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## **Paleomagnetic investigations on the Pleistocene lacustrine sequence of Piànico-Sèllere (northern Italy)**

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### **Abstract**

The Piànico-Sèllere is a lacustrine succession from northern Italy that records a sequence of climatic transitions across two Pleistocene glacial stages. The intervening interglacial stage is represented by well-preserved varves with calcitic summer and clastic winter laminae. There is a tight coupling between climate-driven lithologic changes and magnetic susceptibility variations, and retrieved stable paleomagnetic components from all investigated lithologies including the largely diamagnetic calcite varves. These components were used to delineate a sequence of magnetic polarity reversals that was interpreted as a record of excursions of the Earth's magnetic field. Comparison of the magnetostratigraphic results with previously published data allows discussion of two possible models which have generated controversy regarding the age of the Piànico Formation. The data indicates that the Piànico Formation magnetostratigraphy correlates to geomagnetic field excursions across the Brunhes/Matuyama transition, and consequently the Piànico interglacial correlates to marine isotope stage 19. This correlation option is substantially consistent with K-Ar radiometric age estimates recently

obtained from a tephra layer interbedded in the Piànico Formation. The alternative option, considering the Piànico interglacial correlative to marine isotope stage 11 within the Brunhes Chron as supported by tephrochronological dating reported in the literature, is not supported by the magnetostratigraphic results.

**Keywords:** Piànico Formation; Pleistocene; magnetostratigraphy; polarity excursions; Brunhes Chron; Southern Alps.

## 1. Introduction

The Piànico-Sèllere is a lacustrine succession spectacularly outcropping along the Borlezza River in the Southern Alps of northern Italy (Fig. 1). This succession deposited during two Pleistocene glacial stages embracing an intervening interglacial, the age of which has however not yet been unanimously identified. Despite a wealth of studies carried out over more than a century, “the dispute about the age of these deposits is almost as old as their discovery some 150 years ago” (Brauer et al., 2007b). This failure mainly arises from the traditionally difficult task of dating continental deposits. The Piànico-Sèllere sequence is older than radiocarbon age limits (Orombelli, 1974; Alessio et al., 1978), and attempted U-Th dating is regarded as unreliable because the carbonate succession of Piànico does not represent a closed system (Brauer et al., 2007a). Furthermore, the detailed pollen profile available from Piànico-Sèllere (Moscariello et al., 2000) cannot presently resolve the age uncertainties in absence of a reliable regional palynological chronology.

Two tephra levels, t21d and t32, were identified in the Piànico-Sèllere succession (Pinti et al., 2001; Brauer et al., 2007a). K-Ar dating of t21d yielded an age of  $779 \pm 13$  ka (Pinti et al., 2001), indicating that the Piànico Formation is much older than previously suggested (Riss/Würm interglacial, ~125 ka; Venzo, 1955; Casati, 1968). According to Pinti et al. (2001), this age is supported by the presence in the lower part of the sequence of reverse paleomagnetic polarity referred to the Matuyama Chron, and therefore older than ~783 ka (i.e., the age of onset of the Brunhes–Matuyama polarity transition at Ocean Drilling Program Site 984; Channell et al., 2004). Brauer et al. (2007a), however, questioned the validity of this radiometric age, and proposed an alternative age estimate based on geochemical correlation of tephra t32 with volcanic activity occurring around ~400 ka at Roccamonfina in Latium (Central Italy). These two age options can be tested with paleomagnetism. An age of ~779 ka for the Piànico Formation would imply the presence

of the Brunhes/Matuyama transition, as the preliminary paleomagnetic data of Pinti et al. (2001) seem to suggest. Conversely, if the Piànico Formation is ~400 ka-old, dominant normal polarity pertaining to the Brunhes Chron should be encountered.

This study presents paleomagnetic data from the Piànico Formation in order to address the controversy regarding the age of the Piànico-Sèllere sequence. Due to the fragmentary exposure of sediments along the Borlezza River, three partially overlapping sections were studied, collectively covering the exposed stratigraphic sequence of the Piànico Formation. These are a new stratigraphic section, named the “dike section” (Figs. 1, 2) and sections 4 and 5 of Moscariello et al. (2000) (Figs. 1, 3). A composite profile has been constructed from sections 4 and 5 by means of lithologic correlations (Ravazzi, 2003) and microstratigraphic studies (Mangili et al., 2005) (Fig. 3). The dike section was initially treated separately and subsequently correlated to this composite profile using lithologic and magnetic features.

## 2. Lithostratigraphy

The ~50 m-thick Piànico Formation consists of four main units (Moscariello et al., 2000). These are, from bottom to top: the *Banco Torbiditico Basale* (BTB, basal turbidite bed; not considered in this study), the *Silt e Argille Basali* (SAB, basal silt and clay; Figs. 2, 3), the *Banco Varvato Carbonatico* (BVC, carbonate varved bed; Fig. 3), and the *Membro di La Palazzina* (MLP, La Palazzina member; Fig. 3). The BTB is composed of fine-grained sand and silt intercalated with lenses of poorly sorted, chaotic sandy gravels and slump deposits. The SAB (Figs. 2, 3) mainly consists of laminated mud intercalated with sand-calcarenite layers. The BVC (Fig. 3) consists predominantly of a sequence of sub-millimetric lacustrine varves, each characterized by a biochemically precipitated calcite layer and an organic rich layer. A preliminary varve count yielded a minimum duration of ~16000 years for the BVC (15500 ± 620 varve years; Brauer et al., 2007a). Tephra t21d was identified by A. Brauer in the BVC, 0.6 m below the BVC/MLP boundary, and it was dated by means of K-Ar chronology to 779 ± 13 ka (Pinti et al., 2001). The MLP (Fig. 3) consists of laminated sand and silt with intercalations of biochemical calcite intervals. According to Mangili et al. (2007), the estimated duration of deposition of this unit is ~8500 years mainly based on varve counting. Tephra t32, dated tephrochronologically to ~400 ka (Brauer et al., 2007a), is located in the MLP, 7.5 m above the BVC/MLP boundary. In the MLP, a complete skeleton of *Cervus acoronatus* was discovered in 2001 (Confortini et al., 2001; Govoni et al., 2006).

Moscariello et al. (2000) reported a fifth unit of the Piànico Formation, the *Unità di Ronco Lanzi* (Ronco Lanzi unit; URL), defined as local debris flow deposits interbedded in the lacustrine succession and produced by gravity flows generated along the steep slopes surrounding the Piànico-Sèllere lake. A major stratigraphic hiatus has been hypothesized at the SAB/BVC boundary (Brauer et al., 2007b), based essentially on the occurrence of a slump-debris flow at the base of the BVC (Moscariello et al., 2000). However, because no data have been provided to quantify the temporal extension of this presumed gap, this study considers, as a first order approximation, that the Piànico Formation represents reasonably continuous deposition at the temporal resolution of this investigation. Facies analysis and pollen content refer the BTB to a glacial stage, the SAB to a transition toward the subsequent interglacial stage, represented by the BVC, and, finally, the MLP as a transition toward a next glacial stage (Moscariello et al., 2000; Mangili et al., 2005).

### 3. Paleomagnetic analyses

A total of 160 cylindrical ( $\sim 10 \text{ cm}^3$ ) samples for paleomagnetic analyses were collected from the SAB, BVC, and MLP (Tab. 1). Laboratory analyses were carried out at the Alpine Laboratory of Paleomagnetism. Low field susceptibility was measured in the laboratory with an AGICO KLY-3 kappabridge. The natural magnetic remanence (NRM) was measured with a 2G-Enterprises SQUID cryogenic magnetometer located in a magnetically shielded room with ambient fields of  $\sim 300 \text{ nT}$ . Thermal and alternating field (AF) demagnetization techniques were applied to representative samples from all lithologies. AF demagnetization was found to be the most effective treatment and was adopted for all remaining samples. Standard least-square analysis (Kirschvink, 1980) was used to calculate component directions chosen from inspection of vector end-point demagnetization diagrams (Zijderveld, 1967).

The magnetic mineralogy of the BVC and MLP, investigated by Rouse et al. (2005), is composed of  $>30 \text{ nm}$ , low-coercivity ferromagnetic minerals interpreted as magnetite, maghemite, or greigite in association with high-coercivity phases (i.e. goethite or hematite) often in the superparamagnetic grain size range.

### 4. Paleomagnetic results

#### 4.1. Susceptibility

In the dike section (Fig. 2), the SAB displays at the bottom constant susceptibility values in

the  $10^{-4}$  range, followed upwards by a swing in the  $10^{-6}$ – $10^{-4}$  range. In the BVC, susceptibility data are sparse and display values in the  $10^{-5}$ – $10^{-4}$  range except for a single negative (diamagnetic) value.

In the composite profile (Fig. 3), the SAB displays a broad range of susceptibility values generally comprised in the  $10^{-5}$ – $10^{-4}$  range. The overlying BVC starts with susceptibility values in the  $10^{-3}$  range and becomes up-section mostly diamagnetic with negative or very low ( $<10^{-5}$ ) values. The transition to the overlying MLP is marked by a gradual increase in susceptibility to peak values in the  $10^{-4}$  range. The lower part of the MLP displays constant low values in the  $10^{-5}$  range with occasional negative values. The data above reveal a strong coupling between lithology and magnetic susceptibility. The abrupt transition between detrital (SAB) to biochemical (BVC) sedimentation is well recorded in the susceptibility log by a shift toward diamagnetic values immediately above the SAB/BVC boundary related to the occurrence in the BVC of abundant endogenic calcite (Mangili et al., 2005). At the BVC/MLP boundary, the susceptibility log shows a gradual shift toward higher positive values, suggesting increasing detrital input in the lacustrine succession related to the onset of soil erosion processes (Mangili et al., 2005).

#### 4.2. Natural remanent magnetization

The intensity of the NRM is generally in the  $10^{-7}$ – $10^{-8}$   $\text{Am}^2\text{kg}^{-1}$  range, with maximum values of  $10^{-6}$   $\text{Am}^2\text{kg}^{-1}$  and  $10^{-4}$   $\text{Am}^2\text{kg}^{-1}$  in the MLP and at the SAB/BVC boundary, respectively, and minimum values of  $10^{-9}$   $\text{Am}^2\text{kg}^{-1}$  in the BVC. The widespread occurrence of diamagnetic minerals (mainly calcite) is responsible for the weak magnetic signal in the BVC. Orthogonal projections of AF demagnetization data indicate the common occurrence of viscous overprints isolated in the 0–10 mT demagnetization interval (Fig. 4A). Removal of these overprints revealed, in 81% of the collected samples, the presence of characteristic magnetization components with either positive (down-pointing) or negative (up-pointing) inclinations resolved in the 10–50 mT demagnetization interval, locally up to 100 mT (Fig. 4A). In a few cases, a lower coercivity magnetization component with positive inclination is followed by a higher coercivity component with negative inclination isolated at demagnetization fields between 40 and 100–150 mT (i.e. P29; Fig. 4A). These characteristic components are plotted on equal area stereographic projection before (*in situ*) and after correction for bedding tilt (tilting values of 5–20°). High degrees of scattering are visible in both coordinate systems (Fig. 4B). Considering that in the BVC, each paleomagnetic sample contains an average of ~40 varves, the observed scattering is

interpreted as due to the combined effects of secular variations and polarity excursions of the Earth's magnetic field.

## 5. Magnetostratigraphy

Virtual geomagnetic pole (VGP) latitudes were calculated from the characteristic magnetization components and used to outline magnetic polarity stratigraphy. Positive (negative) VGP latitudes indicate normal (reverse) polarity. In the dike section (Fig. 2), VGP latitudes indicate the presence of a magnetic reversal at 8 m from section top within the SAB, which divides an upper normal polarity magnetozone from a lower reverse polarity magnetozone. In the composite profile from sections 4 and 5 (Fig. 3), VGP latitudes indicate the presence of a dominant normal polarity magnetozone in the MLP and BVC, with a short interval of reverse polarity at the base of the BVC between 16 and 18.5 m from section top. A normal polarity magnetozone spanning the SAB/BVC boundary follows down-section from 18.5 to 22.5 m (Fig. 3).

The composite profile from sections 4 and 5 and the dike section were correlated by means of lithostratigraphic and magnetic data, taking into account the general distribution of lithologic units, the presence of a slump-debris flow deposit at the SAB/BVC boundary, the characteristic susceptibility swing in the SAB, and magnetic polarity stratigraphy (Fig. 5). This correlation allowed construction of a complete sequence of magnetozones, labeled from the top as normal magnetozone PS1n (5–16 m), reverse magnetozone PS1r (16–18.5 m), normal magnetozone PS2n (18.5–25.5 m), and reverse magnetozone PS2r (25.5–32.5 m) (Fig. 5).

The overall magnetic polarity stratigraphy outlined for the Piànico Formation is well within the range of polarity excursions typical of the Brunhes Chron or the Brunhes/Matuyama boundary. The BVC undecompressed stratigraphic thickness of ~11 m coupled with the provided varves chronology (~16000 years) implies average undecompressed sediment accumulation rates in the order of ~0.69 mm/a. Therefore, the ~2.5 m-thick reverse polarity PS1r within the BVC should have lasted ~3500 years, whereas the underlying ~7 m-thick reverse polarity PS2r may have spanned a similar duration assuming somewhat higher sediment accumulation rates for the SAB (~2 mm/a).

## 6. Age models

In the recent years, several studies focused on the high-resolution paleomagnetic record of the Brunhes Chron and the Brunhes–Matuyama transition (e.g., Langereis et al., 1997;



Channell et al., 2004; Lund et al., 2006). These studies allowed the detection and age calibration of a number of geomagnetic polarity excursions, the existence of several of which however still awaits confirmation from independent investigations. Figure 6 shows a compilation of Brunhes Chron polarity excursions. These are excursions  $3\alpha$  to  $17\alpha$  from Lund et al. (2006), and two excursions close to the Brunhes–Matuyama transition from Channell et al. (2004) labeled in this study as  $19\alpha$  and  $19\beta$ . This polarity sequence is correlated to the recent  $\delta^{18}\text{O}$  record of Lisiecki and Raymo (2005) and the higher-resolution deuterium ( $\delta\text{D}$ ) record from the EPICA Dome C ice core (Jouzel et al., 2007). The magnetic polarity stratigraphy of the Piànico-Sèllere sequence, the climatic signature of its constituent members, and the (contrasting) age determinations from tephra levels t21d ( $779 \pm 13$  ka; Pinti et al., 2001) and t32 ( $\sim 400$  ka; Brauer et al., 2007a) are correlated to these geomagnetic polarity and climatic ( $\delta^{18}\text{O}$ ,  $\delta\text{D}$ ) records to generate two age models of deposition for the Piànico Formation. In age model A, the Piànico Formation was deposited during the Brunhes Chron around polarity excursion  $11\alpha$  at  $\sim 400$  ka (i.e., the inferred tephrochronologic age of t32); consequently, the BVC interglacial sediment was deposited during marine isotope stage (MIS) 11. In age model B, the Piànico Formation was deposited during the Brunhes–Matuyama transition in substantial agreement with the K-Ar radiometric age estimate of t21d; consequently, the BVC interglacial sediment was deposited during MIS 19 (Fig. 6).

### 6.1. Age Model A

Figure 7 shows the magnetic stratigraphy record from Ocean Drilling Program (ODP) Site 1062 across the 350–450 ka interval used by Lund et al. (2006) to define polarity excursion  $11\alpha$ , in conjunction with the age equivalent  $\delta^{18}\text{O}$  (Lisiecki and Raymo, 2005) and  $\delta\text{D}$  (Jouzel et al., 2007) profiles. Inspection of Figure 7 reveals a poor matching of the magnetic stratigraphy records from the Piànico Formation and ODP Site 1062, essentially because there are no couplets of closely spaced polarity excursions across this age interval. PS1r could correspond to excursion  $11\alpha$  at  $\sim 400$  ka and the BVC interglacial to MIS 11 as mirrored by a  $\delta\text{D}$  increase, but if this were the case, PS2r would find no match in the ODP Site 1062 record. Because of this incongruence, this correlation option is presently less favored.

### 6.2. Age Model B

By adopting the K-Ar age of  $779 \pm 13$  ka for tephra t21d (Pinti et al., 2001), the



magnetostratigraphic record of the Piànico Formation is compatible with the Brunhes–Matuyama geomagnetic polarity transition (Fig. 8). Channell et al. (2004) published a detailed record of the Brunhes–Matuyama transition from ODP Site 984 with a time-resolution comparable with the magnetostratigraphic record of the Piànico Formation of this study. These authors describe at ODP Site 984 two polarity excursions occurring at ~771 and ~779 ka across the Brunhes–Matuyama transition, labeled  $19\alpha$  and  $19\beta$ , respectively, according to the nomenclature proposed by Lund et al. (2001) (Figs. 6, 8). The relatively thick normal polarity PS1n of the Piànico Formation is tentatively correlated to the earliest part of the Brunhes Chron, PS1r to excursion  $19\alpha$ , and PS2r to excursion  $19\beta$  (Fig. 8). According to this solution, the BVC interglacial should correspond to interglacial stage MIS 19 and the overlying MLP transitional deposits to the onset of the younger glacial stage MIS 18, as also indicated by the  $\delta D$  record. This solution implies that tephra t21d is ~5 ka younger than the upper K-Ar age limit obtained by Pinti et al. (2001). This relatively minor incongruence is possibly due to resolution problems occurring when different geochronometric methods are compared in a high-resolution sedimentary sequence such as the Piànico Formation.

## 7. Conclusion

A tight coupling was observed between climate-driven lithologic changes and susceptibility variations in the Piànico Formation whereby higher (lower) susceptibility values correspond to sediments deposited during glacial (interglacial) stages. Moreover, it has been possible to retrieve a magnetostratigraphic signal also from largely diamagnetic lithozones such as the BVC by using detailed AF demagnetization techniques and measurements of the natural magnetic remanence with a sensitive SQUID-based magnetometer.

The sequence of polarity reversals was correlated to paleomagnetic excursions within the earliest Brunhes–latest Matuyama polarity interval in order to contribute to the resolution of the controversy on the age of deposition of the Piànico Formation. Two options are proposed. In favored option B, the magnetostratigraphic record correlates to excursions across the Brunhes–Matuyama transition, and consequently the BVC interglacial to MIS 19 (Fig. 8). This option is in broad agreement with the available K-Ar dating of tephra t21d. The less favored option A requires correlation of the magnetostratigraphic record with the sequence of polarity excursions within the Brunhes Chron around ~400 ka, which is the indirect tephrochronological age of tephra t32 obtained by Brauer et al. (2007a), and found

only a partial and unsatisfactory correlation to excursion 11 $\alpha$  at ~400 ka.

The relatively short stratigraphic thickness of the (exposed) Piànico Formation coupled with relatively high sediment accumulation rates (short time interval materialized in sediments) limited the use of magnetostratigraphy as a dating tool to discern unambiguously between these two options. However, this study suggests that in presence of a longer stratigraphic sequence, magnetostratigraphy could be decisive for a final dating of the Piànico Formation. A longer stratigraphy is now available for the Piànico Formation, from a 77 m-deep core drilled in September 2007 in the Borlezza Valley close to the outcrop sections of this study. Magnetostratigraphic investigations on this core, presently in progress, will test the validity of the presently preferred option that attributes the Piànico Formation to the Brunhes–Matuyama transition and the BVC to MIS 19, in agreement with Pinti et al. (2001).

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### Figure captions

**Figure 1.** Map of the study area with location of the studied sections, topographically placed by means of total station survey.

**Figure 2.** Lithostratigraphy, low field (initial) susceptibility, NRM intensity, VGP latitudes, and magnetic polarity stratigraphy of the dike section. Positive (negative) VGP latitudes indicate normal (reverse) polarity; black is normal polarity, white is reverse polarity.

**Figure 3.** Lithostratigraphy, low field (initial) susceptibility, NRM intensity, VGP latitudes, and magnetic polarity stratigraphy of the composite profile from sections 4 and 5 of Moscariello et al. (2000). Positive (negative) VGP latitudes indicate normal (reverse) polarity; black is normal polarity, white is reverse polarity.

**Figure 4.** (A) Examples of vector end-point demagnetization diagrams of samples from the Piànico Formation. Open (closed) symbols are projections onto the vertical (horizontal) plane. (B) Equal-area projections before (*in situ*) and after bedding tilt correction of the characteristic component directions. Closed symbols are projections onto the lower hemisphere and open symbols onto the upper hemisphere.

**Figure 5.** Overall lithostratigraphy, low field (initial) susceptibility, NRM intensity, VGP latitudes, and magnetostratigraphy of the Piànico Formation derived by combining data from the dike section (Fig. 2) and the composite profile from sections 4 and 5 (Fig. 3). Positive (negative) VGP latitudes indicate normal (reverse) polarity; black is normal polarity, white is reverse polarity.

**Figure 6.** A compilation of geomagnetic polarity excursions across the Brunhes–late Matuyama interval has been correlated to the  $\delta^{18}\text{O}$  and  $\delta\text{D}$  records from Lisiecki and Raymo (2005) and Jouzel et al. (2007), respectively. Excursions  $3\alpha$  to  $17\alpha$  are from Lund et al. (2006), whereas excursions labeled in this study as  $19\alpha$  and  $19\beta$  are from Channell et al. (2004). Excursions labeled in italics and indicated by half bars on the polarity column are regarded as still poorly documented (Lund et al., 2006). Black is normal polarity, white is reverse polarity. Two age models of deposition for the Piànico Formation (options A and B in figure) are discussed in the text.

**Figure 7.** The paleomagnetic inclination record of the Piànico Formation from figure 5 (closed circles) is tentatively correlated to the ODP Site 1062 inclination record around 400 ka (Lund et al., 2006) (open circles). Positive (negative) inclinations indicate normal (reverse) polarity. The age equivalent  $\delta^{18}\text{O}$  (squares; Lisiecki and Raymo, 2005) and  $\delta\text{D}$  (staircase plot; Jouzel et al., 2007) records are shown in lower panel. Tephra t32 age is from Brauer et al. (2007a) whereas the Piànico Formation lithostratigraphy is from Moscariello et al. (2000). See text for discussion.

**Figure 8.** The VGP latitude plot of the Piànico Formation from figure 5 (closed circles) is tentatively correlated to the VGP latitude plot of ODP Site 984 across the Brunhes–Matuyama transition where two geomagnetic polarity excursions, labeled in this study as  $19\alpha$  and  $19\beta$ , were detected by Channell et al. (2004) (open circles). Positive (negative) VGP latitudes indicate normal (reverse) polarity. The age equivalent  $\delta^{18}\text{O}$  (squares; Lisiecki and Raymo, 2005) and  $\delta\text{D}$  (staircase plot; Jouzel et al., 2007) records are shown in lower panel. Tephra t21d age is from Pinti et al. (2001) whereas the Piànico Formation lithostratigraphy is from Moscariello et al. (2000). See text for discussion.

**Table 1.** Studied sections location and collected samples

| Section | Location                  | Units | Thickness | <i>N</i> | <i>n</i> | <i>n/N%</i> |
|---------|---------------------------|-------|-----------|----------|----------|-------------|
| 4       | 45°48'52.81" 10°02'11.04" | MLP   | 8.65      | 26       | 24       | 92          |
| 5       | 45°48'48.87" 10°02'13.98" | BVC   | 11.05     | 73       | 47       | 64          |
|         |                           | SAB   | 3.20      | 14       | 6        | 43          |
| dike    | 45°48'48.74" 10°02'20.18" | BVC   | 3.00      | 3        | 3        | 100         |
|         |                           | SAB   | 12.10     | 44       | 30       | 68          |

Location: latitude and longitude according to WGS84

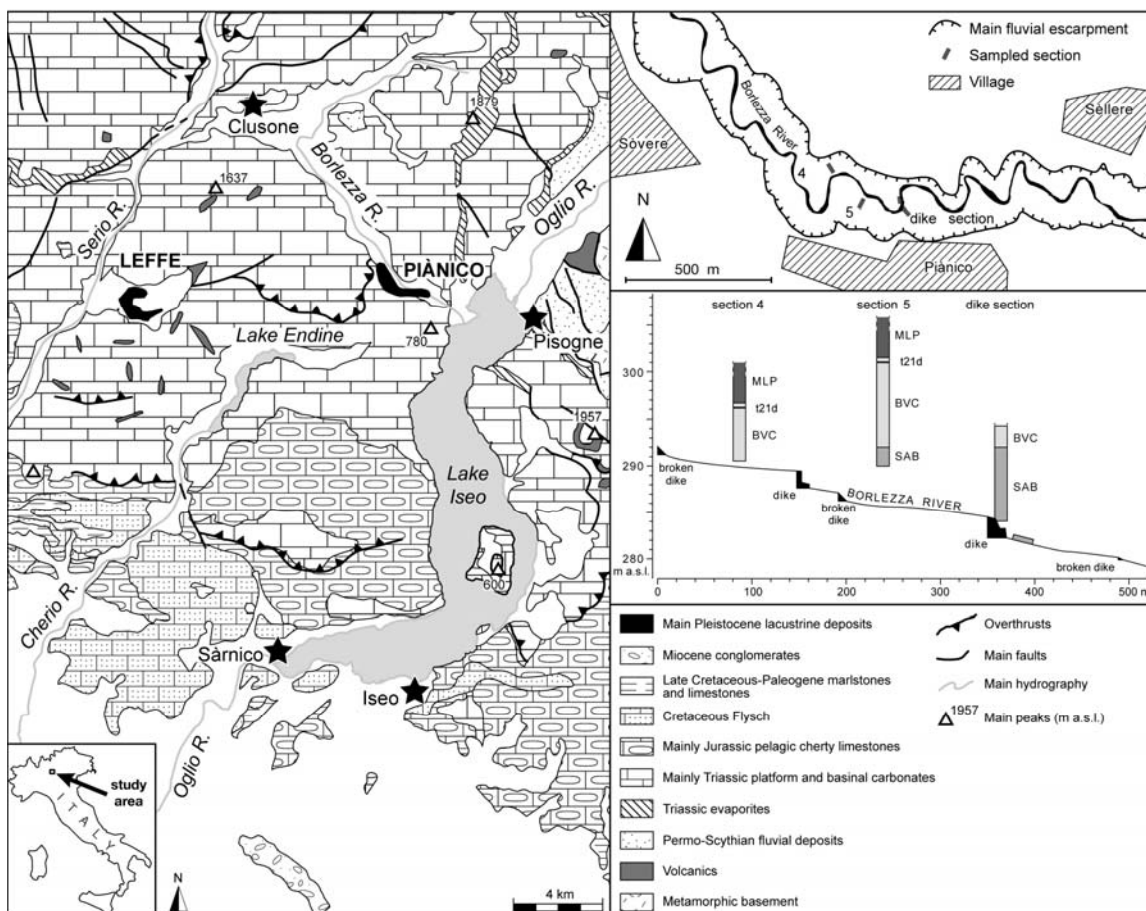
Thickness: measured stratigraphic thickness, in meters.

*N*: number of paleomagnetic samples collected.

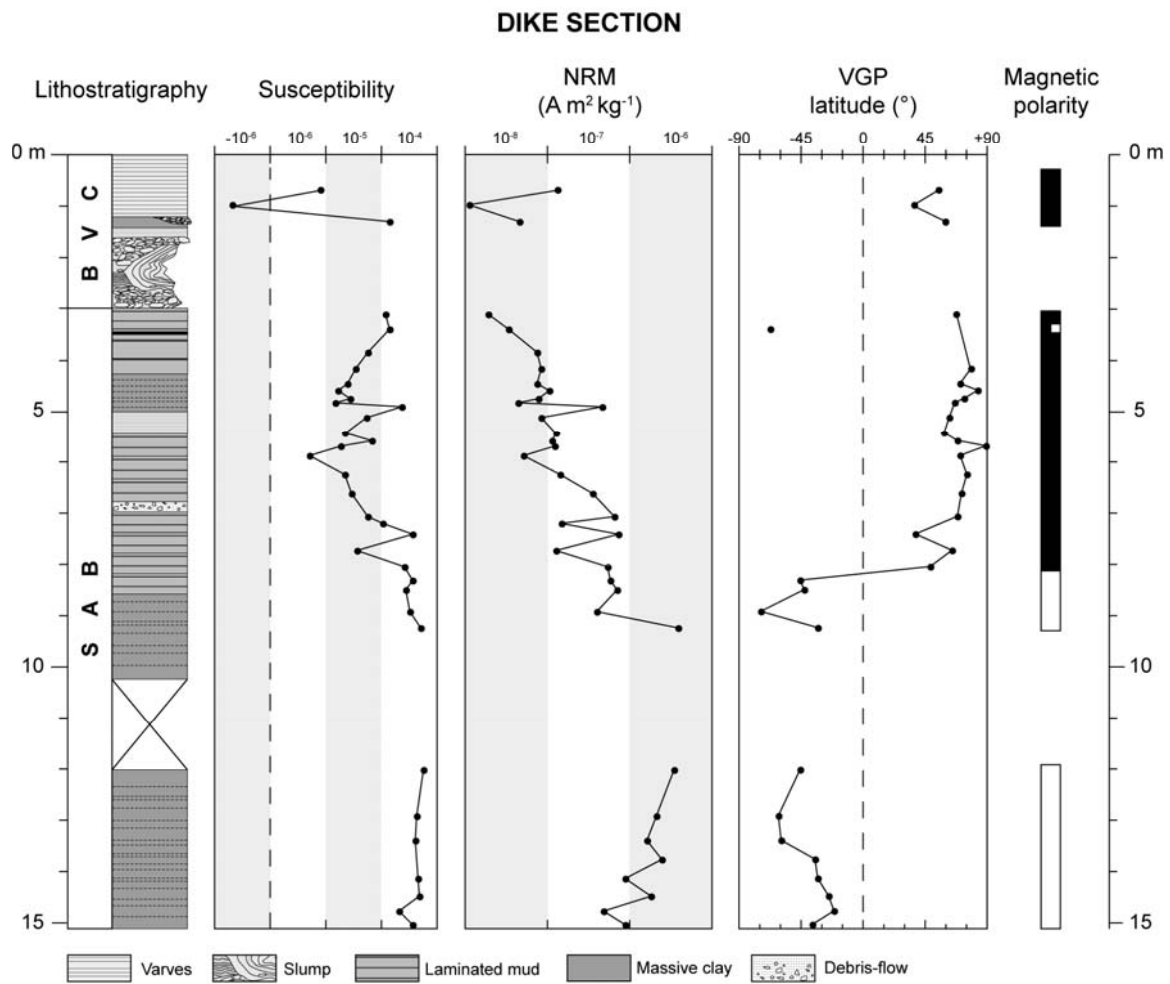
*n*: number of paleomagnetic samples accepted for magnetostratigraphic analyses.



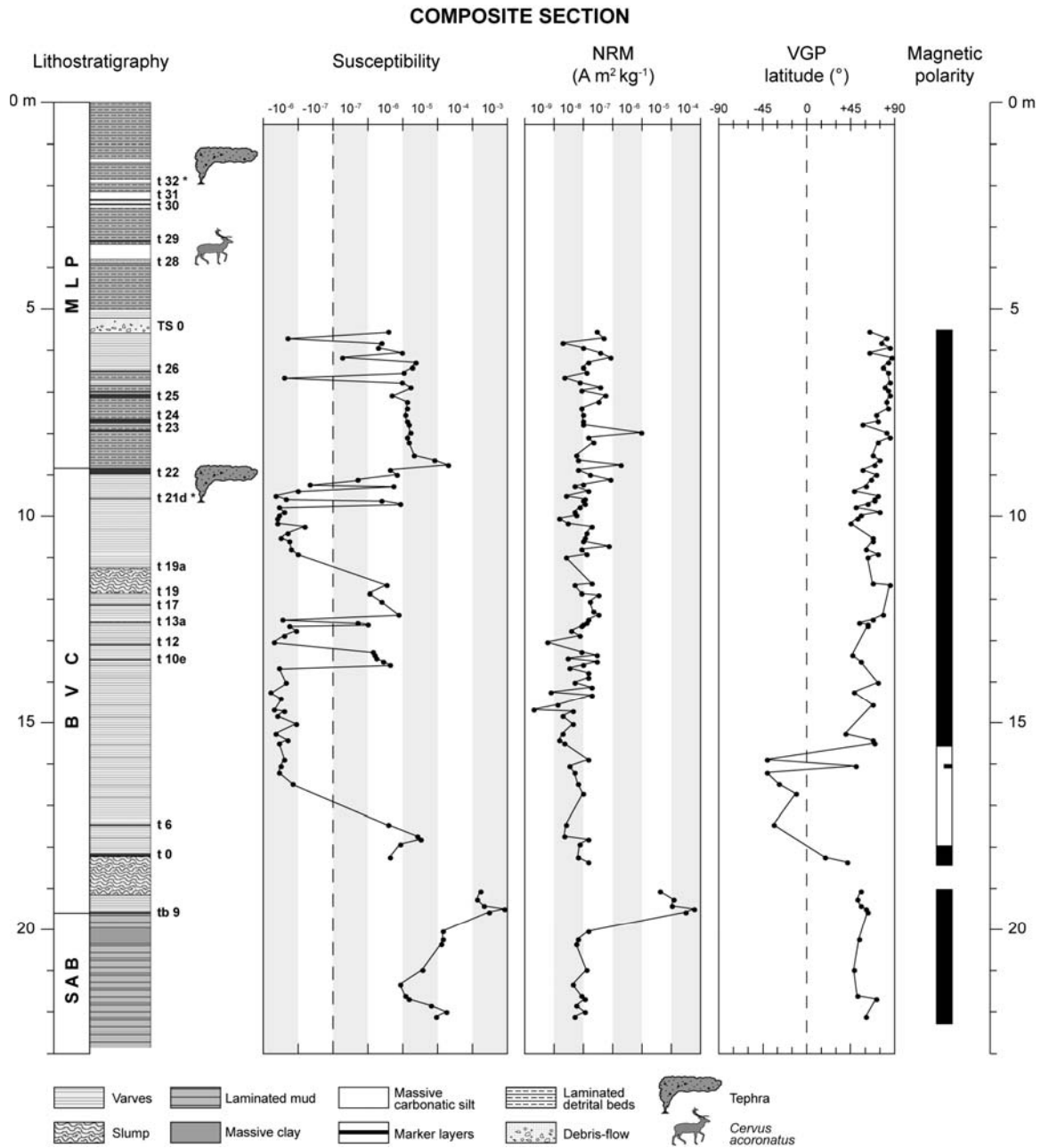
Scardia & Muttoni  
Figure 1



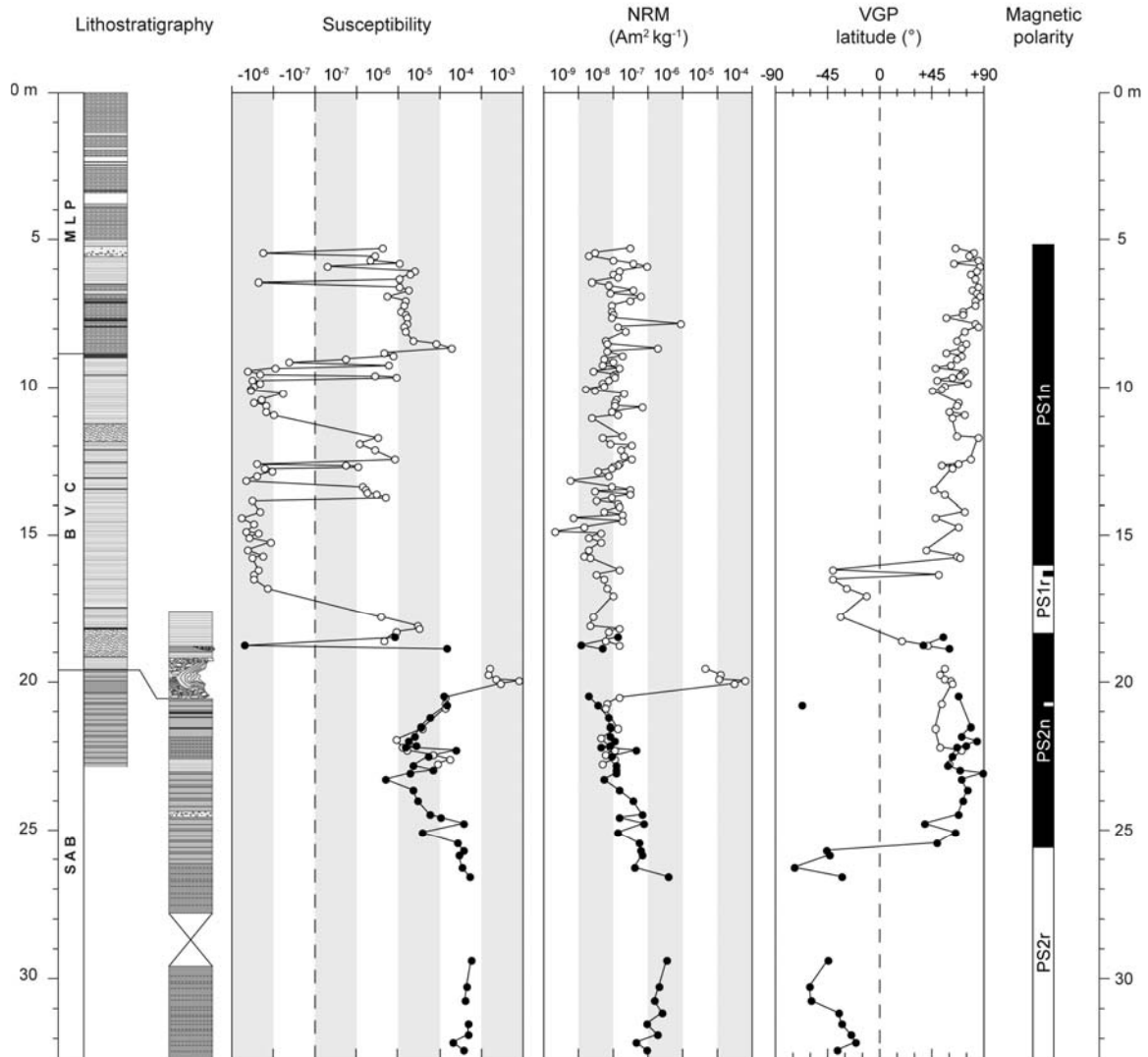
Scardia & Muttoni  
Figure 2

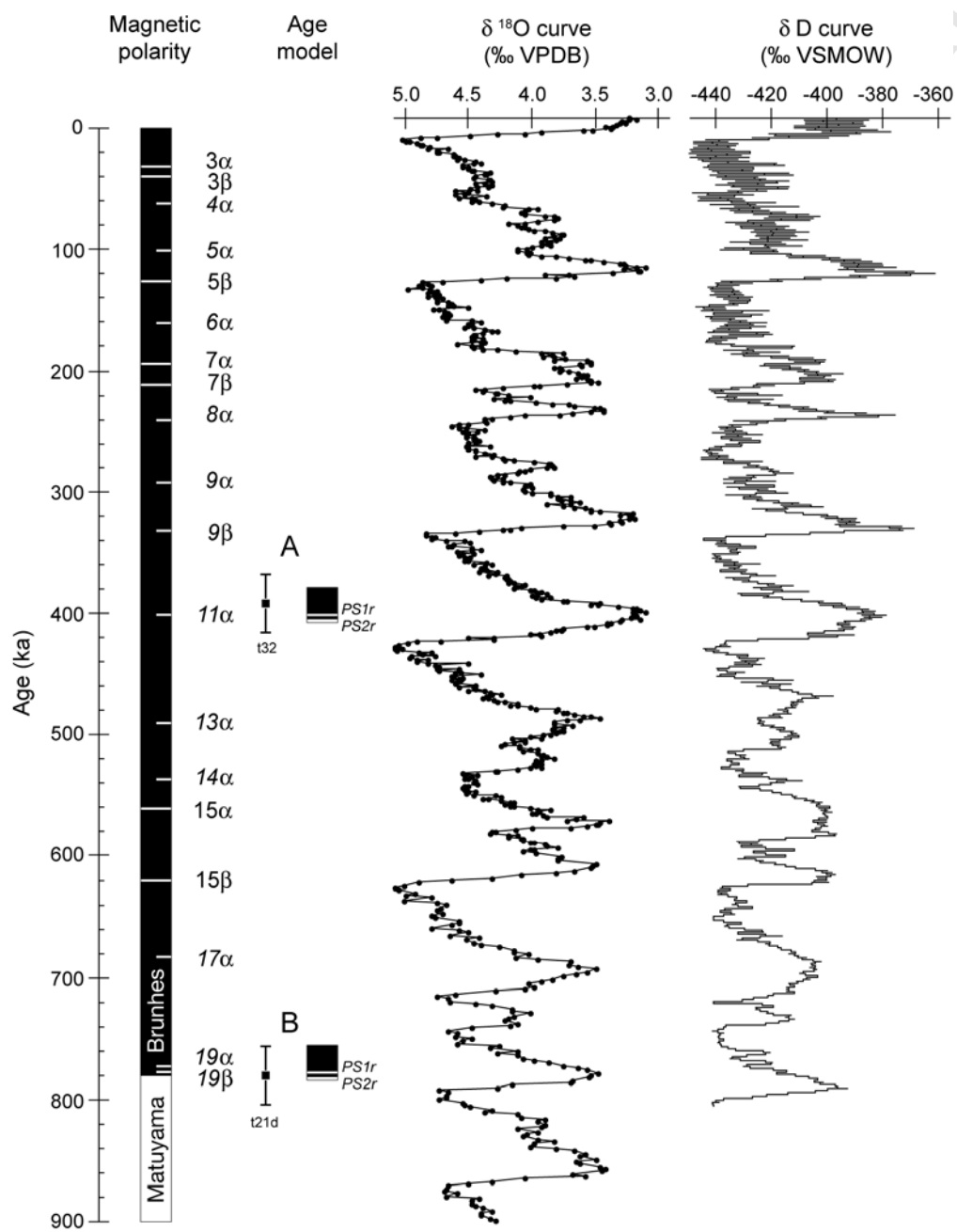


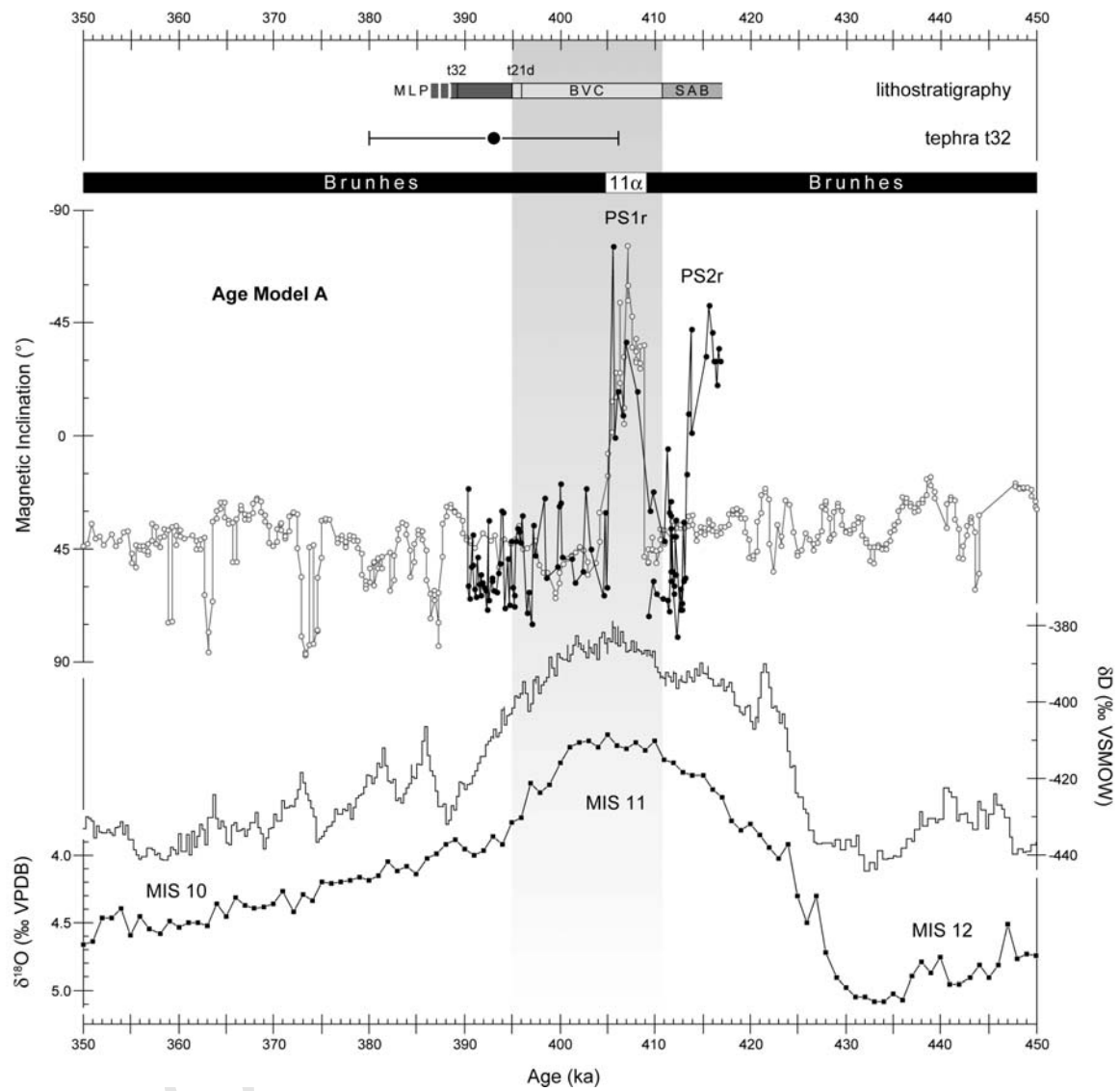
Scardia & Muttoni  
Figure 3





Scardia & Muttoni  
Figure 5

Scardia & Muttoni  
Figure 6

Scardia & Muttoni  
Figure 7



Scardia & Muttoni  
Figure 8

