MAGNETIC STRATIGRAPHY OF THE SCAGLIA ROSSA: IMPLICATIONS FOR SYNDEPOSITIONAL TECTONICS OF THE UMBRIA–MARCHE BASIN

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Key–words: Magnetic stratigraphy, Scaglia Rossa, Upper Cretaceous–Eocene, Northern Apennines, Italy, Synsedimentary tectonics, Paleotopography.

Riassunto. E' stata eseguita una stratigrafia magnetica di dettaglio in 8 sezioni sedimentarie del Cretaceo Sup.–Eocene ubicate in Umbria e nelle Marche (Appennino settentrionale). A tale scopo sono stati prelevati per lo studio campioni paleomagnetici ad intervalli di 1 m circa e sono stati utilizzati i fossili –indice fra i Foraminiferi per una migliore identificazione degli intervalli di polarità magnetica. I risultati congiunti degli studi paleomagnetici e paleontologici hanno consentito di tracciare correlazioni ad alta risoluzione e di ricostruire la storia tettonica del paleobacino in questo intervallo di tempo. A tale riguardo è stato possibile determinare le età magneto–cronologiche del limite Cretaceo–Terziario, del limite Paleocene–Eocene e dell'Eocene medio–inferiore, confermando i risultati forniti da Lowrie et al. (1982). Con lo stesso metodo sono anche stati datati i principali eventi sinsedimentari, come hiatus, sedimentazione torbiditica e slumps nelle sezioni studiate, dimostrandone la contemporaneità messa in relazione con probabili movimenti tettonici sinsedimentari. Utilizzando poi i limiti di inversione magnetica come markers temporali, si sono ottenute informazioni accurate sull'isocronismo degli strati markers litostratigrafici e sui tassi di sedimentazione. E' stata infine ricostruita la morfologia del paleobacino in base alle relazioni spaziali e temporali tra i principali eventi sinsedimentari, la variazione dei tassi di sedimentazione e le facies litostratigrafiche. La paleotopografia irregolare caratterizzata da alti strutturali e dalle relative adiacenti depressioni sembra dovuta ad un fagliamento normale sindeposizionale nel bacino pelagico. Analisi magnetostratigrafiche dettagliate hanno permesso di ricostruire la paleotopografia e le relazioni geografiche tra facies sedimentarie diverse. Questo studio dimostra le varie applicazioni del metodo magnetostratigrafico all'analisi di un bacino.

Abstract. We have determined the magnetostratigraphy in eight Upper Cretaceous to Eocene sedimentary sections in the Umbria and Marche Region of the Northern Apennines, Italy. Paleomagnetic samples were collected at roughly 1 m intervals from the sections studied. Both alternating field and thermal demagnetization were carried out. Microfossils in the specimens were studied to facilitate identification of the magnetic polarity intervals. We have used the combined paleomagnetic and paleontological results in conducting a high–resolution correlation and in reconstructing the paleobasin tectonic history.

The magnetostratigraphic results from this study contribute to the understanding of three aspects

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of the development of the paleobasin. First, we are able to determine the magneto–chronological ages of the Cretaceous–Tertiary boundary, the Paleocene–Eocene boundary, and the lower–middle Eocene boundary; the results reconfirm previous findings by Lowrie et al. (1982). Secondly, we have dated the major synsedimentary events such as hiatuses, turbidite deposition, and synsedimentary slumps with the magnetostratigraphic method. The results indicate that these events occurred during the same magnetochrons in the studied sections. The synchroneity of these events in the widely separated sections implies major tectonic movements in the paleobasin. In addition, since the magnetic reversal boundaries are temporal markers, detailed information on the isochroneity of lithostratigraphic marker beds and sedimentation rates is obtained. Thirdly, based on the spatial and temporal relationship between the major synsedimentary events, the variation of sedimentation rates, and lithostratigraphic facies, we are able to reconstruct the paleobasin morphology at the time of deposition. Syndepositional normal faulting within the pelagic basin has generated an irregular paleotopography characterized by structural highs and relative adjacent depressions. Detailed magnetostratigraphic analysis allows us to reconstruct the paleotopography and the geographical relationship between different sedimentary facies. For instance, major turbidites and slumps at Pietralata and at Furlo (depocenter) correlate precisely with paraconformities at Fossombrone and Acqualagna (adjacent structural highs). In Arcevia, we have used the paleomagnetic results to determine the orientation of the paleoslope. This study demonstrates the various applications of the magnetostratigraphic method to basin analysis.

Introduction.

Sediments within the Northern Apennine Basin in Italy have recorded a complicated tectonic history that involves the development from an extensional regime in Mesozoic to Early Tertiary, to a compressive regime in the Late Tertiary. A thick «miogeoclinal» sequence was deposited from the Jurassic to late Eocene (Bortolotti et al., 1970), followed by a flysch sequence known as the Marnoso Arenacea, deposited during the Miocene in synclinal basin (Centamore et al., 1980). The uppermost part of the miogeoclinal sequence (Upper Cretaceous–Oligocene) is a series of pelagic carbonates, known as the «Scaglia». Previous studies of the Scaglia limestones at Gubbio have yielded very good records of Upper Cretaceous–Paleogene magnetic stratigraphy and biostratigraphy (Lowrie & Alvarez, 1977a; Roggenthen & Napoleone, 1977; Lowrie et al., 1982; Napoleone et al., 1983; Premoli Silva, 1977). These records were used for calibrating the geomagnetic reversal timescale (Lowrie & Alvarez, 1981; Lowrie et al., 1980), for determining the rotation history of Italian Peninsula (Lowrie & Alvarez, 1975, 1976; Channell, 1976; Vandenberg et al., 1977; Channell et al., 1978), and for dating and analyzing the synsedimentary slump events in the sediments (Alvarez & Lowrie, 1984). In the present study, we attempt to extend the application of the magnetostratigraphic method to an analysis of the development of the Northern Apennine Basin during Late Cretaceous to Eocene time.

For this purpose we carried out a detailed magnetostratigraphy in eight sections in the Umbria and Marche Region. The identification of foraminiferal index fossils was utilized for a better identification of the magnetic polarity intervals. The main objectives of this study are to correlate the sedimentary sections in the area with both magnetostratigraphy and biostratigraphy, to study problems concerning the synchroneity of the lithostratigraphic markers and development of synsedimentary slumps, and to date the major synsedimentary tectonic events.

The use of magnetostratigraphic methods in correlating sedimentary sections has some distinctive advantages over other means of correlation: (1) the synchroneity of reversals helps to resolve the temporal relationships among different sedimentary sections; (2) for intervals containing short magnetic polarity zones, magnetostratigraphy is conducive to high–resolution correlation, which is particularly useful in areas with nondistinctive lithology. The combined use of magnetic and micropaleontological stratigraphy improves the accuracy and precision of the correlation. Furthermore, it also puts constraints on the reconstruction of the paleobasin, on the determination of the spatial variations of sedimentation rates, and on the dating of slumps and turbidite events related to syndepositional tectonic movements.

The magnetostratigraphic results from this study have improved the understanding of the tectonic evolution of the Umbria–Marche Region during the Late Cretaceous to Early Tertiary time. First, we are able to correlate accurately the studied sections to the magnetic polarity sequence at Gubbio. The correlation is difficult with biostratigraphic or lithostratigraphic methods alone due to possible diachroneity of the lithostratigraphic markers, poor preservation of fossils, and complications by synsedimentary slumps and tectonic deformations. In specific cases, the magnetostratigraphic method also helps to resolve problems related to the morphology of the paleobasin. For instance, in the Arcevia section, the paleomagnetic directions obtained have helped us to determine the parts of the section which have undergone physical rotation and the orientation of the paleoslope. The detailed results from this section are discussed later in this paper.

Secondly, the thickness of the different magnetic polarity zones reveals a record of the spatial variations in sedimentation rates. Based on the magnetostratigraphic results from Fossombrone, Pietralata, and Acqualagna, we have carried out a refined structural reconstruction of the studied area. The determination of the sedimentary thickness also allows us to put constraints on the timing and direction of sediment transport during sedimentation.

Thirdly, the observed slumps and turbidites events were found to occur at particular levels within the different sections. These events are probably associated with synsedimentary tectonic movements. The detailed dating of the synsedimentary slumps and turbidites in different parts of the Northern Apennines Basin has provided a data base for further structural and stratigraphic interpretation. This paper describes the results of the magnetostratigraphic and foraminiferal studies of the eight sections, while the detailed morphology and tectonic history of the sedimentary basin will be discussed in the context of the regional structure (Montanari et al., in preparation).

Litho–, Bio–, and Magnetostratigraphy of the Scaglia

The Scaglia was formed during the Late Cretaceous through Early Tertiary. The Cretaceous–Lower Tertiary lithostratigraphic units in the Umbria–Marche Region, from the youngest to the oldest, are:

1) the Scaglia Cinerea (upper Eocene–Oligocene, about 100 m at Contessa);

2) the Scaglia Variegata (middle–upper Eocene, about 60 m at Contessa);

3) the Scaglia Rossa (Turonian–middle Eocene, 350 m thick at Gubbio);

4) the Scaglia Bianca (upper Albian–lower Turonian, about 70 m thick at Gubbio); and

5) the Fucoid Marls (Aptian–Albian, thickness varying from 10 to 80 m).

The Scaglia Bianca is a series of white limestones with little spatial variation in sedimentary thickness over the entire paleobasin (Montanari, 1979). This uniformity in the sedimentary thickness suggests the absence of major

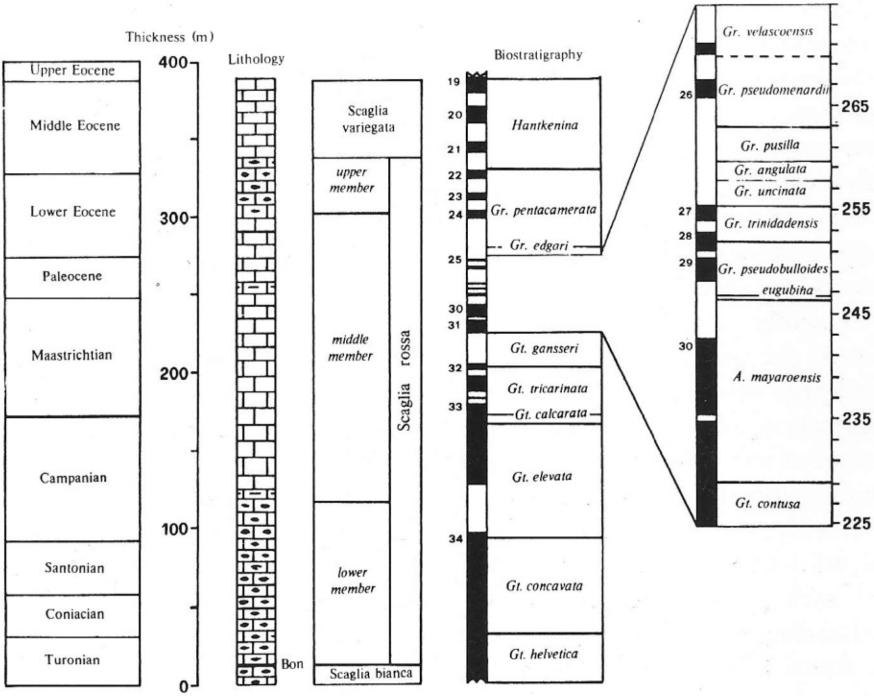

Fig. 1 – The lithostratigraphy, magnetostratigraphy, and foraminiferal stratigraphy of the Scaglia Rossa pelagic limestones, based on previous studies by Lowrie and Alvarez (1977), Alvarez et al. (1977), Lowrie et al., (1982), Vandenberg et al. (1977), Premoli Silva (1977), and other work cited therein.

relief in the sedimentary basin during that period of time. Between the Scaglia Bianca and the Scaglia Rossa is a 1 meter thick level of bituminous shale and chert, called the Bonarelli level, which is regarded in this study as the boundary between the two units. In most sections along the eastern Marchean Anticlorium, two laminated black chert layers, separated from each other by about a meter, are present at 8 meters above the Bonarelli level. They are useful lithological markers in addition to the Bonarelli level (Montanari, 1979).

In the Northern Apennines, the Scaglia Rossa can be divided into three members based on the lithostratigraphic characteristics (Fig. 1) (Renz, 1951). The lower member (Turonian–lower Campanian, 105 meters thick at Gubbio) consists of limestones containing cherts in the form of irregular layers and nodules. The middle chert–free member (upper Campanian–lower Eocene, 180 meters at Gubbio) is a series of well–bedded limestones in the Cretaceous and marly limestones in the Paleocene and the lower Eocene. The upper cherty member (lower–middle Eocene, 32 meters thick at Contessa (Lowrie et al., 1982)) is a series of cherty limestones and marls. This lithostratigraphic division of the Scaglia Rossa is not ubiquitous over the entire Apennines, but locally in the central part of the Marche Region, the first and last appearances of cherts in the lower and upper members and the marly intervals can be used for an approximate correlation.

Between the Scaglia Rossa and the Scaglia Cinerea is a transitional facies, known as the Scaglia Variegata, which consists of interlayering red and grey marls. The Scaglia Cinerea is a series of ash–colored pelagic marls and limestones (Barnaba, 1958; Jacobacci et al., 1974). The uniformity of this unit over the area suggests a stable depositional environment during the late Eocene to Oligocene (Baumann, 1970).

The foraminiferal biostratigraphy (1) of the Scaglia Rossa was studied in detail by Luterbacher and Premoli Silva (1962, 1964), Premoli Silva et al. (1974) and Premoli Silva (1977). The Upper Cretaceous–Eocene biozones are summarized in Fig. 1. The Cretaceous–Tertiary boundary is marked by the total extinction of the planktonic foraminiferal genus *Globotruncana.* The first Paleocene layer is a porcelain–like limestone characterized by a poorly diversified association of tiny globigerinids, mainly *Globigerina eugubina.* Between the *Gg. eugubina* Zone and the end of Paleocene there are six short biozones, each of which spans about 1–2 m.y. (Lowrie & Alvarez, 1981). Biostratigraphic correlation of sedimentary sections is sometimes difficult because of bioturbation, reworking of sediments, and the gradational nature of the biozone boundaries.

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(1) Throughout this report, the authors use the following abbreviations for the foraminiferal genera:

A. = *Abathomphalus, Gt.* = *Globotruncana, Gg.* = *Globigerina, Gr.* = *Globorotalia, H.* = *Hantkenina,* and *Rg.* = *Rugoglobigerina.*

The correlation of the magnetic polarity stratigraphy with foraminiferal biostratigraphy provides a means to identify the magnetic polarity intervals with minimal ambiguity (Fig. 1). In areas where no clear lithological markers are found, or where the biostratigraphic sequence has been disturbed, truncated or repeated, the identification of the magnetic polarity intervals must be based on a combination of different criteria and stratigraphic considerations.

In the subsequent paragraphs, a magnetochron is the geochronological term describing the main subdivision of time recognized on the basis of polarity (Cox, 1982). A magnetozone is a magnetostratigraphic unit formed during the time interval corresponding to magnetochron. In this report, we have employed the numbering system suggested by Cox (1982) to describe the magnetozones. The bracketed symbol following a zone number refers to the corresponding polarity zone found at Gubbio by Alvarez et al. (1977). For example, zone 33R (A-) refers to the magnetostratigraphic unit corresponding to the magnetic polarity chron 33R or Gubbio A- zone.

LaBrecque et al. (1983) have modified the numbering system for the magnetochronological scale. In this system, the authors suggest that an event occurring within a magnetochron should be specified by the fraction of the magnetochron at where the event is located. This system, which deals the magnetic polarity sequence as a continuum, allows a more quantitative representation of the magnetic polarity time scale. In the last section of this report, we have also used this system to discuss the ages of the chronostratigraphic boundaries.

Paleomagnetic Measurements of the Scaglia Rossa.

Application of various paleomagnetic tests indicates that the Scaglia Rossa limestones possess a stable remanent magnetism. The successful fold test on the natural remanent magnetization (NRM) directions (Lowrie & Alvarez, 1977b), the well–demonstrated antiparallel polarity in the magnetization, the thin magnetic polarity zones observed in the Gubbio section, and the vectoral analysis of the magnetic components from detailed sampling across a reversal boundary (Channell et al., 1982), all yield evidence of early acquisition of the remanent magnetism in the sediments. The application of magnetostratigraphy to synsedimentary slumps has contributed further to our understanding of the nature of the remanent magnetism in these limestones (Alvarez & Lowrie, 1984).

Oriented specimens were collected at 1 meter intervals from the eight sections. All the measurements were done with a superconducting magnetometer at Stanford University. (Help from the Stanford paleomagnetic group is gratefully acknowledged). The magnetometer system has a sensitivity of 10^{-9} emu. Stepwise alternating field demagnetization up to 80 milliteslas (mT) and thermal demagnetization up to 650° C were carried out to remove the magnetic overprints.

The results of the paleomagnetic determination reveal the presence of multicomponent magnetization in the specimens. The orthogonal vector projections of some typical results are depicted in Fig. 2. Most of the specimens carry a viscous remanent magnetization (VRM) in alignment with the present geomagnetic dipole field. The VRM was easily removed in an alternation field

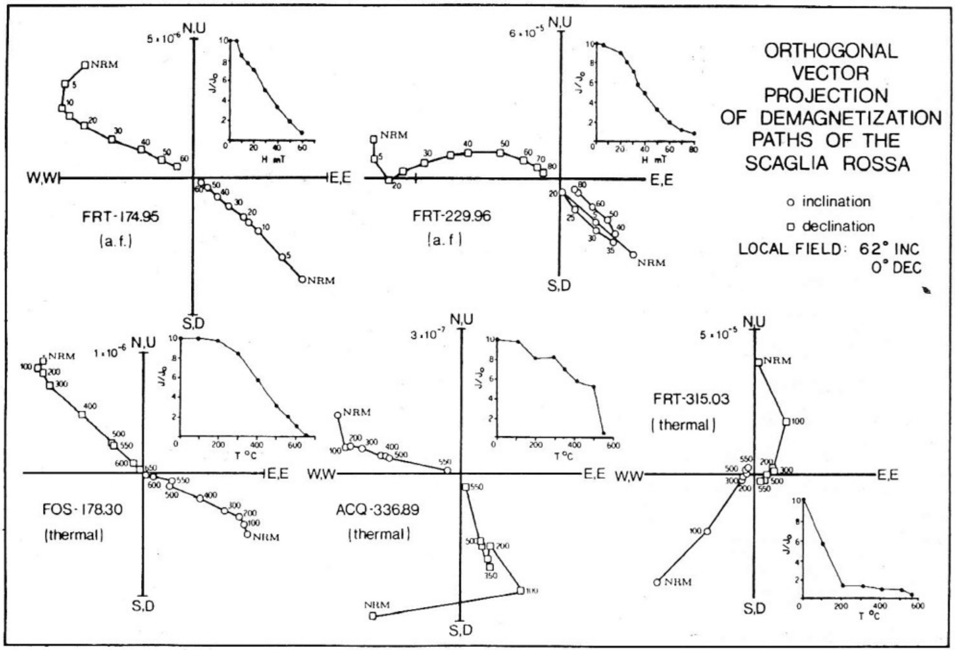


Fig. 2 – Orthographic vector projections of demagnetization paths indicate the presence of multiphasal magnetization in the Scaglia Rossa limestones. The upper diagrams are results of alternating field demagnetization and the lower ones are thermal demagnetization. Normalized intensity are plotted against progressive demagnetization steps in the small figures to the left of each orthogonal vector projection. The axial lengths of the graphs are given in emu. A magnetic overprint, probably a VRM, in alignment with the present field direction, is recognized in most specimens. This overprint can easily be removed at a low applied alternating field of 10 mT or at temperatures of 100–200°C. Specimens FRT–174.95, FOS–178.30, and ACQ–336.89 all show a characteristic remanent magnetism (ChRM) after the removal of the VRM. FRT–229.96 shows the presence of three magnetic components -- a present field overprint, a reversely magnetized component, and a normally magnetized component identified as the ChRM, indicating the acquisition of remanent magnetism across a reversal boundary. The limestones exhibit a various magnetic properties, as indicated by the different blocking temperature spectra possessed by FOS–178.30 and ACQ–336.89 . The former shows a broad blocking temperature range and a Curie temperature of about 650°C, and the latter has a comparatively narrow blocking temperature range and a Curie temperature of about 550°C. Such differences in magnetic properties are probably due to the different composition of the magnetic carriers in the limestones. In some specimen, e.g. FRT–315.03, the ChRM was isolated only at above 500°C, suggesting the presence of a secondary component with a high blocking temperature.

of 10–20 mT or below 100–200°C. But in some specimens, e.g. FRT–315.03 (Fig. 2), a magnetic component with an orientation similar to the characteristic direction of the region was isolated only above 550°C. In specimen FRT–174.95, the magnetic direction isolated at above 20 mT represents the stable remanent magnetism of the specimen. Specimen FRT–229.96 contains at least three magnetic components with different orientation. Besides the VRM which is removed at 20 mT, the specimen carries a component with a negative inclination between 20 and 50 mT and a stable magnetic direction above 50 mT.

The thermal demagnetization results indicate that the specimens contain both magnetite and hematite as the magnetic carriers. The thermoremanent intensity curve for specimen FOS–178.30 reveals a maximum blocking temperature at 650°C, which is close to the Curie temperature of pure hematite (Tc = 675°C). The thermoremanent intensity curve for specimen ACQ–336.89, however, shows a sharp decrease in the intensity between 500°C and 550°C, which is close to the Curie temperature of magnetite (Tc = 578°C). The differences in the magnetic mineralogy in the specimens possibly result from a different diagenetic environment in the sediments.

We follow the procedures described by Lowrie et al. (1982) to determine the magnetic polarity in the individual specimens. The analysis of the magnetic components in the specimens is done with orthogonal vector projections of

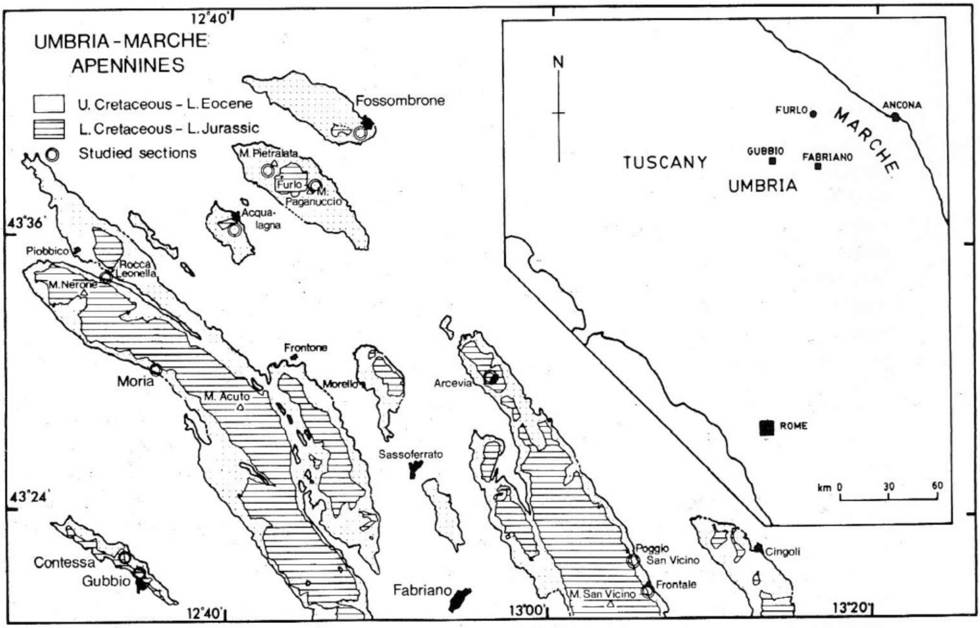


Fig. 3 – Locations of sites for the magnetostratigraphic and foraminiferal study in the Umbria–Marche Apennines. Stippled areas are the Scaglia Rossa. Detailed locations of the studied sections are depicted in subsequent diagrams.

the demagnetization curves. The mean inclination and declination of the stable magnetism in each specimen are used to determine the geographic coordinates of the mean pole for the section. We have occasionally excluded samples collected from synsedimentary slumps from the determination because they may be associated with physical rotations of the sedimentary sections (Alvarez & Lowrie, 1984). The virtual geomagnetic poles (VGP) and the VGP latitudes, are determined on the assumption that secular variations are averaged in the mean paleomagnetic pole. The polarity of a specimen with a VGP latitude close to 90°N is considered to be normal, and one with a VGP latitude close to 90°S is considered to be reversed. Specimens collected from rotated portions of the sedimentary sections often show low VGP latitudes.

Section Descriptions.

The eight sections of the Scaglia Rossa that we have studied are Fossombrone, Lower Pietralata, Monte Paganuccio, Arcevia, Acqualagna, Rocca Leonella, Frontale, and Poggio San Vicino (Fig. 3). Most of these sections are good outcrops suitable for paleomagnetic and stratigraphic studies. Some sections exhibit characteristics, such as unusual thickness of the lithostratigraphic members, and presence of turbidites and synsedimentary slumps, not observed in the Gubbio section described previously (Alvarez et al., 1977). A detailed study of the temporal relationship of these sedimentary structures would promote our understanding of the sedimentation process and the tectonic history of the paleobasin.

Fossombrone (43.68°N, 12.82°E) (Fig. 4, 5, 6).

The Fossombrone section is located in a quarry called Cava del Sasso along the freeway near the city of Fossombrone (Fig. 4). The site is located at the southern tip of the Monti della Cesana anticline. The section is about 100 m thick and contains only part of the lower and middle members of the Scaglia Rossa. Its lithology is characterized by pink micritic limestones with well–defined bedding planes. This outcrop is suitable for magnetostratigraphic studies because it is little disturbed by structural deformation during the folding of the anticline. Pressure–solution stylolites are rarely present except in directions parallel to bedding. Several sets of conjugate shear faults are present, but no substantial displacements on the faults were observed.

Oriented cores were collected at 0.8–1 m intervals along the section. The lowest exposed layer of the Scaglia Rossa was marked as 100 m, with 1 m intervals labeled along the section. The section is covered by a steel–retention net between 139 m and 176 m. Therefore, no paleomagnetic samples were collected within this interval. We studied the foraminifera at 15 levels between 175 m and

207 m. The results were used to identify the magnetic polarity intervals.

Figs. 5 and 6 show the interpreted magnetic polarity sequence of the Fossombrone section. The C–T boundary is represented by a 2 cm clay layer at 204.20 m. The last Cretaceous layer is a white limestone containing abundant *Gt. contusa* and *Abathomphalus mayaroensis.* Worm burrows were observed in the sediments, indicating strong bioturbation at the time of deposition. The Early Tertiary foraminifera *Gr. pseudobulloides* and *Gg. eugubina* were found in the worm burrows. The lowest Tertiary layer is a pink limestone containing abundant foraminifera. At 204.56 m, *Gr. pseudobulloides* comprise over 90% by volume of the limestones. A sample from 205.06 m contains *Gr. ehrenbergi, Gr. uncinata, Gr. pseudobulloides, Gr. trinidadensis* and some reworked *Globotruncana.*

The results reveal the presence of at least two major paraconformities in this section during the early Paleocene. The lowest foraminiferal zone in the Tertiary, the *Gg. eugubina* Zone, is missing. The *Gr. pseudobulloides* Zone lies directly on the Cretaceous sediments. Therefore a major paraconformity is present between the lower Paleocene and the upper Maastrichtian. The first layer above the C/T boundary carries a reversed polarity. This reversed polarity interval is identified as magnetozone 28R because the specimen collected at 204.56 m is located in the *Gr. pseudobulloides* Zone. This biozone spans

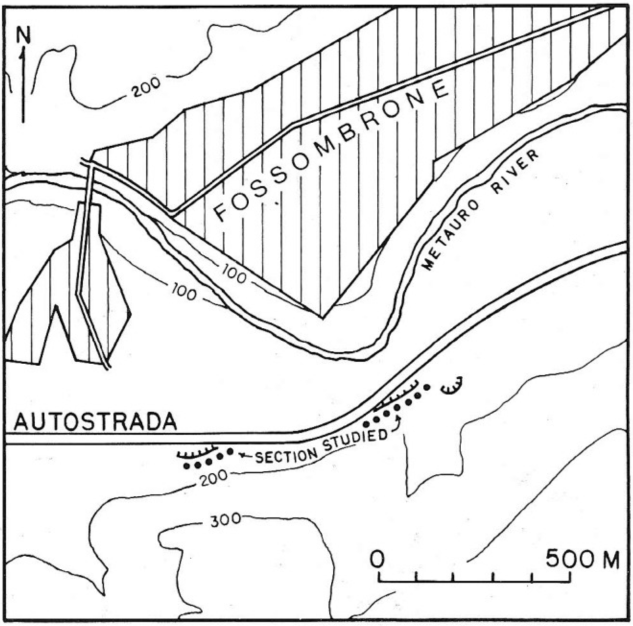


Fig. 4 – Detailed location map of the Fossombrone section.

magnetozones 29R and 28. In the Pietralata section about 6 km away from Fossombrone, the top of magnetozone 29R is located at 30 cm above the C–T boundary. At Fossombrone, the first Tertiary specimen was collected at 36 cm above the C–T boundary. In addition, the *Gg. eugubina* Zone is missing. Therefore, the specimen at 204.56 cm, which carries a reversed polarity, is more likely to be located in magnetozone 28R than in magnetozone 29R.

The second paraconformity is located within the lower Paleocene. The specimen from 205.06 m is already in the *Gr. uncinata* zone. Therefore, the section between 204.56 m and 205.06 m probably contains another major paraconformity. (This part of the sequence is over 6 m thick at Gubbio). The paleomagnetic results of three specimens collected from 204.88 m, 205.06 m, and 205.88 m all indicate reversed polarity. The magnetozones 27, 27R, and 28 are, therefore, either absent or very thin in this sections.

The exposed part of the lower cherty member between 100 m and 139 m falls entirely within a normal polarity interval identified as magnetozone 34 (Gubbio Long Normal Zone). The lower part of magnetozone 33 to the upper part of magnetozone 34, including the upper boundary of the lower member,

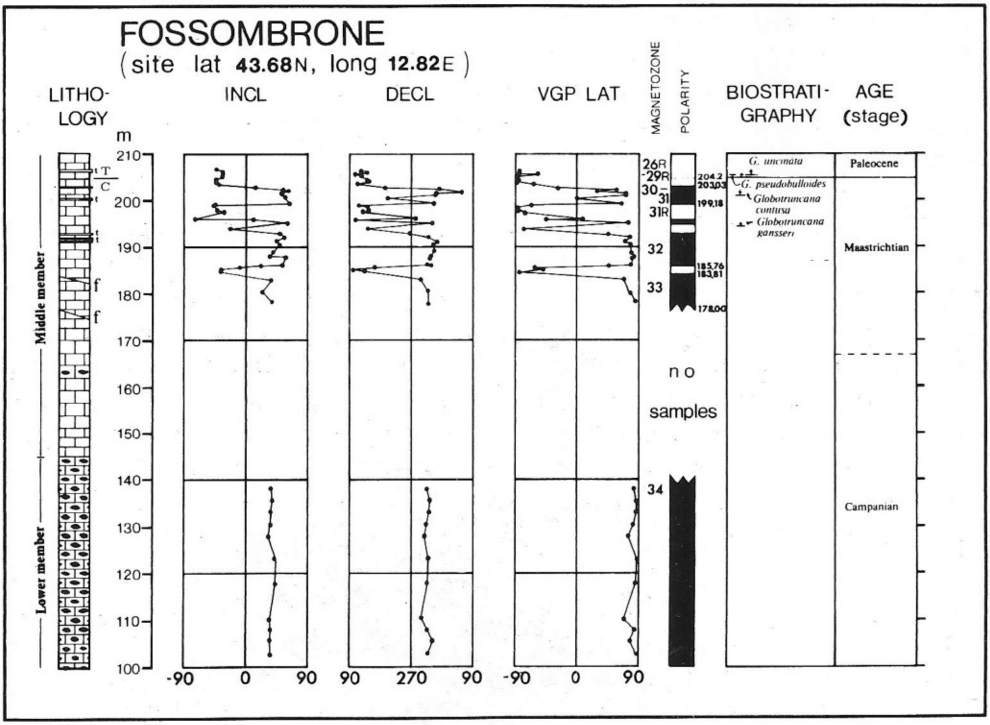


Fig. 5 – Lithostratigraphic characteristics, magnetostratigraphy and foraminiferal zonation of the Fossombrone section.

are apparently contained in the interval covered by the screen where paleomagnetic samples are not available. One single specimen collected at 194.11 m was found to carry a reversed polarity. The presence of a reversed polarity interval at that level was confirmed by remeasuring two samples obtained from 194.00 m and 195.00 m partially oriented with respect to the bedding plane. The polarity intervals between 178.00 m and the C–T boundary (204.20 m) are identified as zone 33 (178.00 m–183.81 m), zone 32R (183.81 m–185.76 m), zone 32 (185.76 m–195.72 m), zone 31R (195.72 m–199.18 m), zone 31+30 (199.18 m –203.03 m), and zone 29R (203.03 m–204.20 m).

In general, the thickness of the magnetic polarity zones shows that the section has an average sedimentation rate of 4 m/m.y. This rate is slower than the average sedimentation rates in other sections. Fossombrone was probably located on a submarine slope where transport of sediments by bottom currents or by gravity was strong during the Early Tertiary time. The biostratigraphic and magnetostratigraphic results indicate a synchroneity between the major

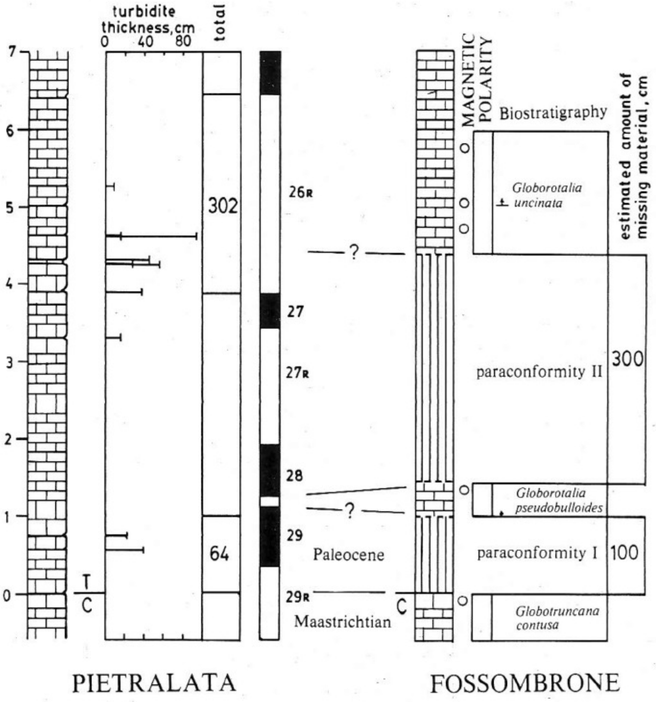


Fig. 6 – Detailed correlation between Pietralata (Alvarez & Lowrie, 1984) and Fossombrone. For Pietralata, the turbidites are omitted in the stratigraphic column; only the pelagic limestones are shown. Horizontal bars indicate the level and thickness of the turbidites. The Fossombrone section is drawn as if it has the same thickness of pelagic limestones as in Pietralata. Vertically shaded areas represent the inferred paraconformities. Magnetic specimens collected are denoted by open circles.

paraconformities at Fossombrone and the turbidite activities at Pietralata. A correlation of this part of the section with that at Pietralata is shown in Fig. 6. At Pietralata, the total thickness of the pelagic limestones between the C/T boundary and the top of the polarity zone 26R is 6.40 meters. The pelagic limestones are interlayering with turbidites. Paleocurrent measurements of some flute structures at Pietralata suggest a northeasterly source from the direction of Fossombrone.

As shown in Fig. 6, we can estimate the total thickness of the sediments missing in the two gaps at Fossombrone, assuming the sedimentation rate of pelagic carbonates in Fossombrone and that in Pietralata to be the same. The missing portions are estimated to have been 100 cm and 300 cm thick at Fossombrone. The estimated total thickness of the turbidites deposited during the corresponding time intervals at Pietralata is 64 cm and 302 cm respectively. A third peak of turbidite influx is present in magnetozone 31R at Pietralata. At Fossombrone, magnetozone 31R is only 3.46 m thick. Compared to the 4 m of pelagic carbonates in magnetozone 31R at Pietralata, and the 4.4 m at Furlo (data from Alvarez & Lowrie, 1984), the thickness of magnetozone 31R at Fossombrone is reduced. Since sedimentation rates in pelagic basins are usually very stable, this reduction in sedimentary thickness is a significant one. Therefore, the maximum in the turbidite activity during magnetochron 31R at Pietralata was also accompanied by a removal of materials from Fossombrone. The results suggest that strong sea floor erosion at Fossombrone was coupled by intensive turbidite activities at Pietralata. Both the paleocurrent analysis and the sedimentation rates determination imply that the turbidites in Pietralata were transported from the direction of Fossombrone.

Lower Pietralata (43.62°N, 12.70°E) (Fig. 6, 7, 8).

The magnetic stratigraphy and biostratigraphy of three sections in Pietralata studied by Alvarez and Lowrie (1984) correlate well with the results from the Contessa section (Lowrie et al., 1982). In the same area, a 50 m section containing the upper part of the Scaglia Rossa and the lower part of Scaglia Variegata is exposed on a curve road below the church of Pietralata on the western side of the Mt. Pietralata–Mt. Paganuccio anticline (Fig. 7). This section (designated Lower Pietralata) is divided into two parts by a fault. The lower and upper parts are marked respectively as 225 m to 240 m and as 0 m to 40 m. The lower and upper boundaries of the upper cherty member in the Scaglia Rossa are exposed at 239.61 m and 20.14 m (Fig. 8). Between 20.14 m and 36.40 m is a series of Scaglia Variegata facies limestones intercalated with marls. The portion between 36.40 m and the top of the section is characterized by folded marly limestones containing cannonball–like chert nodules. This uppermost chert level is a synsedimentary slump occurring during the deposition of the Scaglia Variegata. This slump level was observed near the base of the Scaglia Variegata over the entire Mt. Pietralata–Mt. Paganuccio anticline.

We carried out a magnetostratigraphic and biostratigraphic study in this section in order to examine two specific questions: (1) are the lithological boundaries here synchronous with those in the Contessa section (Lowrie et al., 1982) and (2) what is the age of the big slump observed at the top of the section? The answers to these two questions are useful for our understanding of the nature of the lithological boundaries in the Scaglia and the timing of the synsedimentary tectonic events.

We studied the foraminifera in the specimens collected at 18 different levels. At 229.85 m, the specimen contains *Gr. rex* which has the same first appearance datum (FAD) as *Gr. edgari* in the early Eocene (Postuma, 1971). At 7 m higher in the section, *Gr. broedermanni* and *Gr. aragonensis* were discovered. In the section above the fault, the specimen collected at 7.47 m contains the middle Eocene foraminifera *Gr. bullbrooki* which has the same FAD as *Hantkenina aragonensis* (Postuma, 1971).

The fossils observed are used to constrain the identification of the magnetic polarity intervals. The key to the identification of the polarity intervals in this section is the recognition of the lower–middle Eocene boundary marked by the FAD of *Gr. bullbrooki.* In Contessa, this boundary occurs at the top of

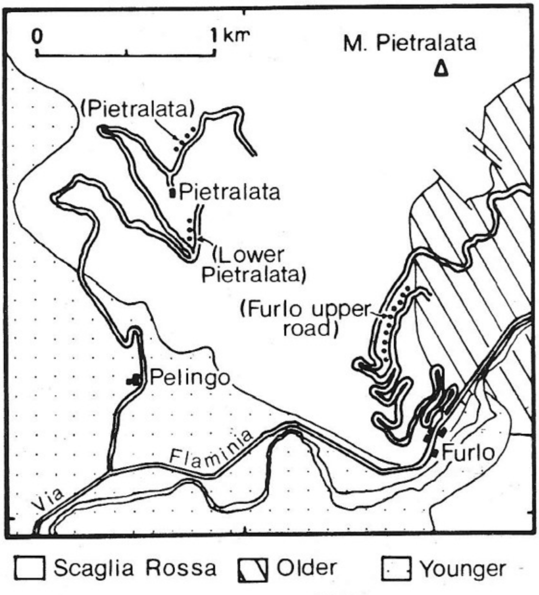


Fig. 7 – Detailed location of the «Lower Pietralata» section. The «Pietralata» section was studied by Alvarez and Lowrie (1984).

the magnetic polarity zone 22. In the section studied here, the boundary is located at 7.47 m above the fault. This puts the normal polarity interval between 4.55 m and 6.20 m as zone 22. Also, a short reversal is present at the top of the magnetic polarity zone 21 in Contessa (Lowrie et al., 1982). The same pattern is observed for the normal polarity interval between 7.73 m and 14.74 m in Lower Pietralata (Fig. 8). The sequence of the polarity intervals in the whole section is identified as zone 24R (base of the section – 232.47 m), zone 24 (232.47 m – fault) below the fault and as zone 22R (fault – 4.55 m), zone 22 (4.55–6.20 m), zone 21R (6.20 m–7.73 m), zone 21 (7.73 m–14.74 m), zone 20R (14.74 m–22.33 m), and zone 20 (22.33 m– top of the section) above. Zones 23, 23R, and parts of zones 22R and 24 are apparently truncated by the fault.

A correlation of the lithostratigraphy, biostratigraphy, and magnetostratigraphy at Lower Pietralata with Contessa indicates that the upper boundary of the upper member of the Scaglia Rossa is not located at the same level in the two sections. The lowest and highest cherts in the upper member are contained respectively within magnetic polarity zones 24 and 20R in Lower Pietralata. At Contessa, these two chert levels are located respectively at the top of magnetozone 24 and at the base of magnetozone 21R (Lowrie et al., 1982).

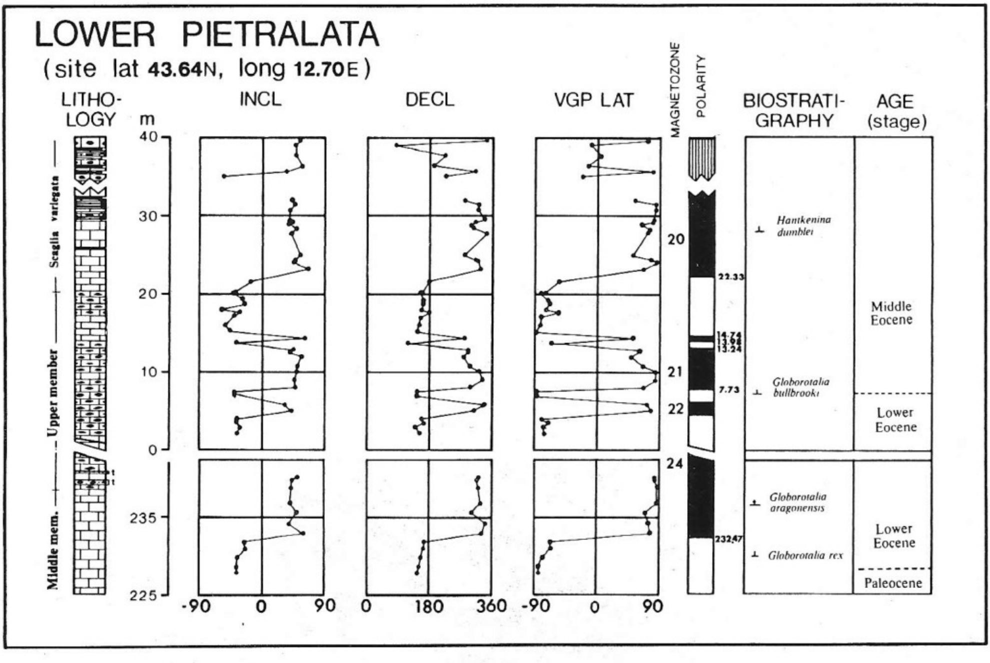


Fig. 8 – Lithostratigraphic characteristics, magnetostratigraphy and foraminiferal zonation of the Lower Pietralata section. The vertically shaded magnetic polarity interval indicates intermediate paleomagnetic directions.

The boundary between the Scaglia Rossa and Scaglia Variegata in this section is put at the cherty layer at level 20.14 m. The cherty level at 36.4 m – 40 m represents a synsedimentary slumps of upper member materials into the Scaglia Variegata. Paleomagnetic measurement of the specimens from the slump shows intermediate directions resulting from folding of sediments. The process of physical rotation in synsedimentary slumps is discussed by Alvarez and Lowrie (1984). During the slumping, cherty materials from the upper member of the Scaglia Rossa were introduced into the Scaglia Variegata. The magnetostratigraphic results suggest that this slump occurred during or after magnetochron 20. Since this slump level can be observed over almost the entire Pietralata – Mt. Paganuccio anticline, its extent indicates that it was probably associated with synsedimentary tectonic movements occurring during middle Eocene time.

Monte Paganuccio (43.63°N, 12.77°E) (Fig. 9, 10).

The Monte Paganuccio section is a 50 m outcrop located on a dirt road near Monte Paganuccio (Fig. 9). The bottom 17 m of the section are composed

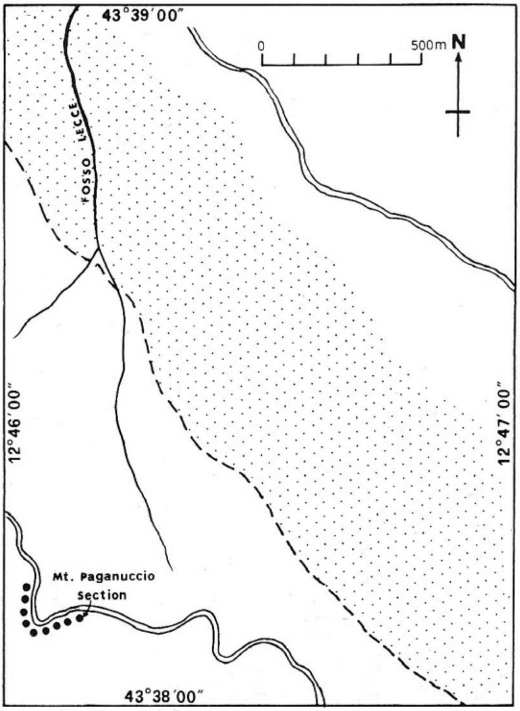


Fig. 9 – Detailed location of the Monte Paganuccio section. Explanations of the symbols are the same as Fig. 7.

almost entirely of turbidites, followed by 20 meters of dominantly micritic limestones interlayering with several thin turbidites.

The lower Paleocene of this outcrop exhibits great stratigraphic complexity. The Cretaceous–Tertiary biostratigraphic boundary is found at two different levels in the section. The lower C–T boundary is located at 135.52 m. The first Tertiary layer above this boundary is a micritic limestone containing abundant *Gg. eugubina.* Two turbidites of 30 cm and 24 cm are present at 40 cm above the boundary. Sediments containing late Maastrichtian foraminifera were found again at 137.00 m. A repetition of the Cretaceous–Tertiary boundary is located at 138.18 m. Two turbidites of 28 cm and 26 cm are present at 42 cm above the boundary. This repetition of the stratigraphic sequence represents a coherent slump block emplaced on top of the early Paleocene sediments.

Alvarez and Lowrie (1984) use the term «autochthon» to describe a local sedimentary sequence that predates a slump and the term «neoautochthon» to describe the normal pelagic sediments deposited on top of a slump. The portion of the outcrop up to 137.00 m, including the first C–T boundary in this section, is an autochthon, while the second C–T boundary is contained in a synsedimentary slump emplaced on it. At 143.97 m, a large synform with its axis trending N30° E and a vergence to the northwest is observed. This synclinal form is overlain by two upright turbidites at 147.00 m.

Magnetostratigraphic and micropaleontological studies were carried out in order to correlate this outcrop with the nearby sections. Forty–eight samples were collected for paleomagnetic measurements. The mean paleomagnetic direction of the specimens collected from this section has a declination of 327° and an inclination of 37°. Rotated paleomagnetic directions recognized at certain levels allow us to recognize allochthonous portions that may be due to physical rotation associated with synsedimentary slumps.

The foraminifera in the specimens were identified at 18 different levels (Fig. 10). Most of the specimens collected from the Cretaceous part of the section show severe reworking of the sediments. Very few indicative foraminifera were found. The specimen at 100.00 m contains *Gt. stuarti, Gt. stuartiformis, Gt. fornicata,* and *Gt. lapparenti.* The late Maastrichtian foraminifera *Gt. contusa* was found at 123.00 m. We can identify magnetozone 31, since the FAD of *Gt. contusa* almost coincides with the base of magnetozone 31. The polarity intervals found are identified on the basis of direct correlation with the Gubbio sequence (Lowrie & Alvarez, 1977a).

The observed maximum in the turbidites is located in magnetozone 32–31R. In Pietralata and Furlo, a turbidite maximum is also observed in the magnetozone 31R (Alvarez & Lowrie, 1984). Therefore, strong turbidites activities were present in this area during the corresponding time interval.

A repetition in the magnetic polarity sequence is associated with the repetition of the C–T boundary. The two turbidites at 40 cm above the lower C–T boundary are located in a normal polarity interval identified as zone 29. The two turbidites 42 cm above the second boundary also carry a normal polarity. The magnetic direction of the specimen obtained at 139.00 m, however, shows a substantial deviation from the mean direction, suggesting a rotation associated with the slump block.

Three samples collected at 141.00 m, 141.92 m and 143.00 m do not show rotated paleomagnetic directions. This part of the section probably represents a neoautochthon overlying the slump interval. The thickness of the slump interval containing the C–T boundary is about 3 meters. At 143.60 m, rotated directions are found associated with the synform. The directions, however, show differential amounts of rotation and substantial variations in bedding attitudes. Two upright turbidites which appear to be undisturbed and show unrotated

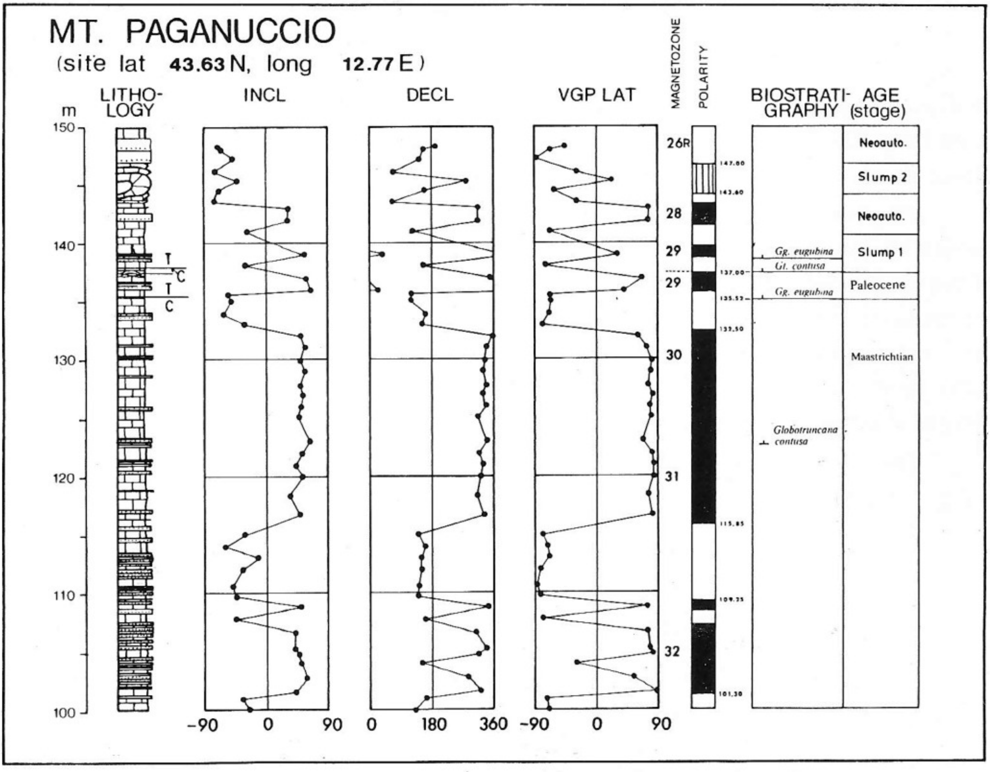


Fig. 10 — Lithostratigraphic characteristics, magnetostratigraphy and foraminiferal zonation of the Monte Paganuccio section. The C–T boundary is found at two levels 135.52 m and 138.15 m. The magnetic polarity sequence also indicates a repetition of the magnetozones in this part of the section.

paleomagnetic directions are present at 147.00 m. The portion of the section from 143.60 m to 147.00 m is, therefore, a second slump which occurred during a later time. The part of the section above 147.00 m represents a second neoautochthon overlying the slump.

The timing of the slumps is difficult to determine here because few indicative foraminifera were found in the specimens collected from the Paleocene. One major clue to the timing is the correlation of the thick turbidites at 147.00 m to the megaturbidite found at Furlo (Alvarez & Lowrie, 1984). A detailed sedimentary analysis of the turbidites at the two sites (Montanari, 1979) indicates that they are the same bed. Magnetostratigraphic data indicate that the megaturbidite at Furlo was deposited during magnetochron 26R during the late Paleocene. By a direct correlation, the second slump in the Paganuccio section occurred in magnetozone 26R.

Arcevia slump (43.50°N, 12.95°E) (Fig. 11, 12, 13, 14).

A 30–meter outcrop exposed in a quarry near the town of Arcevia in the Marche Region exhibits peculiar characteristics. As shown in the sketch in Fig. 11, an apparent angular unconformity divides the outcrop into a lower block with a dip of about 65° and an upper blocking with a shallower dip of about 35°. In between the upper and the lower blocks is a 5–meter shear zone with no clear bedding.

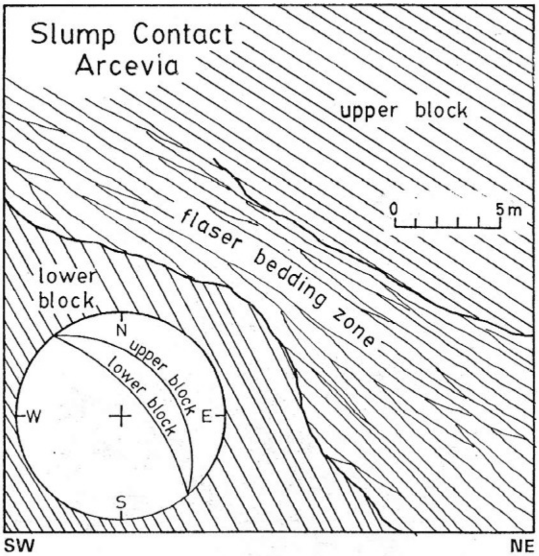


Fig. 11 – A sketch of the slump contact at Arcevia. An angular relation exists between the upper and the lower blocks. The stereographic projection of the bedding planes in the two blocks is shown in the inserted diagram.

The section probably represents the contact between a coherent slump block and a neoautochthon. Any reconstruction of the slump geometry has to account for the high angle (about 30°) between the bedding in the upper and the lower blocks in the outcrop. The geometry of submarine slumps was discussed by Lewis (1971), and Laird (1968). A high angle contact between the coherent slump block and the autochthonous sediments is characteristic of the head of a rotational slump (Fig. 12). This kind of slump geometry is also observed in the seismic reflection profiles across some modern sedimentary basins (e.g. Bally, 1983; Lewis, 1971). As illustrated in Fig. 12, an angular relationship exists both at the contact plane between the slump block and the neoautochthon (model A) and at the contact between the slump block and the autochthon (model B). Since the outcrop is folded, it is difficult to distinguish the slump block from the neoautochthon in the field.

Paleomagnetism provides a means to resolve this problem. The study by Alvarez and Lowrie (1984) shows that coherent slump blocks are sometimes associated with physical rotations. Therefore, by comparing the magnetic directions in the two parts of the outcrop with the characteristic direction in the same stratigraphic unit over the Marche Region, we can distinguish the neoautochthon from the slump.

We have divided the collected samples into two groups. Lower group contains 17 specimens collected from the lower block below the angular unconformity. Upper group contains 9 specimens collected from the upper block above the angular unconformity. The bedding–corrected stable magnetic directions in the specimens measured are shown in Fig. 13. One specimen is rejected because it shows unstable directions upon demagnetization. The two groups form two distinctive clusters in the magnetic directions. Lower group gives a mean inclination of −29.3° and a mean declination of 182.3°. The five specimens that carry a direction significantly different from the rest are excluded from the

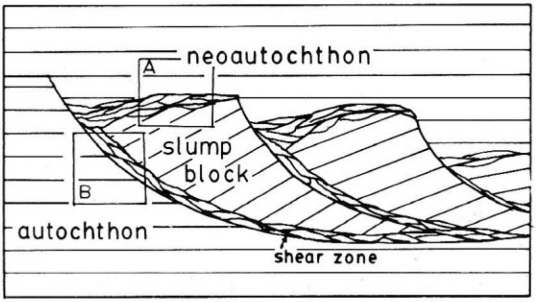


Fig. 12 — The «head» of a submarine slump based on the model suggested by Lewis (1971). An angular contact is present both at the upper and at the lower contact plane of the coherent slump blocks. The bedding in the slump block is opposite to the dip of the paleoslope.

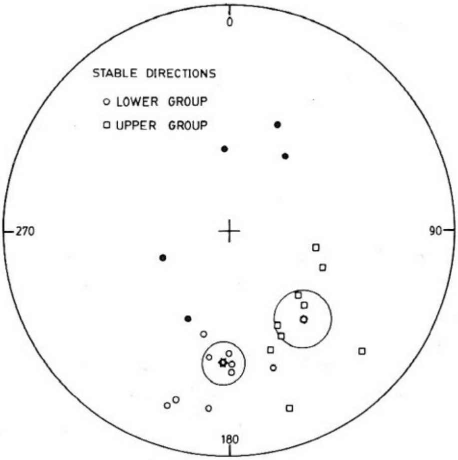


Fig. 13 – Stable magnetic directions (bedding–corrected) in the specimens collected from the upper and the lower groups. The upper group yields a southeasterly declination which is closer to the characteristic direction in the Umbria–Marche Region.

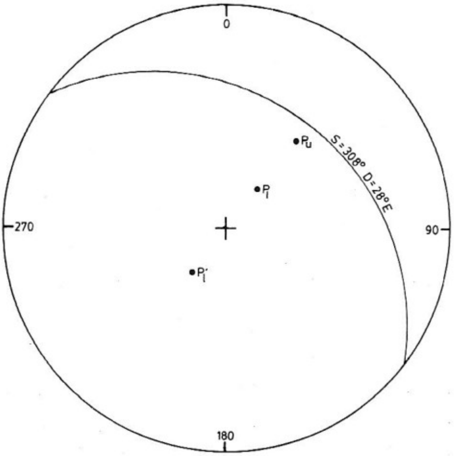


Fig. 14 – Restoration of the bedding planes after unfolding the upper block to horizontal position. Pu and Pl are the poles to the bedding in the upper and lower block respectively. Pl' is the pole to the bedding (great circle) after geometric unfolding of the upper block.

determination of the mean direction. Upper group yields a mean inclination of –35.9° and a mean declination of 139.8°.

Two lines of evidence suggest that the lower block is a slump block and the upper block is a neoautochthon. First, the lower block contains five specimens that show significantly different magnetic directions. These directions probably resulted from local rotation of the sediments or reset of magnetism during the slumping. Secondly, the characteristic stable direction for the same stratigraphic unit in the Umbria–Marche Region has an inclination of –39° and a declination of 140°. The magnetic directions of the two groups suggest that the upper group yields a direction similar to the characteristic direction while the lower group shows a clockwise rotation of about 40° with respect to the characteristic direction. Therefore, the model A depicted in Fig. 12 provides a better explanation to the observed magnetic declination pattern.

Distinguishing the slump block from the autochthonous part of the section allows us to determine the orientation of the paleoslope. Both the upper and the lower blocks are dipping to the northeast. If the suggested slump geometry in Fig. 12 is correct, the bedding in the slump block would be dipping in the direction opposite to the paleoslope. Since the upper block is a neoautochthon, by restoring the bedding of the upper block to a horizontal position, the orientation of the lower block would give a direction opposite to the orientation of the paleoslope. The result suggests that the lower block was dipping to the east (Fig. 14). Therefore, the paleoslope in this area probably dipped to the west.

Acqualagna (43.61°N, 12.67°E) (Fig. 15, 16, 17).

The Acqualagna section is located on a dirt road on a northwest–facing slope parallel to the Burano river south of Acqualagna (Fig. 15). The outcrop is composed of 130 m of Scaglia Rossa and 40 m of Scaglia Variegata. In this section, the upper cherty member is only 11 m thick. The first Tertiary marl interval, commonly at 1 meter above the C–T boundary, is found at 10 m above the C–T boundary in this section. One question associated with the stratigraphy here is whether the lithological markers are isochronous with their equivalents elsewhere. A correlation of this section with Pietralata and Furlo would yield useful information on the basin morphology during the Early Tertiary.

The section was marked as 230 m to 400 m. A major fault with substantial vertical displacement is present at 263.00 m. No significant movement has been determined on the other smaller faults. Paleomagnetic samples were collected at 1 m intervals. We have also studied the foraminifera in the specimens collected at 18 different levels. Fig. 16 shows the results of magnetostratigraphic and the paleontological determination. The part of the section from 234

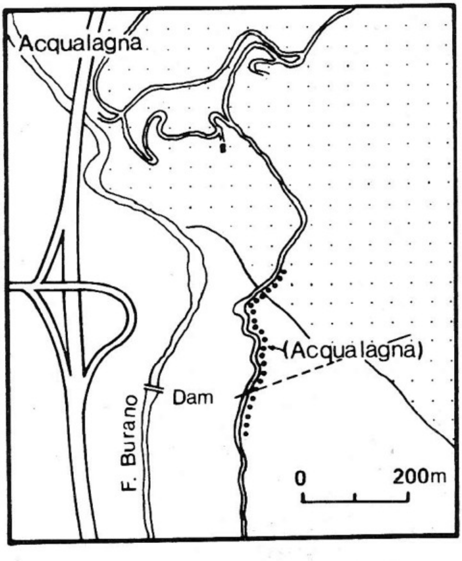


Fig. 15 – Detailed location of the Acqualagna section. Explanations to the symbols are the same as Fig. 7.

m to 270.20 m falls within a normal polarity interval. Lower Maastrichtian foraminiferal species such as *Gt. falsostuarti* and *Gt. stuarti* are present below the fault. Upper Maastrichtian *Gt. gansseri* is present at 263.00 m above the fault. Therefore, part of zone 33, all of zone 32R, and part of zone 32 were truncated by the faults. The normal polarity interval between 278.00 m and 293.74 m is identified as the combined magnetozone 30–31 (F+), because *Gt. contusa* is present at 278 m.

The detailed magnetostratigraphic zonation for the Lower Tertiary in this section is shown in Fig. 17. The C–T boundary is found at 296.50 m in a reversed polarity interval identified as magnetozone 29R (G–). The specimen at 297.30 m contains abundant *Gr. trinidadensis*. Upper Paleocene *Gr. pseudomenardii, Gr. pusilla pusilla,* and *Gr. pseudobulloides* are present at 302.00 m. Lower Eocene *Gr. rex* is found at 317.00 m (Fig. 16). These micropaleontological observations are used to constrain the identification of the magnetic polarity intervals.

The magnetic polarity sequence between 296.50 m and 310.85 m is inter-

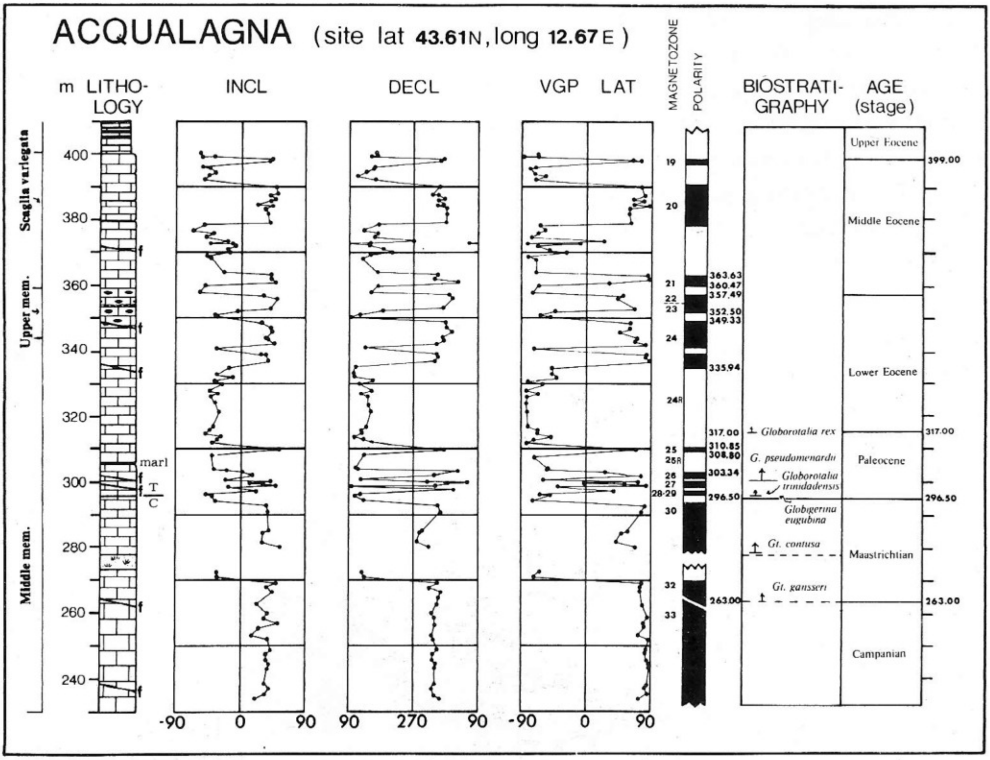


Fig. 16 – Lithostratigraphic characteristics, magnetostratigraphy and foraminiferal zonation of the Acqualagna section.

preted as zone 28 + 29 (296.84 m–297.96 m), zone 27 (298.81 m–300.45 m), zone 26 (301.42 m–303.34 m), and zone 25 (308.80 m–310.85 m). The long reversed interval between 310.85 m and 335.94 m and the double normal interval between 335.94 m and 349.33 m are, respectively. magnetozones 24R and 24. Three normal polarity intervals are present in and close to the upper cherty member. Unfortunately, no unambiguous foraminifera have been obtained from these intervals to better constrain the identification of the magnetozones. One possible way to interpret this part of the magnetic polarity sequence is shown in Fig. 16. Based on a direct lithostratigraphic correlation of the first appearance of the chert levels, the two normal polarity intervals between 335.94 m and 349.33 m are identified as the magnetozone 24. The first chert of the upper cherty member, found at 347.00 m, is contained in this polarity zone. The normal polarity interval between 360.47 m and 363.63 m is identified as magnetozone 21, because the last chert level is located at 357.90 m. A normal polarity interval which may be either magnetozone 22 or 23 is present between 352.50 m and 357.49 m. This sequence implies that some materials are probably missing at this interval. In the field, there is a zone with flaser–bedding located at 354.10 m–354.50 m. This flaser–bedding zone probably represents the trailing edge of a synsedimentary slump. If this interpretation is correct, the magnetostratigraphic results imply a slump accompanied by removal of a substantial amount of the section during magnetochron 22 or 23.

The sedimentary thickness of the Paleocene in this sequence is correlatable to the nearby sections. The total thickness from the C–T boundary to the top of polarity zone 26 is about 6.8 m (Fig. 17). At Pietralata, the total thickness for the same time interval is over 10 m. If the turbidites at Pietralata are omitted, however, the total thickness for the pelagic sediments is only 7 m. Therefore, materials composing the turbidites at Pietralata in the Paleocene are unlikely to be derived from Acqualagna.

At Pietralata and Furlo, large synsedimentary slumps are found in the upper cherty member and at the base of the Scaglia Variegata. The magnetostratigraphic thickness in Acqualagna does not indicate a significant reduction in sedimentary thickness at Acqualagna during the Paleocene. The results suggest that the source of the slumps in Furlo and Pietralata was probably not from Acqualagna. However, the reduction of sedimentary thickness found in the upper cherty member during the Eocene corresponds well with the occurrence of the synsedimentary slump at Pietralata.

Rocca Leonella (43.58°N, 12.56°E) (Fig. 18, 19).

The Rocca Leonella section is located near the small town of Bacciardi about 3 km from Piobbico on the road to Cagli (Fig. 18). The section rests on top of a condensed Jurassic sequence, postulated to be a structural high in the paleobasin during the Jurassic (Colacicchi & Pialli, 1969). The sedimentary characteristics of the Scaglia Rossa at Rocca Leonella are different from the other sections studied. The lower member has a high concentration of cherts in the first 6 m of section above the Bonarelli level. The last chert was found at 134.7 m, giving the total thickness of the lower cherty member 34.7 m, which is substantially thinner than that in other Umbria–Marche sections. From the Bonarelli level to the top of the lower cherty member, bedding is clear and

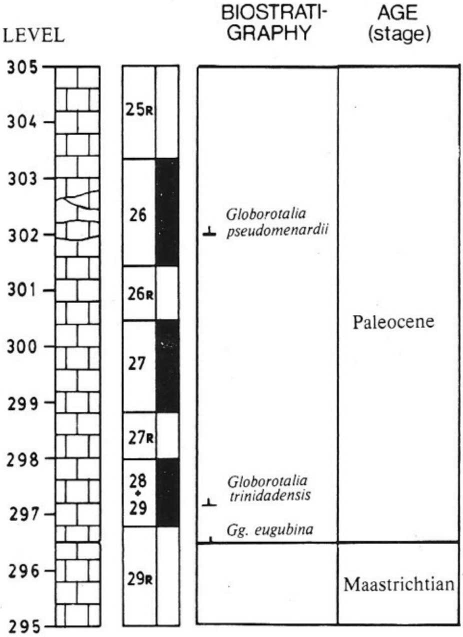


Fig. 17 – Magnetozones of the Paleocene in Acqualagna.

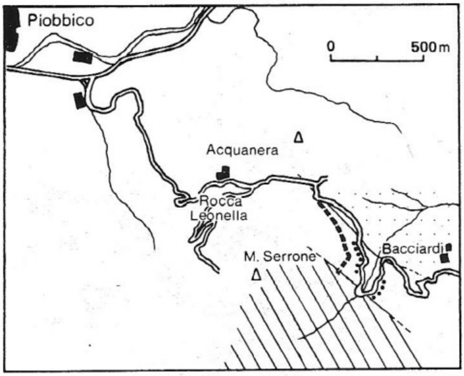


Fig. 18 – Detailed locations of the Rocca Leonella section. Explanations to the symbols are the same as in Fig. 7.

emphasized by bedding–plane stylolites. Between 152 and 300 m about 80 meters of the section are covered by debris and vegetation. The sediments are undeformed between 300 m and 318 m but become massive and fractured between 318 m and 330 m. The C–T boundary is represented by a 2–meter soft–sediment deformation zone at 348.70 m, with limestones containing a mixture of Cretaceous and Tertiary sediments. Fluidal structures are observed in this slump zone, suggesting a hydroplastic deformation in a semiconsolidated state. *Gr. pseudomenardii* was found in the undisturbed sediments above the slump zone.

Oriented cores were collected from this section at 1 m intervals. Magnetostratigraphic study at this section was done to correlate the lower cherty member with the Gubbio section in an attempt to determine whether the uppermost chert in this member is isochronous with that of the Gubbio section, and to date the slump at the C–T boundary.

As shown in Fig. 19, the entire lower section falls in a normal polarity

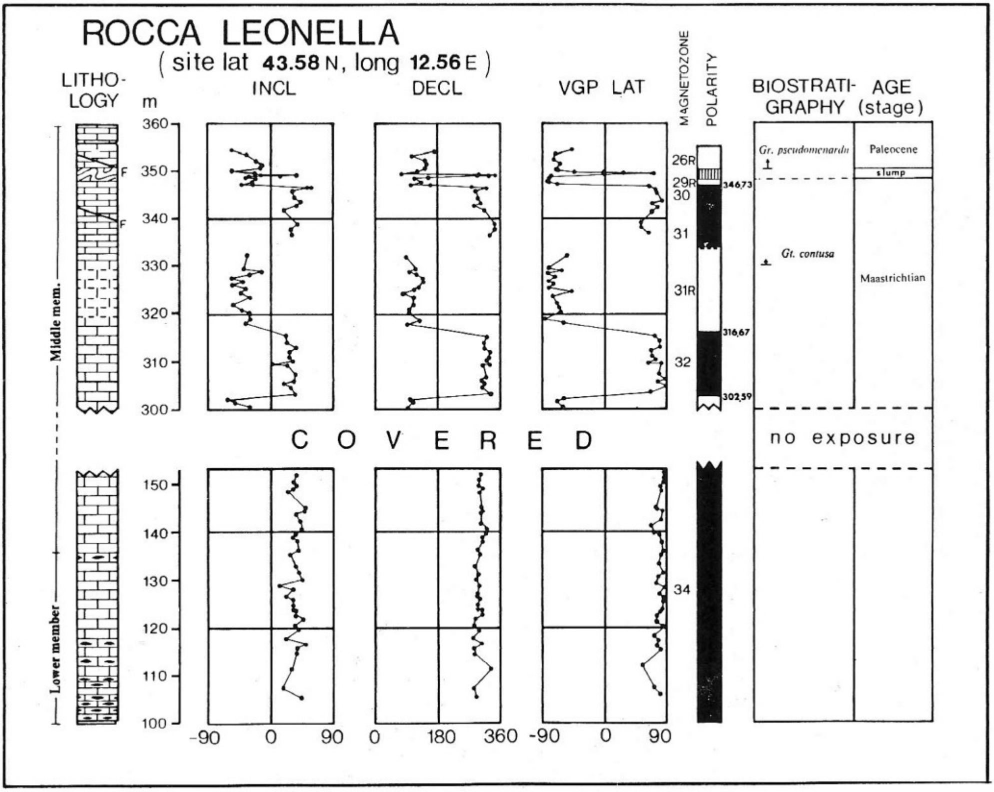


Fig. 19 – Lithostratigraphic characteristics, magnetostratigraphy and foraminiferal zonation of the Rocca Leonella section.

interval. Zone 33R (A–), which contains the last chert level in the lower cherty member at Gubbio, was not observed in this section. Therefore, the chert level observed at 134.7 m in this section is possibly not isochronous with the uppermost chert in Gubbio. However, it is possible that the last chert in the lower member is actually hidden under the debris, or was removed by a slump. Then, the chert level present at 134.7 m cannot be used to represent the lithostratigraphic boundary of the lower member.

Three reversed and two normal polarity intervals are present between 300 m and the C–T boundary at 349 m. *Gt. contusa* is present at level 330 m, indicating that the normal polarity interval between 334.28 m and 346.73 m is the combined magnetozone of 30 and 31 (F +). The normal polarity interval between 302.59 and 316.67 m and the reversed polarity interval below the C–T slump between 346.73 m and 348.70 m are identified respectively as magnetozone 32 and zone 29R. All the specimens collected below the slump fold show directions similar to the characteristic direction of the Umbria region (Fig. 19). This suggests that the section between 318 and 330 m has a uniform bedding although bedding planes in that interval are not well defined. Intermediate magnetic directions were observed in the slump zone. The first undisturbed layer above the slump zone at 352 m is located in a reversed polarity interval identified as magnetozone 26R.

The section covered by the debris is estimated to be 80 meters thick. Including the covered portion, the total thickness between the Bonarelli level and the C–T boundary is about 180 m, which is about 55 m shorter than the corresponding section in Gubbio. The slower sedimentation rate at Rocca Leonella suggests that during the Late Cretaceous time, the area was located on a topographic high or on a slope, probably formed by the reactivation of the Jurassic normal faults flanking the seamount. The similarities in the morphological setting of the Jurassic and Late Cretaceous–Eocene suggest that the reactivated tectonic movements probably had the same sense of motion as in the Jurassic. The magnetic stratigraphy suggests that the slumping occurred in zone 26R during the late Paleocene which probably represents a time of reactivated movements on the Jurassic normal faults.

Frontale (43.35°N, 13.01°E) (Fig. 20, 21).

Both the Frontale and the Poggio San Vicino sections are located on the northern slope of Monte San Vicino (Fig. 20). The structure and stratigraphy of this area are complicated (Coltorti, 1980; Montanari et al., 1983) as demonstrated by the remarkably different stratigraphic characteristics of the two sections which are separated by only one kilometer.

The Frontale section is located in a quarry near the village of Frontale. The Scaglia Rossa in this section is underlain by the Scaglia Bianca, the Fucoid

Marls and the Upper Jurassic–Lower Cretaceous Maiolica limestones. Part of the Scaglia Bianca, the Bonarelli level, and part of the lower cherty member of the Scaglia Rossa were truncated by a fault at 182 m. The two black laminated marker chert beds were found at the footwall of the fault, indicating that the Bonarelli level should be within seven meters of the fault. The well–bedded, lower cherty member of the Scaglia Rossa here is 53 meters thick between the fault and 235.88 m. In the middle member between 235.88 m and 280 m, the lithology is characterized by thick–bedded limestones with several sets of fracture planes criss–crossing the outcrop. Identification of bedding planes is very difficult here. Since the sampling site is located in a limestone quarry, some blocks might be detached from the quarry wall resulting in local rotations of the rocks in this part of the section.

The Cretaceous part of the middle member is 60 meter thick with no turbidites. The C–T boundary is located at level 294.63 m with the *Gg. eugubina* Zone overlying the C–T clay layer. The first turbidite in the Scaglia Rossa in this section occurs at 298.45 m. Some marl layers, which may correspond to the first Tertiary marls observed in the Gubbio and Moria sections, are found at 297 m. Between 303 m and 307 m evidence for synsedimentary slumping was found. The upper cherty member is intensely folded, making it impossible to determine the stratigraphic succession. Paleomagnetic cores were collected at 1–2 meter intervals in the Scaglia Rossa in this section.

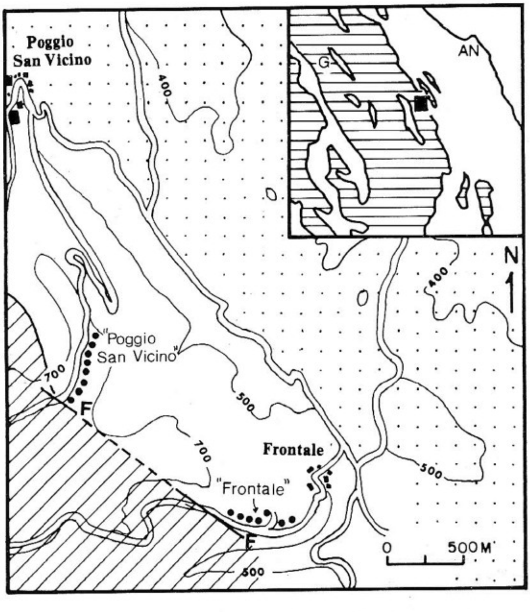
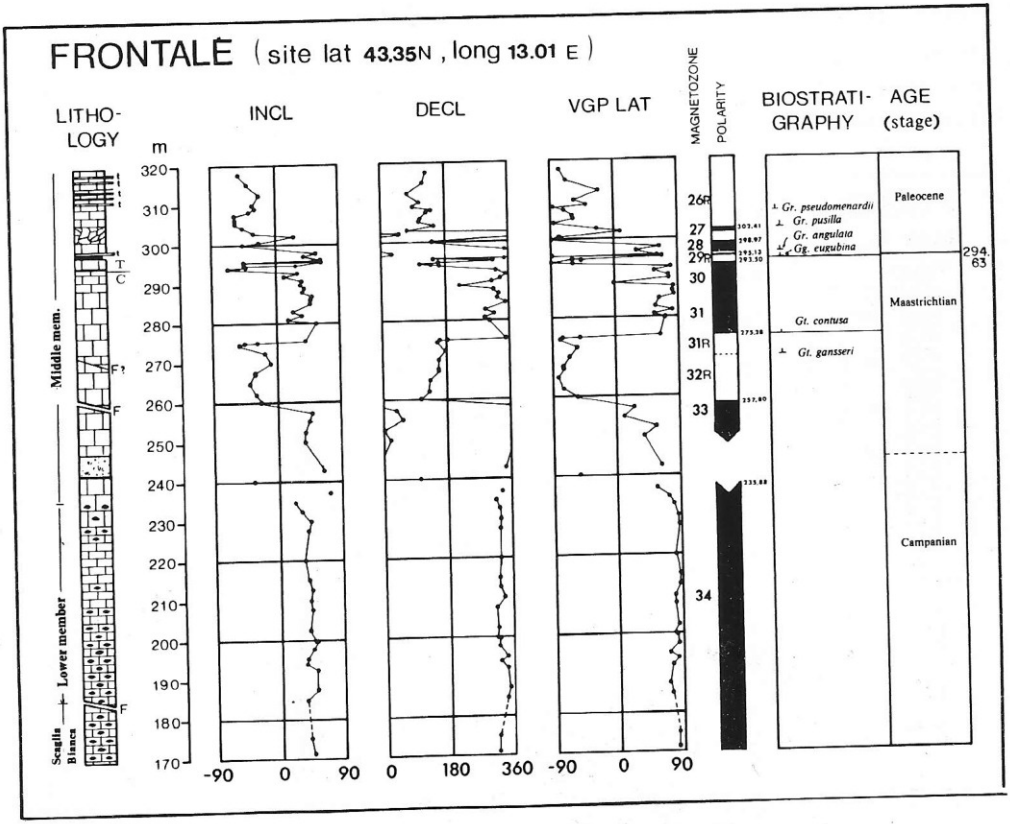


Fig. 20 – Detailed location map of the Frontale and Poggio San Vicino sections. Explanation of symbols is the same as in Fig. 7.

The results of magnetic stratigraphy measurements of the Frontale section are shown in Fig. 21. The entire lower cherty member falls in a normal polarity interval correlated to magnetozone 34 (Gubbio Long Normal Zone). A reversed polarity interval was found at between 258.7 m and 275.26 m, but this part of the section was disturbed by faulting and synsedimentary slumps. The part of the reversed polarity interval between 270 m and 275.26 m is probably zone 31R (E–) because *Gt. contusa, Gt. stuarti, Gt. conica* and *Gt. gansseri* occur in specimens at 270 m. The part between 258.7 m and 270 m is possibly magnetozone 32R which was brought into contact with zone 31R by a fault. The magnetic polarity zonation is uncertain between 235.88 m and 258.7 m because some portion of the section was probably truncated by a fault hidden under the debris cover at 242–248 m. Zone 29R (G–) containing the C–T boundary is represented by a very short reversed polarity zone between 293.50 m and 295.13 m. The reversed polarity interval observed between 302.41 m and the



top of the section contains *Gr. pusilla pusilla* and *Gr. pseudomenardii*, indicating that this is magnetozone 26R. Three short normal polarity intervals corresponding to magnetozones 29 to 27 are found between 295.13 m and 302.41 m. The total thickness of zone 26R is over 15 meters, probably due to plentiful turbidites and slumps as a result of the synsedimentary tectonic movement. The presence of turbidites and slumps in magnetozone 26R suggests that the Frontale section was situated on a slope during the Paleocene.

Poggio San Vicino (43.36°N, 13.01°E) (Fig. 20, 22, 23).

This section is exposed on the road between the town of Poggio San Vicino and Monte San Vicino. Turbidites are present in both the Cretaceous and the Tertiary parts of this section (Fig. 22). Only part of the middle chert–free member is exposed. A fault, represented by a 15 m tectonized zone near the base of the section, has brought the Scaglia Bianca against the middle member of the Scaglia Rossa. A few faults with small displacements of less than 2 m are present at several levels in the section. The bottom 60 m of the section are characterized by undisturbed sediments, with continuous bedding and frequent turbidites. The Cretaceous–Tertiary boundary occurs at a synsedimentary slump containing a mixture of Cretaceous and Tertiary foraminifera.

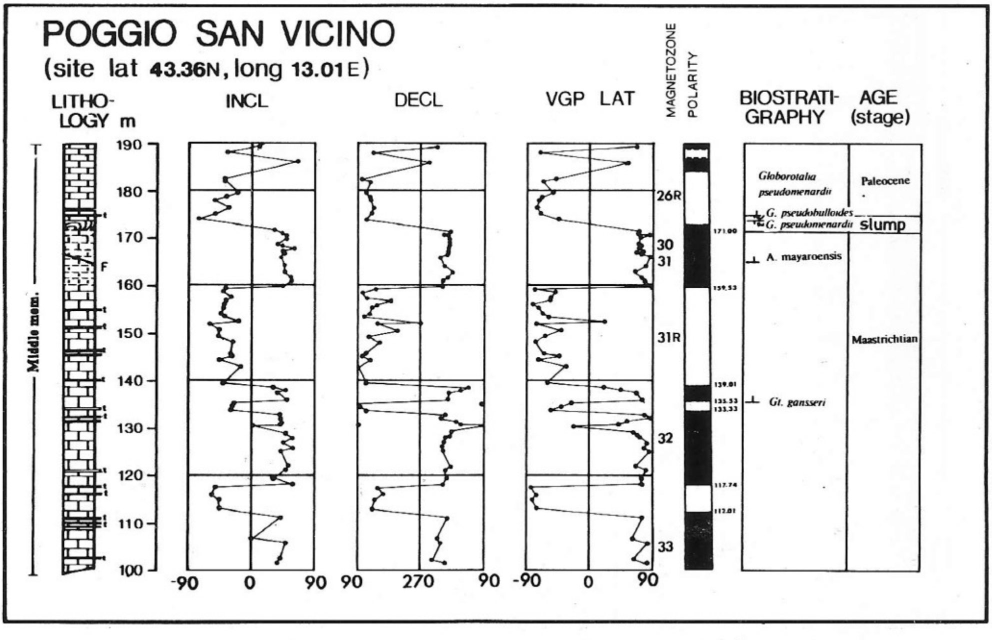


Fig. 22 – Lithostratigraphic characteristics, magnetostratigraphy and foraminiferal zonation of the Poggio San Vicino section.

The foraminifera were studied at 40 different levels in this section. Between 100.00 m and 133.00 m, the following species of *Globotruncana* are found: *Globotruncana stuartiformis*, *Gt. ventricosa*, *Gt. arca*, *Gt. lapparenti*, and *Gt. stuarti*. No distinctive biozones have been determined in this part of the outcrop. At 136.00 m, late Maastrichtian *Globotruncana gansseri* and *Rugoglobigerina rotundata* are present. At 165.00 m, *Abathomphalus mayaroensis* is found in the sediments. The first appearances of the *Gt. gansseri* and *Globotruncana contusa* are located respectively at the top of the magnetic polarity zone 32 and near to the base of polarity zone 31 at Gubbio. The positions of these FAD's facilitate the identification of the magnetic polarity intervals in the Cretaceous part of the section.

The Tertiary part of the section contains an inverted biostratigraphic sequence near the C–T boundary overlain by upper Paleocene sediments. At 173.00 m, *Globorotalia pusilla pusilla*, *Gr. pseudomenardii*, and *Gr. angulata*, were found. The presence of these species puts this specimen in the *Gr. pseudomenardii* Zone in the upper Paleocene. At 174.00 m, lower Paleocene *Globorotalia pseudobulloides* and *Gr. trinidadensis* are present, putting the specimen in the older *Gr. pseudobulloides* Zone. This sequence is overlain by an upright turbidite containing *Globorotalia pseudomenardii*. The inverted sequence is part of the synsedimentary slump which occurred during the late Paleocene.

The magnetic polarity in this section is shown in Fig. 22. The appearance of *Gt. gansseri* at 136.00 m indicates that the reversed polarity interval between 139.01 m and 159.53 m is magnetozone 31R. Zones 32 and 32R are present respectively at 117.74 m–139.01 m and 112.01 m–117.74 m. A 2.2 meter reversed interval is found between 133.33 m and 135.53 m at the top of magnetozone 32. This short reversed polarity interval is also present in Gubbio (Lowrie & Alvarez, 1977) and in the marine magnetic anomaly sequence (LaBrecque et al., 1977). The normal polarity interval between 159.53 m and the C–T boundary slump is identified as the combined magnetozone of 30 and 31 (F+). The presence of *A. mayaroensis* at 165.00 m supports this identification. The thin reversal separating zones 30 and 31 has not been found. The sequence containing part of magnetozone 30 and magnetozone 29R is probably involved in the C–T boundary slump.

The section from the slump to 182.55 m lies within a reversed polarity interval. This interval is identified as magnetozone 26R because of the presence of *Globorotalia pseudomenardii* in both the slump and the overlying sediments. Therefore, the slump occurred during magnetochron 26R in the late Paleocene.

There is evidence that the magnetization in the C–T boundary slump was reset during the slumping. The stable magnetic remanence in the specimens collected from different parts of the slump shows similar directions before applying the correction for the local bedding but diverse directions afterward (Fig.

23). The mean inclination and declination for the 10 specimens collected from the slump are −26.5° and 80.7° respectively, with an α_{95} = 9.4°. This direction is in similar to the direction of the specimens obtained from the overlying magnetozone 26R.

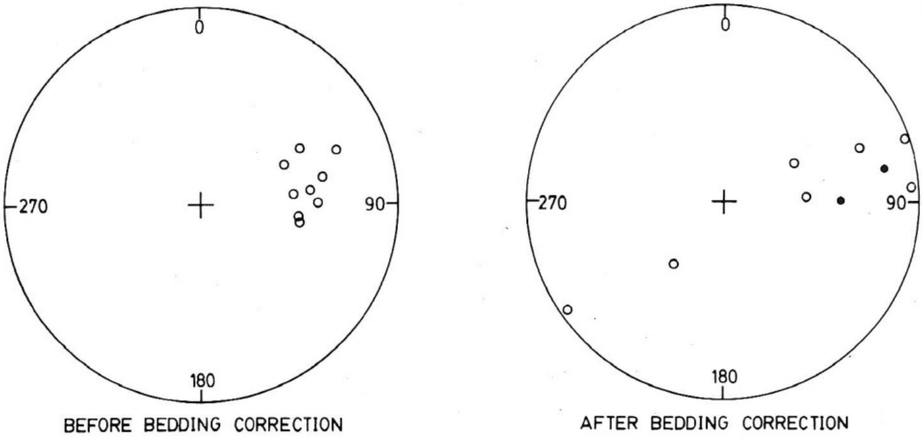


Fig. 23 – Stable magnetic directions of the specimens collected from the slump near the C–T boundary at Poggio San Vicino. The in situ magnetic directions (left) cluster better than the directions after applying bedding correction (right) suggesting a post–slump acquisition of the remanent magnetism.

Sedimentary and Tectonic Implications

Implications for chronostratigraphic boundaries.

The magnetostratigraphic sequences in the studied sections generally correlate well with the previously studied sections at Gubbio and Contessa. The present study further reconfirms the previous determination of three epoch and stage boundaries in the Northern Apennines (Lowrie et al., 1982). In all the sections studied, the Cretaceous–Tertiary boundary falls within magnetozone 29R. The recent interest in mass extinction problems (e.g. L.W. Alvarez et al., 1980; Chan et al., 1982) has led to an increasing demand for a refined dating of the events near the C–T boundary. Geochronological determination with a resolution of 0.1 million years or better is often desired. The precise position of the C–T boundary within the magnetozone is therefore significant in the discussion of the mass extinction problems.

In conducting a more quantitative measurement of the C–T boundary events, we have applied the numbering system for magnetochrons proposed by LaBrecque et al. (1983). In this system, the location of an event within a magnetochron is specified by the fraction of the magnetochron (both normal and reversed portions -- e.g. 29 + 29R) measured from its younger boundary. For example, the C–T boundary is located at 347.6 m in the Gubbio section within magnetozone 29R. The top of magnetozone 29 is located at 351.5 m and the base of magnetozone 29R is located at 343.9 m (Alvarez et al., 1977). Since

(351.5–347.6) / (351.5–343.9) = 0.51,

the position of the C–T boundary in this section is therefore designated as C29.51R. With the same method the C–T boundary in the Frontale, Moria (Alvarez & Lowrie, 1978), and Acqualagna sections are located respectively at C29.45R, C29.43R and C29.35R. The average of the four data is C29.43R. This number, however, does not represent the true chronostratigraphic position of the boundary because of variations in the sedimentation rate within the magnetozone. Based on radiometric data, Cox (1982) suggested an age of 65.0 m.y. for the C–T boundary. The results from marine magnetic anomalies suggest that the upper and lower boundaries of anomaly 29 are at 63.99 m.y. and 65.34 m.y. Using the same method, the C–T boundary is located at C29.75R. The chronostratigraphic position of the C–T boundary in the Umbria–Marche sections is therefore significantly higher than that extrapolated from the marine anomalies. The discrepancy can be explained by a reduction of sedimentation rates by a factor of 3 at the C–T boundary. This reduction in the sedimentation rate in the Scaglia Rossa was also suggested by Arthur and Fischer (1977) and by LaBrecque et al. (1983).

This study also adds information about the Paleocene–Eocene boundary. Previous magnetostratigraphic studies put this boundary in magnetozone 23 (LaBrecque et al., 1977), magnetozone 24 (Ness et al., 1980), or magnetozone 24R (Lowrie et al., 1982). The Paleocene–Eocene boundary coincides with the FAD of *Gr. rex* (Postuma, 1971). In the present study, the FAD of *Gr. rex* is found in magnetozone 24R at both Pietralata and Acqualagna. The finding agrees with the suggestion by Lowrie et al. (1982) and rejects the others.

The results from this study have constrained the magnetostratigraphic age of the lower–middle Eocene boundary. At Lower Pietralata, middle Eocene *Gr. bullbrooki* is found near the top of magnetozone 21R. However, the resolution in this study does not indicate unambiguously whether the boundary is contained within zone 22 or zone 21R.

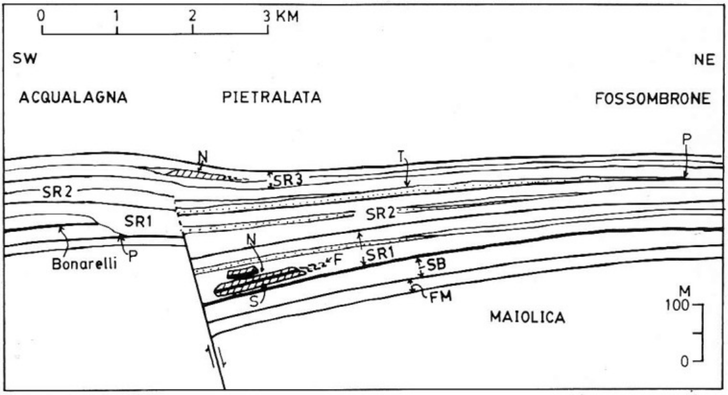
Correlation between stratigraphic sections.

Based on the observed lithostratigraphy, biostratigraphy, and magnetostratigraphy, a hypothetical reconstruction of the Acqualagna–Pietralata–Fossombrone area is suggested here. This reconstruction is based on the following observations.

1) The Pietralata–Paganuccio area represents a basinal facies. Turbidite

activity and slumps occurred episodically in the basin. At Pietralata, two maxima in the turbidite concentration are present in the Paleocene (Montanari, 1979). The earlier maximum, located in magnetozone 29, has a total turbidite thickness of 64 cm, while the later one, in magnetozone 26R, has a total thickness of 302 cm. The thickness of the pelagic sediments can be obtained by subtracting the thickness of the turbidites from the total thickness of the section. The pelagic limestones at Pietralata, obtained by this calculation, is 7 m. Since materials may be lost due to submarine erosion and mass wastings the true total thickness of pelagic sediments deposited in the basin should be greater than this number.

2) During the same time intervals, materials were removed from the Fossombrone area. Two major paraconformities are present in the Fossombrone section. The first paraconformity is located between upper Maastrichtian and magnetic polarity zone 28R and the second one between magnetozone 28R and magnetozone 26R. Based on the thickness of the pelagic sediments at Pietralata, we estimate that the two paraconformities represent about 100 cm and 300 cm of missing sediments. The figures are roughly equal to the total thickness of the turbidite in magnetozone 29 and 26R at Pietralata. The result does not necessarily imply that materials removed from Fossombrone were redeposited at Pietralata, but it suggests that removal of materials from the former area was accompanied by strong turbidite activities at the latter area.



Fig, 24 – A hypothetical reconstruction of the Fossombrone–Pietralata–Acqualagna area. The symbols are: FM) Fucoid Marls; SB) Scaglia Bianca; SR1) Scaglia Rossa, lower member; SR2) Scaglia Rossa middle member; SR3) Scaglia Rossa, upper member; P) paraconformity; T) turbidites; F) slump folds; N) neoautochthon; S) coherent slump block. In this model, slumps and turbidite activities in Pietralata are coupled with development of paraconformities at Fossombrone and Acqualagna.

3) The total thickness of the Paleocene at Acqualagna is the same as the thickness of the pelagic sediments in Pietralata. This suggests that little material was transported from Acqualagna to Pietralata during this interval of time. However, the upper cherty member in Acqualagna is substantially thinner than that at Pietralata. If the interpretation of the magnetic stratigraphy at Acqualagna is correct, a major paraconformity is possibly present between magnetozone 21 and magnetozone 23R.

4) In addition to these magnetostratigraphic observations, the sedimentary facies at Acqualagna and Pietralata are also remarkably different. The former section contains only pelagic carbonates and marls while the latter section is rich in turbidites, although the two sections are just 3 km apart.

A possible paleomorphological reconstruction of this area is shown in Fig. 24. In the model, a fault is present between Pietralata and Acqualagna. Pietralata is located in a basin receiving turbiditic sediments and slumps from both the direction of Fossombrone and of Acqualagna. The structural high prevents the turbiditic sediments from being transported further to the southwest, resulting in a turbidite–free facies at Acqualagna. Fossombrone is located on a slope where turbiditic materials are occasionally deposited. But more often, sediments are removed and transported from this area to the basin at Pietralata. The relationship among the different sedimentary events are shown in the figure. Tectonic movements along the fault triggered the occurrences of turbidites and slumps from both sides of the fault. As materials were removed from Fossombrone or Acqualagna, paraconformities are formed. At the same time, intensive turbidite activities are present at Pietralata.

This postulated normal fault located between Acqualagna and Pietralata possibly extended to the southeast, since similar synsedimentary tectonic activities intervals were also present at Arcevia, Poggio San Vicino, and Frontale during the same time intervals. During the Late Tertiary deformation of the Northern Apennines, a thrust fault was formed on the eastern side of the Arcevia–Monte San Vicino anticline. The normal fault active during the Late Cretaceous–Eocene time was possibly reactivated to form the thrust fault during the Late Tertiary deformation.

Synchroneity of the lithostratigraphic markers.

Previous lithostratigraphic division of the Scaglia Rossa was based on the first and last appearance of cherts in the upper and lower members (Renz, 1951; Arthur & Fischer, 1977). The magnetostratigraphic results from Rocca Leonella indicate that the highest chert in the lower member does not occur at the same level as its equivalent in the Gubbio section. Unless this observed chert level is actually not the highest chert level in the lower cherty member of the

Scaglia Rossa, we are able to infer that the lithostratigraphic markers are at least locally diachronous.

LaBrecque et al. (1983) suggested that the formation of the upper cherty member in the Umbria Region was probably an Atlantic phenomenon. The magnetostratigraphic results from the upper cherty member in Acqualagna and Lower Pietralata provide a means to test this theory (Fig. 25). At Contessa (Lowrie et al., 1982), the first chert in the upper cherty member is found at the boundary of magnetozone 24 and 24R. In the Lower Pietralata section, the first chert is found in magnetozone 24. In the Acqualagna section, this first chert level is also present near the top of magnetozone 24. The small discrepancies in the stratigraphic level of the first chert in the upper member probably result from statistical fluctuations. There is no firm evidence suggesting a diachroneity of the first chert levels in the upper cherty member.

The highest chert in the upper member, however, occurs at different levels at Contessa and Lower Pietralata. In the former section, the last chert is seen at the base of magnetozone 21, while in the latter section, it is present within magnetozone 20R. If we use the last chert at Lower Pietralata section as a reference level, then there is a gap of at least 10 m existing between the observed chert level and the reference level at Contessa. In order to determine whether a 10 m gap can result from statistical fluctuations, we have conducted the following test:

1) By studying the distribution pattern of the chert levels in the upper member, we have found that the chert levels are, in general, randomly distributed within this member.

2) Since the chert levels are randomly distributed in the upper member, we have used a Poisson distribution to approximate their occurrences. The Poisson distribution function is given by

$$P(n) = e^{-x} x^{n} / n!$$

in which P (n) is the probability of obtaining exactly n chert levels within a specified interval, and x is the expected number of chert levels for that interval. Therefore, the probability of obtaining no chert within a specified interval is

$$P(0) = e^{-x}$$

3) To obtain the expected number of cherts within a 10 m interval, we need to determine the mean density of the chert levels. We do not have the exact count of the number of chert levels in the Contessa section, but at Pietralata, there are 31 chert levels between 1.80 m and 20.14 m. Therefore, the mean density of the chert levels is

$$31 / (20.14 \text{ m} - 1.80 \text{ m}) = 1.69 \text{ m}^{-1}$$

4) Thus, the probability of obtaining a 10 meter gap in the upper member is given by

$$P(0) = e^{-(10)(1.69)} = 5 \times 10^{-8}.$$

The vanishingly small probability suggests that the 10 meter gap is unlikely to be a result of statistical fluctuations. The negative result of this statistical test has two significant implications: first, the diachroneity of the chert levels implies that they cannot be used as accurate markers for boundaries of chronostratigraphic units. Secondly, it has led to doubt whether the occurrences of the chert beds were related to an Atlantic event. A similar comparison of the occurrences of the cherty units around the Atlantic on a quantitative basis would help to answer this question.

Magnetostratigraphic dating of synsedimentary tectonic events.

The magnetostratigraphic results have provided information on the timing of the turbidite and slump activities. A summary of the magnetostratigraphic correlation of the sections studied to the Gubbio and Contessa sections studied previously is shown in Fig. 25. The results indicate that these turbidites and slumps are concentrated in particular time intervals. Since these turbidites and slumps are related to tectonic movements occurring during the time of deposition, determining their magnetic polarity zones provides a means of direct dating of the syndepositional tectonic movements.

The time intervals corresponding to magnetic polarity zones 32–31R, 29–28R, and 26R represent three periods of intensive tectonic activities.

1) Zone 32–31R – During the time interval from the end of magnetochron 32 to magnetochron 31R, there were extensive turbidite deposition and slumping in the paleobasin. At Frontale, synsedimentary slumps are present in this interval. At Poggio San Vicino, Monte Paganuccio, Pietralata and Furlo, maxima in the turbidite activities were observed. At Fossombrone, materials were intensively removed and transported to the Pietralata–Mt. Paganuccio basin. The stratigraphic characteristics in these sections are diagnostic of strong submarine erosion and resedimentation resulting from extensive tectonic movements in local parts of the Umbria–Marche Basin during the late Maastrichtian.

2) Zone 29–28R – During the early Paleocene, turbidites were formed in the Pietralata–Mt. Paganuccio basin. Slumps and turbidite activities culminated shortly after the C–T boundary. At Pietralata and Paganuccio, turbiditic sequences are present at a few meters above the C–T boundary. In some areas, this sequence of turbidites was contained in a synsedimentary slump occurring during a later time. At Fossombrone, a hiatus is present between the upper Maastrichtian and the lower Paleocene.

3) Zone 26R – Occurrence of turbidites and slumps culminated during the late Paleocene. This was the interval of most active tectonic movements during the Late Cretaceous–Eocene in the paleobasin. Extensive slumps and turbidites are present in Frontale, Poggio San Vicino, Monte Paganuccio, Furlo, and Rocca Leonella. Bulk sedimentation rates at the Fossombrone, Acqualagna, Furlo and Contessa sections decreased substantially during the Paleocene, probably because of strong removal of the sediments by the bottom currents. The undisturbed layers on top of the synsedimentary deformation zone often contain the late Paleocene *Globorotalia pseudomenardii.*

Besides these three major phases, other tectonic movements also occurred at a smaller scale in the Umbria–Marche Basin during the Late Cretaceous–Eocene. These tectonic movements were generally separated by long intervals of tectonic quiescence. A correlation of these tectonic phases with the major tectonic events in the surrounding areas would certainly facilitate the interpretation of the evolution of the Northern Apennines.

Acknowledgments.

The present study is part of LSC's PhD dissertation under the supervision of Prof. Walter Alvarez. LSC thanks WA for continuous support and encouragements throughout his graduale career. The paleomagnetic measurements in this study was carried out at the Magnetics Lab at Stanford University. Help from the paleomagnetic group there is acknowledged. The authors also thank Prof. Michael McWilliams and Prof. Carla Rossi Ronchetti for reviewing the manuscript. This research was supported by National Science Foundation grants EAR–80–22846 and EAR–83–18660, and also in part by Chevron Oversea Petroleum, Inc. The Marche Region in Italy has also provided field and material support for this research project.

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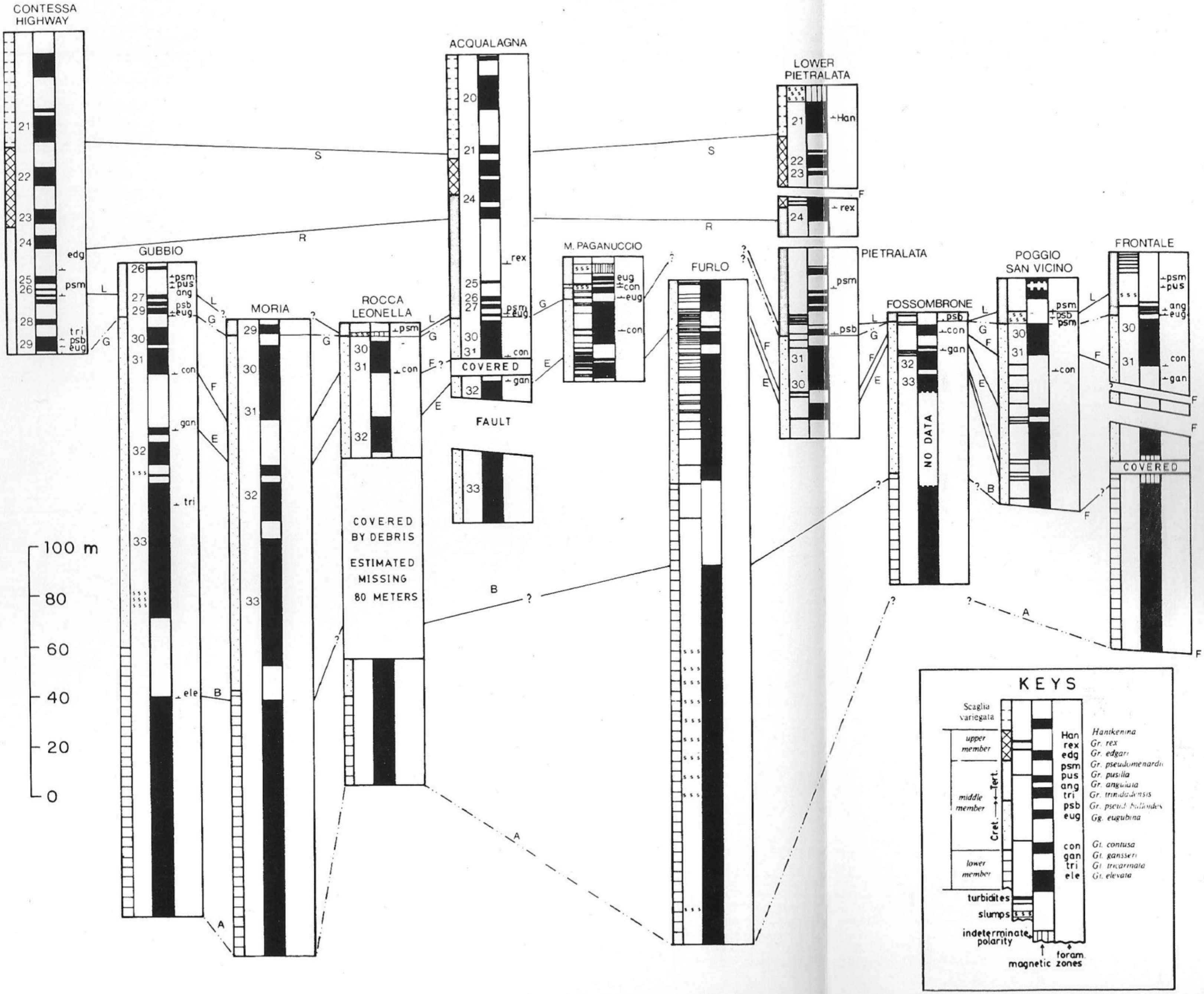

Fig. 25 – Correlation of the studied magnetostratigraphic sections to the Gubbio, Furlo and Moria sections studied previously (Alvarez et al., 1977; Alvarez & Lowrie, 1978, and 1984). Dotted lines are isochronous lines determined on the basis of lithostratigraphic markers; solid lines are determined on the basis of reversal boundaries. The symbols for the different isochronous lines are: A) Bonarelli shale layer; B) upper boundary of zone 34; E) upper boundary of zone 32; F) upper boundary of zone 31R; G) C–T boundary; L) upper boundary of zone 27; R) lower boundary of zone 24; S) upper boundary of zone 22.