195 m (C) corrispondenti ai periodi dell'obliquità e della precessione, e il solo picco di 40 m, fino alla base (D), che aveva dominato in tutta le serie.

series in two steps. First, the upper 195 meters, approximately containing the latest Gauss and the Kaena magnetochrons, were considered using the same constraints as for the entire series; it yielded the power spectrum shown in Figure 7C. The magnitude of the power content was distributed in three strong peaks, at 8 m, 16m, 40m, which are exactly in the ratios of the Milankovitch index periods, as recorded by various proxies (see, for example, Tiedemann *et al.*, 1994) and despite their variability (Shackleton, 1995). The spectrum for the lower section, 195-283 m (Fig. 7D), was more confused, and devoid of the short cycle peaks quite closely reproducing the pattern of the bulk profile of the upper spectrum (Fig. 7B).

Such a behavior was also found for the Mesozoic turbiditic carbonates of the external Apennine sequence, where repeatedly short-term disturbances and well recognized in its sedimentation pattern as continuous resedimentation episodes altered the spectral content in the short period indexes (Albianelli *et al*., 2003). In the present time series, all this is supported by the presence of strong magnetostratigraphic constraints, later shown in Figure 8. The three chrons before the latest Gauss (C2An.1n) are respectively lasting in the GPTS 70 ky, 110 ky, 110 ky, which at the still constant rate of 40 m/100 ky would imply thicknesses of nearly 30 m, 45 m, 45 m. This is not the present case, because already the upper magnetozone, at the Kaena chron, contains only a little more than half the thickness required by the fully sedimented sequence: but, even more so the underlying normal chron does. Our explanation for their reduced extent is that about a 25 m section, distributed on both magnetozones, is missing and actually obliterated by a slice of sediments slipped undisturbed during the emplacement of the sequence or later. The lower portion, with reversed polarity, is even more effectively altered, up to a duplication of its thickness. The spectral distribution seems to confirm this hypothesis, because the short cycles are more disturbed by the sampling rate at 1m spacing.

4.3 Magnetostratigraphic profiles

The interpretation of the magnetic polarity zonation identified two profiles, the Mt. Ascensione and the Offida profiles, both reaching an important boundary, the Late Pliocene and the Pleistocene. For this purpose, all samples were demagnetized as in Figure 5; the characteristic direction of each one was taken to indicate the primary magnetization, yielding the directions used to calculate the virtual geomagnetic pole (VGP) latitudes. The full set of samples represented the succession of the fossil-vector directions, and these were used for interpreting the polarity sequence in both profiles, as discussed below.

4.3.1 Calibration of the Mt. Ascensione profile as the earliest Gelasian

The magnetostratigraphic sampling was scanty in the few silty-sand levels of the 400 m thick conglomerate complex of Mt. Ascensione. In the fine grained material between the second and third level from the base, one sample recorded a reversed polarity, above one sample with the normal polarity (Fig. 8). Downwards, the 283 m of the examined Fosso Morignano sequence, which is separated from the gravel by an erosive surface, showed on top a long normal polarity. Its duration preceding the Middle/Late Pliocene boundary was calculated since the lower time-marker measuring the Milankovitch cycles there recognized with the criteria used for the Upper Valdarno and Valtiberina (Albianelli *et al*., 1999; Napoleone *et al*., 2003a).

As aforesaid, the boundary of the Matuyama chron (2.58 Ma) was found ca. half-way in the conglomerate complex, and the latest Gauss was still incomplete in the pelite marls. The estimation of the time span needed for the conglomerate deposition was out of the biostratigraphic resolution, nor was resolved by the comparative analysis of the sedimentary characters discussed in Cantalamessa *et al.* (2002), but provided by the cyclostratigraphic content of the susceptibility record (Fig.7).

In the present sequence of Fosso Morignano, a normal polarity was recorded from top to 165 m of stratigraphic depth, followed by nearly 30 m of reversed polarity and 20 m of normal polarity; the end section was again in a reversed magnetozone. The profile is then interpreted as made of two reversed magnetozones, prior to the latest Gauss dated 3.04 Ma in the GPTS geochronology, and correlated with the Kaena (3.11-3.04 Ma) and Mammoth (3.33-3.22 Ma), respectively, with its normal chron (3.22-3.11 Ma) there enclosed. These three dates represent tight constraints on the pelite series, whose extremes were also defined with a still high resolution: the upper extreme was found at 2.63 Ma with an accuracy better than 10 ky from the cyclostratigraphic resolution (Fig. 7C), and the lower extreme being inferred of the same order of magnitude, as the Mammoth 110 ky are already represented by a thick pile of sediment. From such markers, a thinning of the short normal and a much larger thickness in the Mammoth are evident, if the accumulation rate would have been steady, and accounts were given for the disturbances in sedimentation rates that affected the spectral analysis of the continuous magnetic signal.

Upward in the profile, above the conglomerate complex, the Mt. Ascensione profile was completed by the Rotella section, which followed in continuity with the pelites measured for nearly 45 m. Its magnetic record showed only one reversed polarity, in the earliest Matuyama, for a time span which will be discussed later on, and begins 50 ky after the boundary, the normal chron of Reunion not being reached. Nor was it found in the exposure of the Fornace pelites underlying the Offida gravel complex, which still continued recording a reversed magnetozone. The sampling in it was more than 2 m spaced.

4.3.2 Calibration of the Offida profile to the late Gelasian

The composite profile shown in Figure 8 assembles all sections surveyed with the magnetic stratigraphy, which are though discussed individually. For example, the uppermost section of the profile, sampled at a much closer spacing than that used for the others, contains the P/P boundary close to the end of the Olduvai, in the short profile measured at the Colle Tafone section. Also the Vrica stratotype with its split Olduvai is represented for comparison by the side. The P/P boundary, placed just before the end of the Olduvai, is one of the most significant tie points marked on the whole profile, together with the Late Pliocene boundary, which had been calibrated to the Gauss-Matuyama

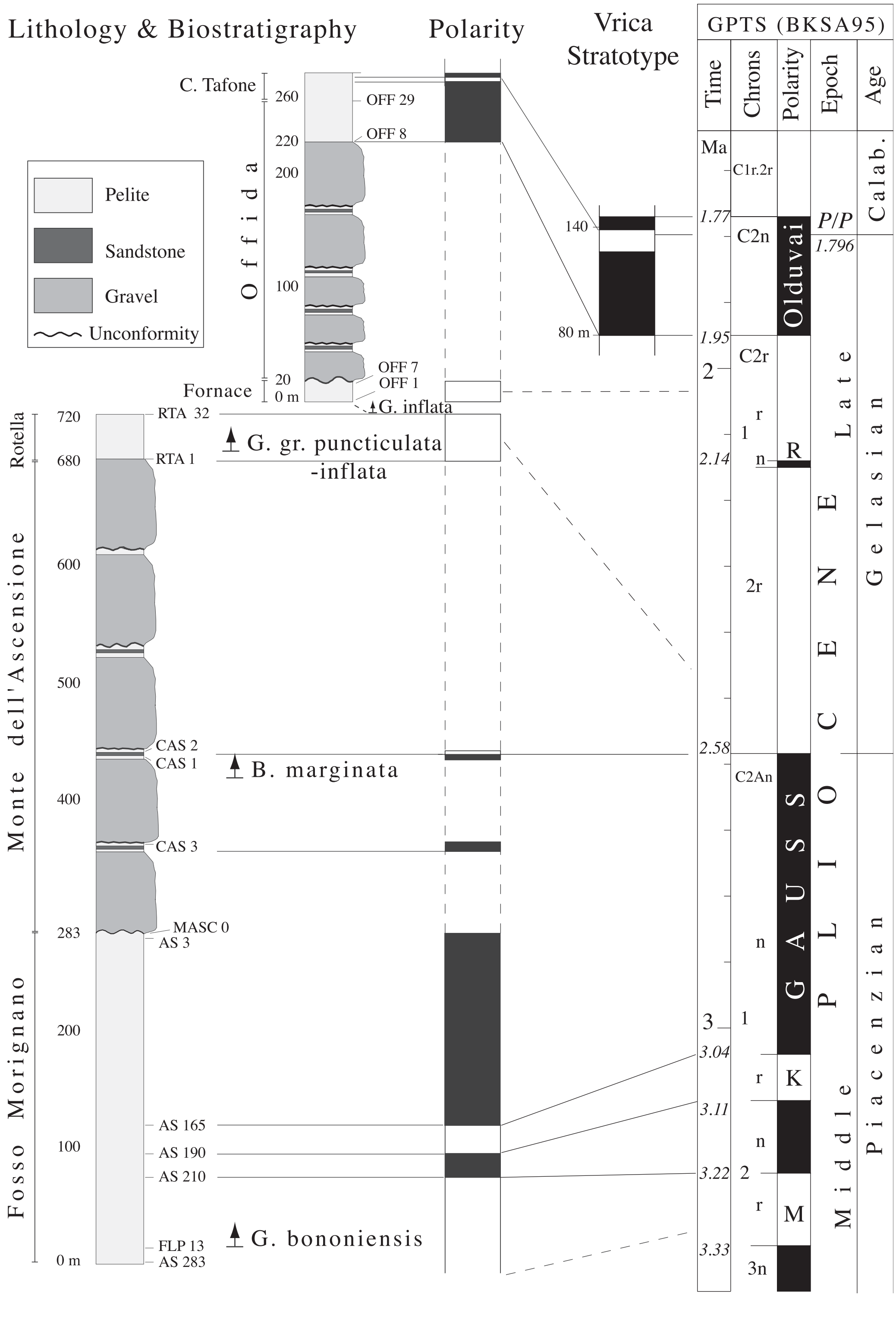

Figure 8 - The magnetochronologic conclusive asset of the series of pelitic-and-coarse deposits here studied yielded dates from nearly the base of the *Globorotalia* gr. *crassaformis* of the early Piacenzian to the top of *Globorotalia inflata* biozone in the Gelasian Stage, concluding the Pliocene in the split Olduvai. The numerical dates of the GPTS are 3.33 Ma for the base of the Mammoth, 3.22 Ma for the base of the normal chron before the Kaena at 3.11 Ma, and 3.04 Ma for the base of the latest Gauss. The dates for the succeding Matuyama and Olduvai are a little less accurate, due to interruptions of the series: the first and longest one of 300 ky in correspondence with the Reunion chron (2.15-2.14 Ma), is followed by a possibly short one at the onset of the Olduvai (1.95 Ma).

Diagramma conclusivo dell'assetto magnetocronologico della serie pelitica con i suoi depositi conglomeratici, a partire quasi dalla base della biozona a Globorotalia *del gr.* crassaformis *del Piacenziano inferiore fino alla fine di quella a* Globorotalia inflata *del Gelasiano, che conclude il Pliocene all'interno della breve inversione alla fine dell'Olduvai. Le date numeriche nella scala dei tempi magnetici GPTS partono da circa 3.33 Ma alla base del Mammoth e toccano 3.22 Ma dell'intervallo a polarità normale prima del Kaena a 3.11 Ma e 3.04 Ma dell'inizio del Gauss terminale. Quelle successive del Matuyama e dell'Olduvai sono meno accurate a causa delle interruzioni nella serie: la prima è risultata di circa 300 ka in corrispondenza del crono Reunion (2.15-2.14 Ma)), e la seconda, più breve, in corrispondenza dell'inizio dell'Olduvai (1.95 Ma).*

boundary of the GPTS, at 2.58 Ma. Therefore, the beginning of the Gelasian stage was marked by this date correlated with the middle of the conglomerate section (between its second and third boulder episode), for a time span calculated according to the previously determined tie-points. The date of the top of the underlying pelite resulted only 50 ky older than the Gauss/Matuyama boundary, as provided by the cyclostratigraphic record. This implies that also the upper half of the conglomerate body may be assigned the same duration of nearly 50 ky, and the overlying pelite of the Rotella section would thus begin not later than 2.53 Ma, while its duration will be discussed in the next chapter. The Gelasian profile, in the surveyed area, was extended into a separate pelite sequence exposed in the Fornace section. It still recorded a reversed polarity, interpreted as shortly preceding the onset of the Olduvai, while the pelites above the conglomerate recorded a normal polarity, i.e. they were deposited during the Olduvai chron. The transition should have occurred in the gravel complex. The smaller thickness of the Offida gravel body, compared with that (almost double) of Mt. Ascensione, would not imply a shorter duration, as the same five episodes of boulder banks separated by the thin pelite levels are recognized. A half rate of deposition would account for the same time span as that in Mt. Ascensione, and the sedimentary conditions for such a smaller rate may be related to a more distal position from the ridge of the Offida body than that of Mt. Ascensione.

With such time constraints, the profiles of Mt. Ascensione and Offida in Figure 8 are fully correlated with the GPTS, only one tie point remaining less tightly constrained, the un-defined portion of the conglomerates matching the Olduvai boundary at 1.95 Ma. The underlying and overlying pelites would date few tens of ky earlier and later than the boundary, respectively. The remaining Olduvai profile was completed by the new sequence sampled at Colle Tafone, on the road from Offida to Castignano. This contains the uppermost Olduvai with the same split interval as in the Vrica stratotype, whose short reversed portion was dated 1.815 to 1.785 Ma. The end of the normal chron (1.770 Ma) was there not reached, but only a few meters are lacking to it, considering that nearly 10 ky are missing.

5. DISCUSSION ON THE MAGNETOCHRONOLOGIC SETTING

An evaluation of dates at great resolution may be now summarized with these magnetostratigraphic details, on which the aforesaid results are based. The Mt. Ascensione lower profile was, indeed, better specified in its sedimentation rates, as accounted by the spectral processing of the time series. Here, only the dates for the sequence above the Mt. Ascensione gravel complex will be further discussed.

The Rotella sequence was already dated 50 ky after the Gauss/Matuyama boundary; its duration would have been ca. 100 ky, if the sedimentation rate was the same as for the earlier pelite deposition, which was averaged at nearly 40 m/100 ky in the spectral analysis, and its date would be placed at 2.53 to 2.43 Ma. The next Fornace section, in the outskirts of Offida, remained poorly constrained between the end-Reunion (2.14 Ma) and the Olduvai onset (1.95 Ma). Previous litho- and biostratigraphic reconstructions would poorly define the uppermost *Globorotalia crassaformis* biozone passing to the next one of *Globorotalia inflata*, as the zonal marker is present only in the lowermost Offida gravel levels. In that scheme, the Fornace section would be assigned an age with a wider range of incertitude in the *Globorotalia crassaformis* biozone, which might be reduced by the present magnetostratigraphic date, after some considerations to be pointed out.

Also this 20 m thick section, underlying the Offida gravel body with an evident unconformity (Fig. 4), would have lasted ca. 50 ky, if sedimentation remained at the same rate as before. The problem arises when considering that its magnetic signature was in a reversed polarity, and therefore its date somewhat earlier than the transition to the Olduvai normal chron at 1.95 Ma. This implies that the whole lower Matuyama, lasting 630 ky from the boundary placed in the Mt. Ascensione gravel unit (2.58 Ma) to the onset of the Olduvai (1.95 Ma) in the Offida gravel unit, would be represented by less than 80 m of pelites from the Rotella and Fornace sections. This gap is now considered as covered elsewhere in the Fermo sector, e.g. farther away in the Colle Cilestrino and Castignano sequences. The missing part, including the Reunion chron (2.15-2.14 Ma), and the shortness of the sequences here prevented the spectral analysis for the Milankovitch cycles recognition, and the gap could not be much better placed in the GPTS.

However, a finer magnetostratigraphic assignment may be attempted placing the Fornace section close to the Olduvai boundary, or at least younger than the Reunion, presuming that the slight angular discontinuity of the Offida gravel complex on it would not too much differ from the Mt. Ascensione one on the Fosso Morignano pelites. In the upper profile, lacking the cyclostratigraphic resolution, the biostratigraphic dating was unable to specify the duration of the missing portion. An upper limit for the date of the bottom of the Fornace section would not be younger than 2.0 Ma, and a lower limit not older than 2.14 Ma. The missing sediments between the Rotella and Fornace sections would at least extend over 2.43 to 2.14 Ma. On the other hand, the 45 m of pelites, overlying the Offida conglomerate in continuity, extended over a normal interval spanning between 1.95 Ma (at most, if the onset of the Olduvai was on top of the conglomerate), but not reaching 1.815 Ma. Between these limits, its suggested date could average 1.93 ± 0.02 Ma to 1.84 ± 0.02 Ma, which seems a good compromise for a duration shortly longer than 100 ky within the 1.95-1.815 Ma interval, and the allowance of 20 ky for the error bar. Similarly, a duration in the order of 100 ky would not contradict an accumulation rate as the nearly 40 ky interval represented by the next 17 m section, containing the split Olduvai on top of the profile.

For the end of this profile, the biostratigraphic record indicated the latest Gelasian age, marked by the presence of *Bulimina elegans-marginata, Globigerina calabra, G. calida*, etc. Thus, the normal polarity in the uppermost marls -not in contact with those immediately overlying the Offida gravel complex- would indicate the presence of the Olduvai chron before its split interval, where the P/P boundary was calibrated in the Vrica stratotype. All these Olduvai dates provide very sharp time signals, altough that at 1.95 Ma in the GPTS was impossible to sample in the scanty fine-grained marls within the gravel layers of the Offida complex. The overlying section was fully contained in the lower Olduvai portion, whose end at 1.815 Ma was found in the Colle Tafone section with the short reversal until 1.785 Ma. In this split Olduvai portion the P/P boundary was marked at 1.796 Ma, and such a tight correlation thus becomes the highest geochronologic resolution ever reached on Italian land exposed Pliocene series, in spite of the shortness of both sections which prevented the cyclostratigraphic reconstruction.

The results of the previous dates, adding to the Mt. Ascensione dates, summarize more than 1.5 my calibrated by several tie-points to the GPTS magnetochronology, thus leading to the cumulative representation of the Middle and Late Pliocene interval in the Periadriatic Basin deposits (Fig. 8). Starting from nearly the base of the Mammoth, at a date of 3.3 Ma, the continuous sedimentation in the pelitic marls recorded the Kaena at 3.11 Ma and the polarity event between them at 3.22 Ma; the following uppermost Gauss chron (3.04 Ma) almost reached in the marls its end of 2.58 Ma, missing only the last 50 ky, as shown in the cyclostratigraphic reconstruction. The magnetostratigraphic reconstruction yielded the occurrence of the Gauss/Matuyama boundary in the overlying conglomerate, which led to this important result: the Mt. Ascensione complex represents the stratigraphic continuation of the pelites. The possible gap involving such a deep change in the sedimentary regime would have been confined in a very few ky, which was recognized also in the adjacent intermontane basins (Napoleone *et al.*, 2003a) and will be further discussed in a forthcoming paper. At the onset of the Matuyama chron, a time span of the same short duration may be lacking in the overlying marls, while a much longer one was measured after these latter of the Rotella section of reversed polarity, which did not reach the Reunion (2.15 Ma).

The section just below the Offida gravel complex was biostratigraphically placed close to the P/P boundary: although its paleomagnetic vector still recorded the reversed polarity preceding the Olduvai, and not necessarily too much close to the boundary from the biostratigraphic age resolution, one may mantain its date younger than the Reunion. Thus, the profile before the base of the Olduvai can likely begin in the Fornace section not later than 2.0 Ma and only shortly after the Reunion, and its estimated time span of nearly 50 ky could be best positioned between 2.1 Ma and 2.0 Ma. Finally, the sampled pelitic marls above the gravel complex can be dated from shortly younger than 1.95 Ma to few ky older than the short reversal at 1.815 Ma, which is the lower limit of the split end-Olduvai; its record would range no more than 1.93 ± 0.02 Ma to 1.84 ± 0.02 Ma.

As already noted, both important markers, the short Reunion (2.15-2.14 Ma) and the Olduvai onset (1.95 Ma) were not found, due to interruptions of the series at their occurrence. But the uncertainties on their position are rather reduced. In particular, magnetostratigraphy dated the interruption of the former with the inferences discussed so far, although with lesser accuracy than that yielded by the cyclostratigraphic processing in the lower sequence of Mt. Ascensione.

6. CONCLUSIONS

The criteria for correlating the chronostratigraphic units in the Pliocene Periadriatic Basin sequences resulted largely improved by the present magnetostratigraphic asset. Occurrences of the various sedimentary events on the Apennine sequences, of either marine or continental origins, could actually be detected under variable conditions, and their accurate dating provided. Precise dates could be fixed for 1.5 my of the studied sequence in the Fermo sector, southern Marche, and with several tie-points to the geomagnetic scale GPTS. A finer resolution was added by the cyclostratigraphic analysis of the continuous time series for more than 0.6 my in its lowermost interval.

Two profiles were reconstructed, that of Mt. Ascensione and that of Offida. In the former, the beginning of the polarity zones was in the Gauss sequence at nearly 3.3 Ma of the Mammoth chron, and in the latter the direct calibration to the GPTS, extended almost until the end of the Olduvai chron at 1.77 Ma, including the Plio-Pleistocene boundary, which was fixed at 1.796 Ma in the Vrica stratotype. Two more time markers in this 180 ky spanning chron added a higher resolution with its splitting, as in the stratotype section, while further increse of dating resolution in the lower sequence were obtained with spectral analysis of the continuous magnetic changes recorded through the Gauss. Magnetostratigraphy then revealed also polarity events of 70 and 110 ky durations, which accounted for a steady deposition rate of the upper half of these pelites, while in their lower portion the cyclostratigraphic signal was recorded somehow confused in the three polarity zones from Kaena through the Mammoth. Another important result was found in the uppermost levels, because only 50 ky were lacking before the Gauss/Matuyama boundary, while magnetostratigraphy placed the latter in the mid Mt. Ascensione gravel complex. Therefore, the reduced duration of the pelitic deposition was fully replaced by the nearly 200 meters of conglomerates without implying the removal of a noticeable part of them during the emplacement of the gravel complex. Actually, magnetostratigraphy showed that in the Gauss chron a slice of sediment was lacking in the Kaena reversed magnetozone and in the normal one below it, while the Mammoth chron was almost doubled in thickness when comparing the duration of the chrons in the GPTS with the thicknesses of the magnetozones recorded in the overall 283 meters of the Mt. Ascensione marls. Such thicknesses, and speciallly that of the Mammoth chron, would be related to anomalous synsedimentary accumulation more than to changing sedimentation rates.

An important find was dated in correspondence with the Gauss-Matuyama polarity change with the first occurrence of *Bulimina marginata*; the fact that this form is directly calibrated to the Middle-Late Pliocene boundary represents the biostratigraphic element characterizing the Piacenzian-Gelasian boundary. One more result was obtained dating the duration of the tectonic activity that shortly interrupted or reduced the deposition. In these marine deposits the first tectonic phase took place at the Gauss-Matuyama boundary (2.58 Ma), spanning 100 ky across it, during which the 400 m thick Mt. Ascensione body was rapidly emplaced until the earliest Matuyama. Thus, the new pelitic sequence deposited in continuity over the conglomerate was sampled for its first 100 ky, at Rotella, while the following more than 300 ky are not present in the investigated area, and will be likely measured in the Colle Cilestrino and Castignano sections.

The basal unit of the Offida profile consists of a pelitic facies similar to that exposed at the base of Mt. Ascensione, and is overlain by a similar gravel complex, made of the same five episodes, but only 200 m thick, with an unconformity present at its base. This phase took place at the Olduvai boundary (1.95 Ma), spanning 100 ky across it, and was followed in continuity by a fairly thick pelitic succession, referable to the uppermost Pliocene and Pleistocene. The first 60 m of this sequence were investigated, and the end of the Olduvai was almost reached at the Colle Tafone section, on the road from Offida to Castignano. This chron was recorded also with the split short reversal which contained the Plio-Pleistocene boundary at 1.796 Ma in the Vrica stratotype.

Finally, the pelite deposition was interrupted soon after the boundary, and this date can be applied to confine the tectonic phase which led the marine sequence moving to the Quaternary sandy deposits of the regressive cycle. More details on this new chronicle of the depositional history are under study on both sides of the Apennine margins, and will be possibly extended to the Santernian-Sicilian ages, i.e. calibrated to the Jaramillo and late Matuyama chrons. However, the asset reconstructed in the present investigation seems sufficient to emphasize the entirety of the correlation potentialities inherent in the numerical dating of magnetostratigraphy, also in presence of fragmentary sequences of the Periadriatic Basin here presented, like that of the Offida profile in the Fermo sector.

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