Magnetostratigraphic dating of an intensification of glacial activity in the southern Italian Alps during Marine Isotope Stage 22

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Abstract

We applied magnetostratigraphy and mammal biostratigraphy to date climate-sensitive pollen cycles and lithostratigraphic units of the Pliocene–Pleistocene Leffe sedimentary succession from the Southern Alps, Italy. The Leffe section was correlated to additional sections (Casnigo, Fornaci di Ranica, and Pianengo) to construct a stratigraphic network along a common fluviatile system (the Serio River) sourced in the Southern Alps and flowing southward into the Po River Basin. We obtained a coherent scenario of climate variability for the last ∼2 Myr. At Leffe, lacustrine deposition commenced during the Olduvai Normal Subchron (1.94–1.78 Ma) and lasted up to a chronologic level compatible with Marine Isotope Stage (MIS) 22 (0.87 Ma). Pollen analysis revealed that climate varied cyclically from warm-temperate to cool during this time interval, but never as cold as during glacial intervals. At around MIS 22, climate cooled globally. Gravels, attributed to high-energy braided river systems fed locally by alluvial fans, prograded from the Serio River catchment area over the Leffe Basin and toward the Po Plain in response to a generalized event of vegetation withdrawal and enhanced physical erosion. At this time, Alpine valley glaciers reached their first maximum southward expansion with glacier fronts located at only ∼5 km upstream from Leffe.

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Introduction

Understanding the geological effects of climate change requires the application of robust chronologies to climate-proxy data retrieved from stratigraphically continuous sedimentary successions. We investigated the climatic evolution of a sector of northern Italy across the onset of the so-called mid-Pleistocene Revolution (MPR; Berger et al., 1993), one of the most critical transitions of Pleistocene climate. The onset of the MPR between 0.94 and 0.89 Ma is characterized by an increase of global ice volume that culminated with Marine Isotope Stage (MIS) 22 at 0.87 Ma (Maslin and Ridgwell, 2005). The waxing and waning of Alpine valley glaciers, known since the early days of the ice age theory, should have followed, at least in principle, global ice volume variations. We would therefore expect to observe evidence of increased glacial activity in the Alps across the MPR, which would result in higher probabilities for valley glaciers to expand symmetrically away from elevated Alpine source regions into nearby less elevated foreland basins, namely those of Central Europe (e.g., northern Switzerland, southern Germany, Austria) and northern Italy (Po River Basin). Glaciogenic and glaciofluvial deposits attributed to such major pulses are indeed known from Central Europe since Penck and Brückner (1909), and from northern Italy since Venzo (1950), but they were rarely accurately dated, leaving open the question whether the MPR represented a turning point in style and intensity of Alpine glacial activity. More generally, it also left

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unresolved the age of onset of the oldest major glaciations in the Alps. For example, evidence of glacial activity as old as late Pliocene was reported from the foreland basins of northern Switzerland (Ellwanger et al., 1994; Bolliger et al., 1996) and northern Italy (Uggeri et al., 1997). However, according to classical chronostratigraphic schemes recently updated with

Figure 1. (a) Global elevation model of the Alpine region and (b) simplified lithologic map of the studied region with indication of the stratigraphic sections discussed in the text (white dots); the actual extension of the Leffe Basin is indicated by the outcrop area of the “mainly fluviatile and lacustrine deposits” around the white dot assigned to Leffe in panel (b); the coordinates of the center of the Leffe Basin are 45°49′N, 9°51′E. All sections discussed in the text lie south of the last glacial maximum (LGM; solid line in a) and the maximum extent of any Pleistocene glaciations (dashed line in b) along a common longitudinal fluviatile system sourced in the Southern Alps (i.e., the Serio River system).
paleomagnetic and biostratigraphic data, the oldest glacial amphitheaters north of the Alps formed during the Brunhes Chron (Husen van, 2004), i.e., after the Brunhes–Matuyama boundary (0.78 Ma; Cande and Kent, 1995).

Recently, a core taken at Pianengo in the Po River Basin yielded sedimentological and vegetationary evidence for a first major glaciation pulse dated magnetostratigraphically to ∼0.87 Ma and correlated to MIS 22 (Muttoni et al., 2003). These authors concluded that during MIS 22, closed forests withdrew regionally as global climate became colder. A regional unconformity, called the R surface (Eni Divisione Agip and Regione Lombardia, 2002), formed in response of reduced vegetation and enhanced erosion that triggered the rapid progradation of braidplain systems from the Southalpine belt in the north toward the Po River Basin in the south. During MIS 22 global cooling, Pleistocene Alpine valley glaciers reached presumably their first maximum southward expansion. According to this model, the R surface should correlate to the onset of deposition of higher-energy braided river systems at locations proximal to glaciated areas within the Southalpine belt.

In order to test this model, we applied magnetostratigraphy to date lithostratigraphy, vegetation cyclicity as revealed by pollen analysis, and mammal biostratigraphy of a Pliocene–Pleistocene lacustrine succession from the Leffe Basin of the Southern Alps (Fig. 1). The Leffe succession was then correlated to two partially coeval key sections located nearby at Casnigo and Fornaci di Ranica (the latter by Ravazzi et al., 1995), as well as to the Pianengo core (Fig. 1b). The intramontane Leffe, Casnigo, and Fornaci di Ranica successions lie immediately south of the maximum extent that Alpine glaciers reached during the last glacial maximum (LGM; Fig. 1a), or any of the preceding Pleistocene glaciations (Fig. 1b). In contrast, Pianengo lies more southward in the Po River Basin. Relevant to our research question is the observation that all of these study areas belong to the same fluviatile system, namely the Serio River, sourced in the Southern Alps and flowing southward into the Po River Basin (Fig. 1b).

Study area and geological background

The Pliocene–Pleistocene Leffe Basin is located in Valgandino, a tributary valley of the Serio River north of Bergamo (Fig. 1). Mainly Upper Triassic carbonate rocks cut by andesite dykes of Cenozoic age are exposed in Valgandino. The much larger Serio River catchment area cuts across the whole Permian–Mesozoic sedimentary succession of the Southern Alps, which rests nonconformably upon the Variscan metamorphic basement. Authigenic and autocyclic processes, influenced by a complex interplay of climatic and probably also tectonic factors, controlled the evolution of the Leffe Basin. The sedimentary succession consists of a lower interval of alluvial fan-river delta deposition overlain by a middle authigenic–autocyclic phase of lacustrine–palustrine sedimentation, where episodes of terrigenous deposition triggered by enhanced river aggradation phases are recorded. Above lie mainly alluvial-fan deposits, which in the nearby Casnigo section interfinger with high-energy braided river gravels.

These are fluvioglacial, originating from glaciers located only 4 to 6 km upstream (Jadoul and Forcella, 2000; Bini and Zucchi, 2004) that discharged meltwater directly into the Casnigo area (as well as farther south into the Po River Basin at Pianengo). Details on the lithostratigraphy, mammal biostratigraphy, and pollen record of the Leffe Basin are reported hereafter.

Lithostratigraphy of the Leffe Basin

A 189-m-long core, known as Fornace Martinelli core, was drilled in 1991 in the Leffe Basin (Fig. 2) (Cremaschi and Ravazzi, 1995). In this study, we completed the original stratigraphic description of the core (Cremaschi and Ravazzi, 1995) with stratigraphic observations from nearby key outcrop sections, other scientific drillings, and lignite mines, in order to reconstruct a complete sequence of Leffe Basin sedimentary units, summarized as follows from bottom to top in meters above sea level (Figs. 2 and 3).

Leffe Formation, lower unit

From 294.3 to 353.5 m (subunit #1): gravel, sand, and clay resting upon a bedrock of altered greenish andesite dykes. From 353.5 to 373.0 m (subunit #2): finer-grained sand and silt, com- pressed peat, and gyttja (i.e., organic mud).

Leffe Formation, biogenic unit

From 373.0 to 385.8 (subunit #3): gyttja and brown coal; the organic bank between 384.0 and 385.8 m is known as the “third lignite bank”. From 385.8 to 396.0 m (subunit #4): shell marls with very low organic matter content, calcareous gyttja, and gyttja. From 396.0 to 407.45 m (subunit #5): brown coal and gyttja of the “second lignite bank”. From 407.45 to 424.4 m (subunit #6): carbonatic gyttja and shell marls. From 424.4 to 431.31 m (subunit #7): brown coal and gyttja forming the “first lignite bank”. From 431.31 to 432.73 (subunit #8): shell marls.

Leffe Formation, upper unit

From 432.73 to 447.35 m (subunit #9): clays, gyttja, and compressed peat. A paleosol is present at the top of the upper unit in the western part of the Leffe Basin (labeled as ‘P’ in Fig. 2).

Gandino Formation, Peia-Gandino unit

From 447.35 to 465.0 m: moderately to poorly sorted, virtually monogenetic breccias and conglomerates of local provenance within the Leffe Basin catchment area. This unit thickens in the eastern part of the Leffe Basin, where it interfingers with the Cà Manot unit (Fig. 2), described hereafter.

Gandino Formation, Cà Manot unit

From 465.0 to 494.0 m: cyclic repetitions of fine-grained sand and clay arranged in typical turbidite sequences. This unit
interfingers with the main body of the Peia-Gandino unit in the eastern part of the Leffe Basin, and, in the western part, with the Casnigo unit (Fig. 2).

Casnigo unit

This unit consists of a 30-m-thick succession of polygenetic gravels of regional provenance within the Serio River catchment area. This unit, which interfingers with the Cà Manot unit in the western part of the Leffe Basin (Fig. 2), forms the highest fluviatile terrace of the Serio Valley and can be correlated to glacial deposits located 4–6 km upstream (Jadoul and Forcella, 2000). The Casnigo unit was considered by Penck and Brückner (1909) to be the genetic equivalent of the “Ältere Deckenshotter” of the northern Alpine foreland.

Paleosols and loess

These units cap in this order the Leffe stratigraphic sequence from 494.0 to 498.0 m.

In summary, subunit #1 of the Leffe Formation can be attributed to alluvial fan-river delta deposition. A main lacustrine–palustrine phase commenced with subunit #2 and ended with subunit #9, and was characterized by dominantly terrigenous (subunits #2 and #9) or biogenic (subunits #3–#8) deposition. A paleosol is present at the top of subunit #9 and is overlain by alluvial fan deposits of local provenance of the Peia-Gandino unit. A second phase of lacustrine deposition, rich in terrigenous turbidites, subsequently began (Cà Manot unit) and was coeval to the deposition of the main body of the Peia-Gandino alluvial fans in the east and the high-energy braided river gravels of the Casnigo unit in the west. The stratigraphic sequence of the Leffe Basin was deeply dissected by the modern Serio River Valley after the deposition of the Casnigo unit (Fig. 2, left side).

Mammal biostratigraphy

The Leffe sequence yielded several mammal remains brought to light since the mid 19th century, especially during the extraction activity of lignite in historical mines and quarries. These previous findings (e.g., Vialli, 1956) are here briefly summarized and arranged in four distinct mammal associations, which we then correlate to faunal units of the Italian biochronological scale (Azzaroli et al., 1986, 1988; Gliozzi et al., 1997; Sardella et al., 1998; Breda and Marchetti, 2005). For more detailed information on the mammal biochronology of the Leffe Basin, see Breda and Marchetti (in press).

Figure 2. General stratigraphy of the Leffe Basin along a NW–SE transect (slightly modified after Cremaschi and Ravazzi, 1995) showing a tentative reconstruction of the original stratigraphic relationships between the Casnigo unit, the Cà Manot unit, and the Peia-Gandino unit. The most important historical mine pits (black rectangles) and sites of scientific drillings (white rectangles) are also shown. The Fornace Martinelli core was drilled in the central portion of the Leffe Basin. The figure is drawn with a fivefold vertical exaggeration.
Mammal association #1

The “second lignite bank” of subunit #5 yielded Mimomys savini, Castor fiber, Stephanorhinus ex gr. etruscus, Leptobos cf. vallisarni, Capreolus sp., Pseudodama sp., Eucladoceros sp. (gr. E. ctenoides-dicranios), Megaloceros cf. obscurus, and a mammoth variable in size between Mammuthus meridionalis meridionalis and Mammuthus meridionalis vestinus. This
association is attributed to the Upper Villafranchian Mammal Age (Azzaroli et al., 1986) broadly between the end of the Tasso Faunal Unit (FU) and the beginning of the Farneta FU. The Tasso FU has been referred to the Matuyama Reverse Chron (Torre et al., 1993, 1996) and given an age of ~1.5 Ma (Breda and Marchetti, 2005).

Mammal association #2

The carboneous gyttja and shell marls of subunit #6 yielded a specimen of Pachycrocuta brevirostris (at first attributed to a dirk-toothed cat by Breda and Marchetti, 2004) in association with Stephanorhinus ex gr. etruscus and Pseudodama eurypgonos, whereas the “first lignite bank” of subunit #7 yielded Stephanorhinus ex gr. etruscus and Cervulces cf. carnatorum. This overall association is broadly consistent with that of the Farneta FU and/or the Pirro FU, ranging approximately from 1.4 to 1.1 Ma according to Breda and Marchetti (2005).

Mammal association #3

The interval of subunit #9 yielded M. m. vestinus, Megaloceros verticornis, and Megaloceros sp. The mammoth from this subunit is more evolved than the one from the “second lignite bank” (subunit #5). Similar evolved forms of mammoth co-exist with Megaloceros verticornis in the Colle Curti FU, attributed to the Jaramillo Normal Subchron (1.07–0.99 Ma; Cano and Kent, 1995) by Gliozzi et al. (1997) and Coltorti et al. (1998).

Mammal association #4

The paleosol and loess succession at the top of the Leffe Basin yielded a specimen of Palaeoloxodon antiquus. This species belongs to a generic time interval straddling the early Middle Galerian–Late Aurelian Mammal Ages, i.e., from the Silvia FU (0.7 Ma) to the last interglacial (0.1 Ma) (Breda and Marchetti, in press).

In conclusion, the published literature of the Leffe Basin articulates a sequence of early Pleistocene mammal associations that started around 1.5 Ma during the Matuyama Reverse Chron and lasted up to 1.07–0.99 Ma during the Jaramillo Normal Subchron. Younger mammal remains of association #4 postdate the lacustrine–fluvialite succession of the Leffe Basin.

Pollen analysis

The interval of lacustrine–palustrine deposition of the Leffe Basin is rich in fossil pollen, mostly airborne from local plants growing in the basin and from vegetation belts distributed at different elevations on the surrounding mountain slopes. Reworked pollen does not seem to occur. The history of vegetation is described in a continuous pollen record consisting of 457 samples, which was partly discussed by Ravazzi and Rossignol Strick (1995), Ravazzi and Moscariello (1998), Ravazzi et al. (2004), and is schematically presented here using cumulative pollen curves. Considering that the Leffe Lake had a surface of 4.2 km² (Ravazzi, 2003) and was surrounded by high mountain ranges, the estimated relevant source area of pollen (Sugita, 1994) should have been no more than 40 km².

Key percentage pollen curves illustrate how vegetation types are arranged in climatically driven cyclic patterns (Fig. 3). A single pollen cycle is defined by the vertical superposition of four main vegetation stages, as described in detail by Ravazzi and Rossignol Strick (1995): stage a1 is dominated by mixed-oak taxa showing abundance peaks initially of Quercus/Eucomia and subsequently of Corylus/Ulmus/Carpinus/Fraxinus; stage a2 is dominated by Juglandaceae (Carya sp. pl., Pterocarya, Juglans sect. Cardiocaryon), Fagus, Aesculus aff. hippocastanum; stage b1 is dominated by conifers (Picea, Tsuga, Cedrus, Abies); and stage b2 is characterized by open vegetation (Artemisia, Chenopodiaceae, Ephedra, Betula, and Larix). A single climate cycle was initially dry and warm-temperate (a1), then warmer and very moist (a2), subsequently cool-temperate and wet (b1) and, finally, dry and continental during short intervals with increasing open vegetation (b2) (climate classification according to Koeppen).

This basic cycle is repeated 18 times in the studied portion of the Leffe sequence – from cycle A to cycle R (Fig. 3) – with minor variations from cycle to cycle. Each cycle is dominated by persistent forest vegetation, as indicated by the Arboreal Pollen (AP) sum that is on average 88% of the total pollen content (90.6% including shrubs) (Fig. 3). From these data, we conclude that climate oscillated from warm-temperate to cooler conditions, but it never reached truly glacial ones, which are usually associated with persistent steppic vegetation and loess deposition, which are, respectively, subordinate and absent in this interval of the Leffe succession.

Above cycle R (i.e. in the lower part of the Peia-Gandino unit), pollen cycles are discontinuous and characterized by more pronounced cool phases b1 and b2 and less pronounced warmer phases a2 (see Juglandaceae sum in Fig. 3). Finally, the overlying Cà Manot unit contains only pollen grains of Pinus and Artemisia in very low concentration, despite the fact that this lacustrine unit is potentially favorable for pollen preservation. The exclusive presence of Pinus and Artemisia is consistent with a persistent cool to cold climate, whereas their rarity can be taken as indirect evidence of generalized forest withdrawal.

A similar cyclic pattern of warm-temperate to cooler (but never glacial) conditions was observed also in the Pianengo core (Muttoni et al., 2003) and at Fornaci di Ranica, albeit this latter succession covers a much shorter time span (Ravazzi et al., 2005). Moreover, above the warm-temperate to cooler cycles the Pianengo core displays a cold, drier, and more continental phase indicated by the expansion of partially open vegetation, very much like the pattern observed at Leffe. The timing of this transition toward cold conditions is virtually identical at both sections, as discussed below.

Paleomagnetism

The magnetic polarity stratigraphy of the Leffe sequence was initially investigated along discontinuous outcrop sections (Bucha and Sibrava, 1977; Billard et al., 1983). In 1991, the
Fornace Martinelli core was taken and the initial susceptibility and natural remanent magnetization (NRM) were measured (Barthes and Thomas, 1992). No progressive and complete demagnetization was applied to retrieve paleomagnetic components. Therefore, we decided to undertake a new study of the paleomagnetic properties of the Leffe sediments.

A total of 282 standard paleomagnetic samples were measured in the paleomagnetic laboratories of Gif-sur-Yvette, Lamont-Doherty, and ETH-Zürich on a 2G Enterprises DC-SQUID cryogenic magnetometer. Eight of these samples were taken along an outcrop section straddling the Cà Manot unit of the Gandino Formation. The other samples came from the Fornace Martinelli core (Fig. 3).

The initial susceptibility, measured every 5 cm with a MS2 Bartington susceptibility bridge, shows that the lacustrine subunits #2 to #9 are characterized by values that are in general one order of magnitude lower than those of the underlying predominantly terrigenous subunit #1, rich in porphyritic grains. By considering only subunits #2 to #9, we observed highest values in levels containing clayey gyttja (e.g., upper part of subunit #4, lower and upper parts of subunit #6, subunit #9), and lowest values in levels with shell marls or peat (e.g., lower parts of subunits #4 and #5, middle part of subunit #6) (Fig. 3).

The intensity of the NRM varies similarly to susceptibility with average values of 2 mA/m in subunits #2 to #9 and 7 to 60 mA/m in subunit #1.

The magnetic mineralogy of selected samples was inferred from thermal decay of a composite isothermal remanent magnetization (IRM) (Lowrie, 1990) and acquisition curves of IRM. Thermal decay of composite IRM shows that samples commonly contain a sulfide phase with maximum unblocking temperatures ($T_{\text{max}}$) of ~300°–350°C (Fig. 4a, samples 3281, 3592, 7979), occasionally associated with magnetic phases with unblocking temperatures higher than 350°C (probably iron oxides; sample 4561). Less frequently, a higher coercivity phase with $T_{\text{max}}$ of ~680°C interpreted as hematite is also present, possibly in association with subsidiary sulfides as deduced by an inflection in the 2.5 T curve that is sometimes observed broadly between 250° and 350°C (samples 9807, 1176). Susceptibility increased upon heating sometimes by up to one order of magnitude. This behavior is attributed to the breakdown of primary minerals (e.g., sulfides) that led to the creation of new magnetic phases. IRM acquisition curves show that samples bearing hematite do not saturate at fields up to 2.5 T (Fig. 4b, sample 1176), whereas those dominated by sulfides tend to saturate at fields <0.5 T (samples 3281 to 7979).

![Image](image-url)
Stepwise thermal demagnetization was applied to retrieve paleomagnetic directions visualized by means of orthogonal projection plots (Zijderveld, 1967). In 66% of the samples, an interpretable characteristic component of magnetization was observed, usually after removal of an initial viscous overprint (Fig. 5). This characteristic component was isolated to the origin of the demagnetization axes from about 100°C to about 250°C–300°C in samples bearing dominant sulfides (Fig. 5, samples 3592, 4561), whereas in samples dominated by iron oxides, unblocking temperatures of 400°C–500°C up to 600°C were observed (samples 9807, 1552, 11501).

The Fornace Martinelli core was not oriented with respect to the geographic north; therefore, only magnetic inclination was used to delineate polarity stratigraphy. The characteristic magnetization component bears either positive or negative inclinations with mean values of +50 and −48°, respectively, indicating normal and reverse polarity, respectively. No systematic correlation was observed between maximum unblocking temperatures and inclination values of the characteristic components (Fig. 3), suggesting no evident correlation between magnetic phases (sulfides or iron oxides) and polarity reversals. The mean inclination values observed are some 15° lower than those expected from a geocentric axial dipole field at the latitude of Leffe, likely because of inclination error due to sedimentary compaction.

Starting from the top, the Cà Manot unit of the Gandino Formation and the underlying Leffe Formation from subunits #9 to #3 were deposited during a period of reverse polarity (Fig. 3). An interval of normal polarity was herein recognized between 438.8±0.8 and 429.2±0.3 m a.s.l. within subunits #9 to #7. The base subunit #3 and the underlying subunit #2 were deposited during a period of normal polarity in which two short reverse-polarity intervals are present, one in the middle part, and one at the base of subunit #2 where it is truncated at the boundary with the underlying subunit #1. Subunit #1 contains an upper normal-lower reverse-polarity sequence with reverse polarity probably continuing down to the core bottom as revealed by the preliminary geophysical survey of Barthes and Thomas (1992). No major temporal gap is assumed between subunits #3 and #2, as suggested by the substantial similarity of depositional environments and the apparent continuity of pollen cycles across this boundary. A temporal gap is likely present between the onset of lacustrine deposition of subunit #2 and the alluvial fan-river delta gravels of subunit #1, as suggested by the drastic change of depositional environment and the abrupt truncation of the magnetostratigraphic sequence across this level.

Age model

A complete chronology of the Leffe Basin succession was obtained by merging mammal and pollen biostratigraphy with magnetic polarity stratigraphy, adopting the time scale of Cande and Kent (1995) (Fig. 6). Starting from the top, mammal biostratigraphy indicates that the paleosol and loess capping the Leffe sequence were deposited most probably after the Brunhes–Matuyama boundary (0.78 Ma), although no direct paleomagnetic evidence is available to confirm this age attribution. Downcore, the stratigraphic interval from the Gandino Formation to subunit #3 of the Leffe Formation was deposited during the Matuyama Reverse Subchron from >0.78 Ma (Brunhes–Matuyama boundary, not recorded) to 1.78 Ma (end of Olduvai Normal Subchron). The Jaramillo Normal Subchron (1.07–0.99 Ma) was herein recorded between 438.8±0.8 and 429.2±0.3 m a.s.l. This is confirmed by the attribution of the mammal fauna of subunit #9 to the Colle Curti FU of Jaramillo Normal Subchron age (Gliozzi et al., 1997; Coltorti et al., 1998), and of the mammal fauna of the “second lignite bank” (subunit #5) to the Tasso FU–Farneta FU interval of Matuyama Reverse Chron age (Torre et al., 1993, 1996). The base of subunit #3 is interpreted to contain at 376.2±9 m a.s.l. the end of the Olduvai Normal Subchron (1.78 Ma). The underlying subunit #2 of the Leffe Formation was deposited during the Olduvai Normal Subchron, assuming no major temporal gap between subunit #3 and #2 (see discussion above) (Fig. 6). We hesitate to make any further downcore age interpretation in the general absence of independent age constraints.

The proposed age model implies average sediment accumulation rates, not corrected for dewatering and burial, of ~70–80 m/Myr for the biogenic lacustrine deposition of the Leffe
Figure 6. The Leffe Basin lithostratigraphy, magnetostratigraphy, and key mammal biostratigraphy compared to the geomagnetic polarity time scale of Cande and Kent (1995) for construction of an age–depth model. See text for discussion.
Figure 7. Correlation of stratigraphic data from Leffe, Casnigo, and Pianengo to variations of northern hemisphere ice volume. The glacioeustatic curve was constructed by scaling the astronomically tuned ODP677-SPECMAP (Ocean Drilling Program leg 677-mapping spectral variability in global climate project) benthic oxygen isotope record (Shackleton, 1995) to the 120–140 m glacioeustatic drop at the last glacial maximum (Fairbanks, 1989; Lambeck et al., 2002). The onset of deposition of the high-energy gravels of the Casnigo-Peia-Gandino units correlates magnetostratigraphically to the onset of formation of the R surface in the Po River Basin. Both events are virtually coeval to the end of the warm-temperate to cooler cycles and onset of persistently cool to cold climate, which occurred during the mid-Pleistocene Revolution (MPR) culminating with marine isotope stage (MIS 22) at 0.87 Ma.
Formation. Actual sedimentation rates estimated from inspection of annually laminated sediments at six different intervals of biogenic lacustrine carbonates were in the order of $\sim 60 \pm 30$ m/Myr, whereas higher values probably characterized compressed peat intervals (Ravazzi and Moscariello, 1998).

**Magnetostratigraphic and palynostratigraphic correlations**

The Leffe Basin succession correlates magnetostratigraphically to the Pianengo core sediments (Muttoni et al., 2003). Both sections contain a record of the Matuyama Reverse Chron straddling the Jaramillo Normal Subchron (Fig. 7). The Brunhes–Matuyama boundary, recorded at Pianengo, was not found at Leffe, the youngest sampled sediments of which were still deposited during the latest part of the Matuyama Reverse Chron. This correlation implies that much of the lacustrine deposition at Leffe up to the boundary with the overlying Peia-Gandino alluvial fans, is equivalent in age to floodplain-deltaic-shelf sediments passing upward to meandering river sediments in the Po Plain at Pianengo (Fig. 7). This correlation is supported also by the similar structure of the warm-temperate to cooler pollen cycles observed throughout this interval in both sections, as well as by the pollen assemblages, dominated in both cases by *Carya, Pterocarya, Juglans* sect. *Cardiocaryon, Cedrus*, and *Tsuga*, common in the early Pleistocene of northern Italy (Ravazzi et al., 2005; Pini, 2005).

The onset of deposition of the Peia-Gandino alluvial fans at Leffe and of the coeval braided river gravels of the Casnigo unit at Casnigo occurred after the Jaramillo Normal Subchron and before the Brunhes–Matuyama boundary (Fig. 7). This level is chronostratigraphically consistent with the onset of formation of the R surface in the Pianengo core and regionally in the Po River Basin subsurface (Muttoni et al., 2003). Moreover, this level is associated with the end of climate cycles of moderate amplitude and onset of persistently cool to cold climate. We therefore infer a mechanistic link between climate cooling and sedimentation style that operated after the Jaramillo Normal Subchron (<0.99 Ma) and before the Brunhes–Matuyama boundary (>0.78 Ma), producing what we term the “Casnigo unit-R surface” event.

This conclusion completes and supersedes conclusions previously reached for the much shorter Fornaci di Ranica succession of Jaramillo Normal Subchron age (Ravazzi et al., 2005). Here, pollen analysis shows a transition from temperate conditions to a mid-Jaramillo cold phase ($\sim 1.05$ Ma), characterized by open taiga vegetation and possibly also fluviglacial deposition in the Serio River Valley. However, this cold phase was less pronounced than the subsequent “Casnigo unit-R surface” event, because the pollen record of Fornaci di Ranica does not show a complete forest withdrawal and the pertinent episode of coarse gravel deposition remained largely confined within the Serio River Valley, as shown in the Pianengo core that the Jaramillo Subchron is entirely represented by a thin prodelta to floodplain sequence (Pini, 2005). In general, by taking into account the greatly expanded record of Leffe and Pianengo, we now consider this mid-Jaramillo cold phase a short-lived event rather than a major climatic turning point toward more persistent cold conditions.

The “Casnigo unit-R surface” event can be correlated to northern hemisphere ice sheet pulsations reflected in benthic oxygen isotope composition (Shackleton, 1995). The “Casnigo unit-R surface” event is magnetostratigraphically consistent with the MPR and more specifically with MIS 22 (Fig. 7, right), which was the first most prominent glacioeustatic lowstand of the Pleistocene with an unprecedented sea level fall of 120–140 m, similar in magnitude to that of the last glacial maximum (Fairbanks, 1989; Lambeck et al., 2002). Glacioeustatic oscillations of the Pliocene–early Pleistocene prior to the MPR were of higher frequency and smaller amplitude than those typical of the glacial Pleistocene intervals.

**Intensification of glacial activity in the Alps at MIS 22**

The stratigraphic information outlined above suggest that the Leffe Lake formed with subunit #2 between 1.94 and 1.78 Ma (Olduvai Normal Subchron) and ended with subunit #9 immediately before 0.87 Ma (MIS 22). During this time, climate was warm-temperate to cool but never cold-glacial. Abundant closed forests, characterized by an alternation of deciduous broad-leaved species and conifers, supported a diverse mammal fauna. Even during the coldest phases of this climatic variability, recorded for example at Fornaci di Ranica during the mid-Jaramillo, no complete forest withdrawal was observed (Ravazzi et al., 2005).

During the MPR culminating with MIS 22 (0.87 Ma), climate cooled globally, as well as regionally in the Southern Alps–Po Plain. Forest withdrawal and eustatic lowstand enhanced erosion on the steep slopes of the Southalpine belt. The high-energy braided river system of the Casnigo unit, fed locally by alluvial fans like those of the Peia-Gandino unit, prograded longitudinally north–south from the Serio River catchment area over the Leffe Basin toward the Po Plain, where it shifted southward and replaced west–east meandering fluvial systems, triggering the formation of the R surface (Muttoni et al., 2003). Considering the regional extension of the R surface, observed seismically across much of the Po Plain subsurface (Muttoni et al., 2003), we regard this scenario described for the Serio River system applicable regionally to the Southalpine margin and adjacent Po Plain area.

Subsequently, a lacustrine basin, represented by the Cá Manot unit, was created at Leffe by damming of the fan forming the Casnigo unit. The turbiditic deposition within this new lake and its pollen record suggest that an outwash fan formed the dam. The glacier front associated with the outwash fan was located only $\sim 5$ km upstream. After this first major cooling phase, paleosols and loess were deposited at the top of the Leffe sequence. The paleosols may be the result of pedogenesis occurring during one or more warm interval(s) between the latest Matuyama and the Brunhes Chrons, whereas the topmost loess cover was deposited during several cooling phases (Cremaschi and Ravazzi, 1995) younger than MIS 22.

By applying magnetostratigraphy to correlate continental sediments from the Southern Alps and the Po Plain subsurface to the global glacioeustatic reference curve, we were able to depict a consistent scenario of climate variability that
determined what we believe was the onset of the first major Pleistocene glaciations in the Alps. The Casmio and equivalent units from the Southalpine margin represent the coarser-grained fluvioglacial equivalents of braided river sediments at and above the R surface in the adjacent Po Plain. They were deposited in response to one single and same global climatic pulse, i.e., the first most prominent cooling event and glacial-eustatic lowstand of the Pleistocene (MPR, culminating with MIS 22), when the Alpine valley glaciers reached their first Pleistocene maximum southward penetration with glacier fronts located at only 4–6 km from the Leffe Basin.

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References


