Onset of major Pleistocene glaciations in the Alps

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ABSTRACT

During maximum Pleistocene glacial expansions, the Alpine ice cap invaded the Central Europe uplands and Italian Southalpine foothills. Periglacial basins, such as the Po River Basin, are natural collectors of sediments that record the past biological and climatic changes that involve the waxing and waning of major ice caps. In a 200-m-long core from the central Po Plain, stratigraphic evidence for one such major glacial pulse of the nearby Alpine ice cap is recorded by a sequence boundary, termed the R surface, associated with a drastic reorganization of vegetational, fluvial, and Alpine drainage patterns. The R surface, seismically traceable across the Po Plain subsurface, was constrained magnetostratigraphically to the first prominent Pleistocene glacio-eustatic lowstand of marine isotope stage (MIS) 22 at 0.87 Ma. MIS 22 corresponds to the end of the Mid-Pleistocene Revolution, a marked reorganization of Northern Hemisphere glaciation pattern that took place in the late early Pleistocene. We suggest that the R surface formed at Mid-Pleistocene Revolution–MIS 22 time, during the onset of the first major Pleistocene glaciation in the Alps.

Keywords: Pleistocene, ice ages, stratigraphy, Po Plain, Alps.

INTRODUCTION

The benthic oxygen isotope record shows more than 100 oscillations between mild and cool climate since 3 Ma (Shackleton, 1995). The greatest ice volumes were produced since ca. 0.9 Ma during the cooling times of five of these oscillations, i.e., those corresponding to marine isotope stages (MISs) 22, 16, 12, 6, and 2.

Such intensification of glacial activity is expected to leave a stratigraphic signature in periglacial sedimentary basins, such as the Po River Basin, which was directly to the south of the Pleistocene Alpine ice cap (Fig. 1).

Analyses of sedimentology, sandstone petrography, biostratigraphy, and magnetostratigraphy (this study; Carcano and Piccin, 2002) were conducted on a 200-m-long Pleistocene core drilled by Regione Lombardia at Pianengo (Fig. 1). ENI E&P seismic profiles were used to trace laterally magnetostratigraphically dated unconformities recognized in the core, potentially associated with climatically driven pulsations of the nearby Alpine ice cap. The aim of this paper is to date the onset of major Pleistocene glaciations in the Alps, because, at present, this date is virtually unknown.

FACIES ANALYSIS

At the core base (Fig. 2), a 3-m-thick marine fossiliferous silty clay (unit 14) is overlain by a 29-m-thick coarsening-upward sequence in which deltaic medium-grained sands pass into very fine grained littoral sands (units 13–12). Next, a 15-m-thick fine-grained sand alternating with greenish or organic-rich silty clay of continental (floodplain) origin (unit 11) is overlain by 4 m of bioturbated or laminated littoral sand and silty clay (unit 10). Above is a 6-m-thick marine-shelf fossiliferous mud (unit 9), overlain by a 24-m-thick transitional-marine, coarsening-upward sequence consisting of silty clay and very fine to medium-grained sand, which is interpreted as a prograding delta (unit 8, prodelta; unit 7, delta front and delta plain). The occurrence of normal-sized *Gephyrocapsa* in units 14, 13, and 9 indicates a Pleistocene age (Pasini and Colalongo, 1997). Fully continental sediments overlie unit 7. Unit 6 consists of very fine to medium-grained, well-sorted, cross-bedded sands interpreted as meandering fluvial-channel and crevasse-splay sequences. Thick packages of gray silty clay (floodplain) and brown organic-rich clay (marsh) are present. Correlations with additional cores and well logs in the Po Plain show a gradual downstream decrease of sand-grain size from west-northwest to east-southeast.

At −80.8 m, unit 6 is abruptly overlain by coarser-grained continental sediments of periglacial braidplain (units 5–2), which consist of medium- to coarse-grained, poorly sorted, massive or cross-bedded sand and pebbly sand and, in the upper part (units 3–2), clast-supported polygenetic gravels with a sandy matrix. Rare thin layers of green or organic matter–rich, dark gray silty clays are present. Within units 5–2, a facies change associated with a grain-size decrease gradually develops downstream from north to south.

The prominent boundary between units 5 and 6 is hereafter termed the R surface.

SEDIMENT COMPOSITION AND PALEODRAINAGE

On 21 samples, 400 points were counted by Gazzi-Dickinson method and 200–250 transparent dense minerals on the 63–250 μm fraction.

Below the R surface, quartz, feldspars, and medium- to high-rank metamorphic lithic fragments dominate (Q66 F14 Lv2 Ls5 Lm13; parameters after Ingersoll et al., 1984; Garzanti et al., 2003). Dense minerals include mainly blue-green hornblende, epidote, and garnet. Such composition documents a provenance from chiefly the amphibolite-facies Lower Penninic nappes of the Lepontine Dome (Central Alps; ''deep structural level,'' Garzanti et al., 2003). Locally, abundant epidotes and significant glaucophane, actinolite, and zoisite indicate subordinate contributions from high-pressure metaophiolites of the Piemontese zone (Western Alps). Detritus was thus carried by a river system whose source was in the Central Alps (paleo-Ticino) with tributaries in the Western Alps (paleo–Dora Baltea).

The interval between the R surface and −39 m in the core (Fig. 2) is dominated, instead, by limestone and dolostone grains and a few felsitic volcanic lithic fragments derived from Permian–Mesozoic successions of the Southern Alps (Q39 F5 Lv8 Ls31 Lm17 to Q14 F1 Lv5 Ls77 Lm2). The concentration of dense-mineral assemblages decreases from 15% to 0.8%, including garnet, staurolite, and andalusite from the Southalpine basement, trace zircon and tourmaline from the Southalpine cover, or hornblende from peri-Adriatic

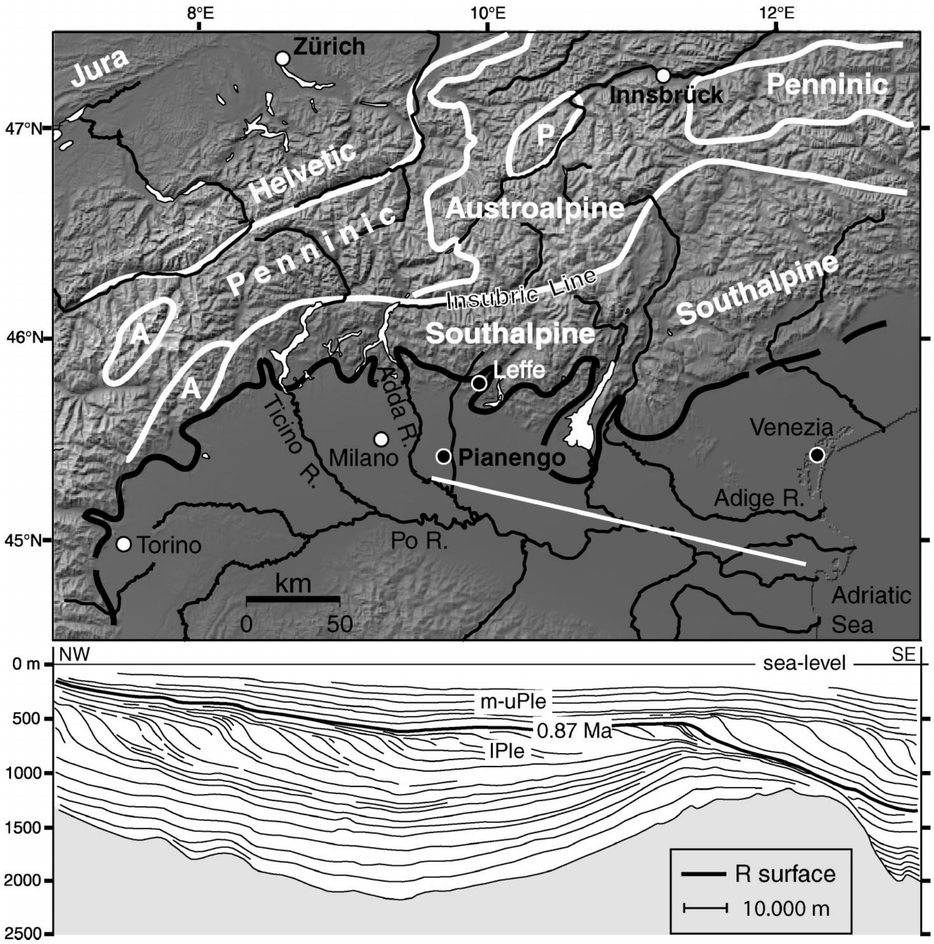

Figure 1. Map of Alps. Pianengo core is south of maximum expansion of Pleistocene Alpine ice cap (solid line). Tectonic domains: Austroalpine (A) and Southalpine = Adriatic continental-margin units. Penninic (P) = thinned outer-continental-margin slivers of uncertain paleogeographic origin. In lower panel, composite seismic profile (location indicated by white line on map) shows lateral extent of R surface; lPle—lower Pleistocene, m-uPle—middle–upper Pleistocene.

plutons. The R surface therefore separates depositional systems with different composition and provenance. Above −39 m in the core, the sediments have a composition similar to the one below the R surface.

POLLEN ANALYSIS

From 76 samples treated, 61 productive samples were analyzed at ×400 and ×1000. On average, 417 ± 150 grains/sample, excluding local taxa, were counted (Fig. 2): 111 well-preserved pollen types were determined (Moore et al., 1991) and named using the Alpine Palynological Database (University of Bern). Pollen types were grouped in cumulative histograms (mixed-oak taxa = deciduous *Quercus*, *Fraxinus*, *Carpinus betulus*, *Ostrya*, *Tilia*, *Ulmus*; Juglandaceae = *Carya*, *Pterocarya*, *Juglans*; conifers = *Pinus sylvestris* or *Pinus mugo*, *Picea*, *Abies*; xerophytes = *Artemisia*, *Helianthemum*, Chenopodiaceae, *Hippophae*, Ephedraceae).

Pollen grains, transported by rivers and/or wind from a wide sector of the Po Plain and Alpine belt, were deposited in low-energy marine or fluviatile environments. No reworked pollen grains were observed.

The interval from the core base up to the R surface is characterized by six vegetational cycles (two complete, four incomplete). This is a minimum estimate, limited by the actual availability of productive pollen samples. A complete basic cycle is defined by the vertical superposition of mixed-oak taxa, Juglandaceae, conifers, and xerophytes, and represents a gradual transition from warm-temperate to cooler climatic conditions. In particular, a one-cycle climate was initially warm-temperate (mixed-oak taxa), then warm-temperate and very moist (Juglandaceae), subsequently colder (*Tsuga* and, in general, conifers) and, finally, cold and dry during short intervals with abundant steppe elements (xerophytes). A similar and coeval sequence of mild to cool climatic cycles bearing no evidence of truly glacial conditions was found in the Pleistocene Leffe core located north of Pianengo (Fig. 1) (Ravazzi and Rossignol Strick, 1995; Pini and Ravazzi, 2002).

In the Pianengo core, the highest abundance of *Betula* and xerophytes occurs just below the R surface, from −81.7 to −80.85 m. This event of forest withdrawal indicates a climate-worsening pulse of higher magnitude than the cooling parts of the underlying mild to cool climatic cycles.

The last occurrence (LO) of *Tsuga* (late early Pleistocene) better defines previous data on the Italian flora (Müllenders et al., 1996); the LO of *Carya* (earliest middle Pleistocene) agrees with data from the magnetostratigraphically dated Venice core sediments (Müllenders et al., 1996; Kent at al., 2002); the occurrence of *Pterocarya* in the middle Pleistocene (from −38.8 to −29.9 m) supports its persistence in Europe up to MIS 11 (Reille et al., 1998).

MAGNETOSTRATIGRAPHY AND AGE MODEL

Stepwise alternating field demagnetization to 100 mT was applied to 43 samples to retrieve paleomagnetic directions. In 35 samples, a univectorial component of magnetization was isolated to the origin after removal of an initial viscous overprint probably induced by core drilling. This characteristic component of magnetization is mainly carried by a low-coercivity phase interpreted as magnetite and bears either positive or negative inclinations with mean values of +48° and −59°, respectively. The Pianengo core was not oriented with respect to the geographic north; therefore only the magnetic inclination of least-square best-fitting lines on Zijderveld demagnetization diagrams was used to delineate polarity stratigraphy (Fig. 2).

The Pianengo core magnetostratigraphy corresponds to a Pleistocene time interval extending from the late Matuyama reversed chron to the early Brunhes normal chron (Fig. 3). An age versus depth plot was constructed of chronostratigraphic control points at 1.07 Ma (base of Jaramillo subchron), 0.99 Ma (top of Jaramillo subchron), and 0.783 Ma (Brunhes-Matuyama boundary) (Cande and Kent, 1995).

The proposed age model implies an average (nondecompacted) sedimentation rate of ~330 m/m.y. and an age of ca. 0.87 Ma for the R surface. According to magnetostratigraphic data, the erosional R surface does not seem to be associated with a major gap in sedimentation.

R SURFACE IN THE PO PLAIN SUBSURFACE

The R surface was traced using ENI E&P seismic profiles across the Po Plain (Fig. 1) and Adriatic offshore. Seismically, the R surface is represented by both an unconformity and its correlative conformity, but is never associated with angular geometries of tectonic

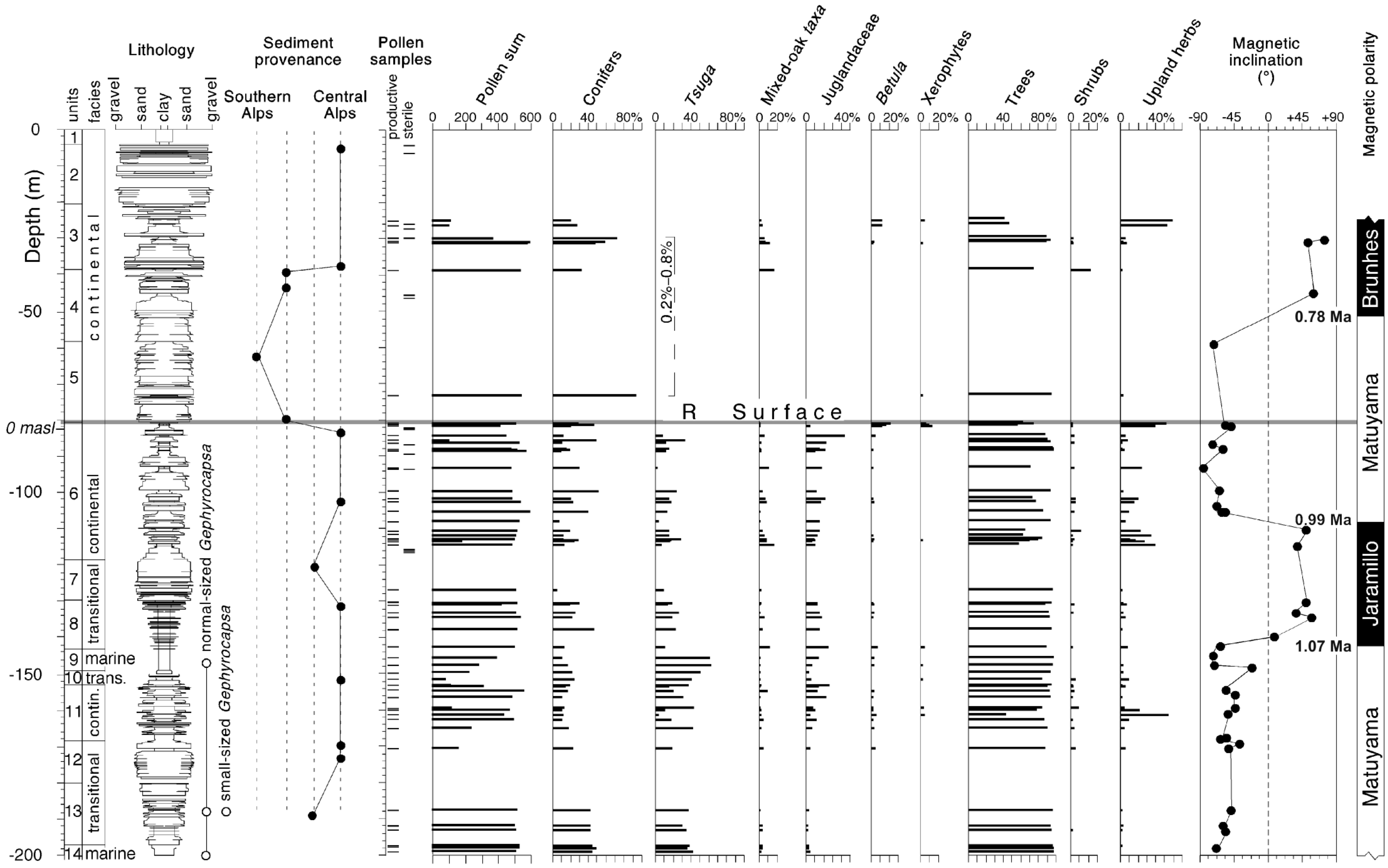

Figure 2. Pianengo core. From left to right: units, facies analysis, lithology, source of Alpine clastic sediments, stratigraphic position of pollen samples, pollen sum histogram (number of pollen grains, excluding local taxa, per sample), cumulative pollen histograms (percent of pollen sum), paleomagnetic inclination, and magnetic polarity attribution (black is normal, white is reverse).

origin. According to data from Pianengo and additional cores under study, the R surface separates different depositional systems. During the times of continental settings, sand-transporting, meandering fluvial systems fed by the Central Alps—flowing axially west-northwest to east-southeast across the Po flood plain—were shifted southward and replaced by coarser grained alluvial fans and braided river systems that rapidly prograded transversally from north to south from the Southern Alps onto the Po Plain. In the Northern Adriatic Sea foredeep, the R surface marks the onset of deposition of coarser-grained and thicker-bedded sandy turbidite systems.

Expansion of transverse alluvial fans and displacement of longitudinal rivers toward the distal basin indicate enhanced erosion rather than thrusting activity (Burbank, 1992), a hypothesis supportive of a climatic rather than tectonic origin of the R surface.

R SURFACE AND CLIMATE CHANGE

The R-surface event was correlated magnetostratigraphically to variations of Northern Hemisphere ice volume, by using the glacio-eustatic curve 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 m glacio-eustatic drop at the Last Glacial Maximum time (Fairbanks, 1989). The R-surface event corresponds to MIS 22 (0.87 Ma). Downcore, marine units 9 and 14 seem to correspond to prominent sea-level highstands of MIS 31 (1.07 Ma) and MIS 37 (1.24 Ma), respectively (Fig. 3).

MIS 22 was the first prominent glacio-eustatic lowstand of the Pleistocene. It occurred during the late Matuyama reversed chron and was associated with a sea-level fall of ~120 m similar in magnitude to the ones of MIS 16, 12, 6, and 2, all entirely contained within the Brunhes normal chron. Glacio-eustatic oscillations prior to MIS 22 (Pliocene and early Pleistocene) were of lower amplitude. The transition from lower-amplitude–higher-frequency to higher-amplitude–lower-frequency glacio-eustatic oscillations that occurred between MIS 25 and 22 is termed the Mid-Pleistocene Revolution (MPR; Berger et al., 1993).

WAXING OF FIRST MAJOR ALPINE ICE CAP

At least six mild to cool climatic cycles bearing no evidence of truly glacial conditions occurred in the Po Plain from 1.24 Ma (MIS 37) to just prior to the deposition of the R surface at 0.87 Ma (MIS 22). Chemical weathering, pedogenesis, and karstification limited detrital production from the vegetated, proximal Southalpine belt. Quartzo-feldspathic detritus derived from distant source rocks located in the Central Alps was redistributed across the Po Plain by a trunk river (paleo-Ticino) flowing longitudinally parallel to the Southalpine belt.

This scenario changed across what would become the R surface when the Northern Hemisphere climate became more arid and colder and sea level dropped to an unprecedented −120 m during the MIS 22 lowstand. Aridity determined the replacement of closed forests by steppe vegetation. Devegetation and eustatic lowstand combined to enhance erosion on the steep slopes of the Southalpine belt. The transition to a chiefly physical mode of detrital production resulted in increased sediment coarseness. Climatically driven devegetation, eustatic lowstand, and erosion triggered the rapid progradation of alluvial fans and coarse-grained braided fluvial systems from the proximal Southalpine belt over the continental Po Plain, as well as for the south-

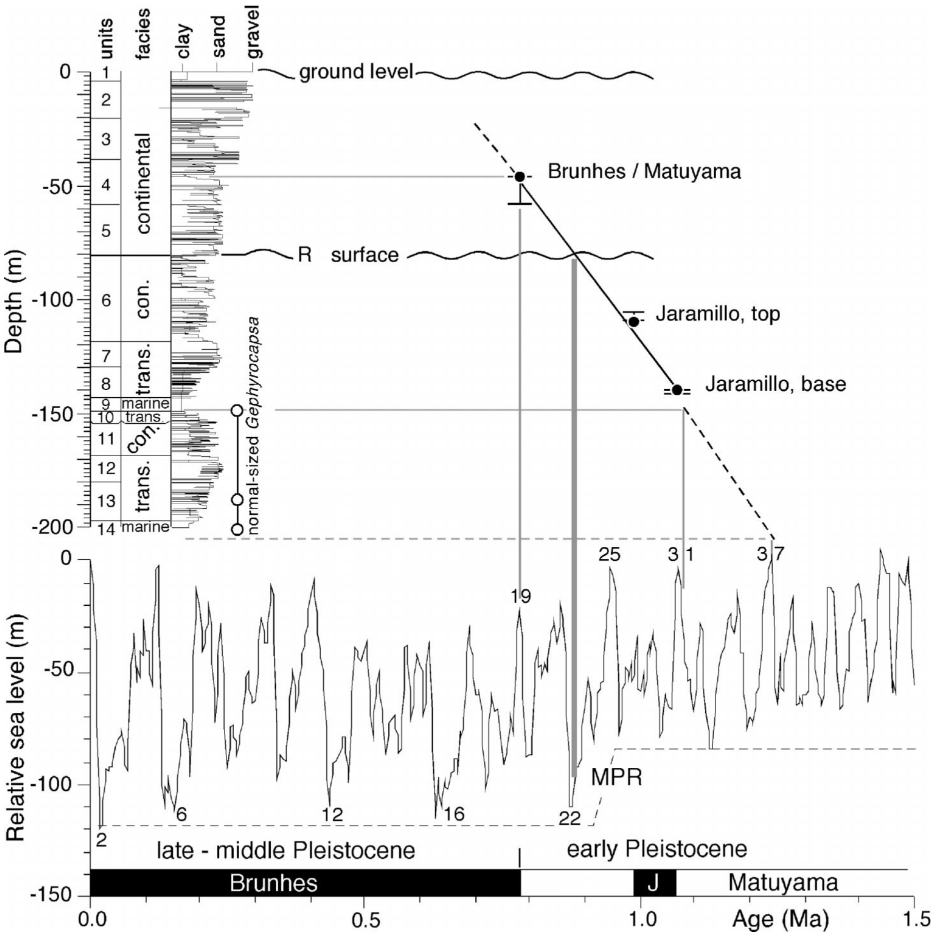

Figure 3. Pianengo age vs. depth model. Correlation with ODP677-SPECMAP record shows that R surface corresponds to MIS 22; MPR—Mid-Pleistocene revolution; trans.—transitional; cont.—continental.

ward shift of the paleo-Ticino trunk river. The Mid-Pleistocene Revolution–MIS 22 climatic event probably also determined deltaic progradation. In the Venice area, a tenfold increase in sedimentation rate occurred just before the Brunhes-Matuyama boundary (Kent et al., 2002). In the Bengal Fan, increasing denudation rates and sediment fluxes from the Himalayas at ~MIS 22 time are indicated by an unconformable transition to a thicker and coarser grained turbidite package (Derry and France-Lanord, 1996).

Penck and Brückner (1909) recognized four Alpine glacial stages. The oldest one (Günz) was tentatively correlated to the increase in Northern Hemisphere ice volume that occurred at 0.87 Ma (MIS 22) (Kukla and Cilek, 1996). A large increase in North American ice volume occurred between the late Matuyama and the Brunhes chrons (Barendregt and Irving, 1998), i.e., at around Mid-Pleistocene Revolution–MIS 22 time, and was responsible for deposition of increased ice-rafted detritus in the North Pacific (Kent et al., 1971).

A cooling event coeval with MIS 22 (0.87 Ma) is recorded regionally in the Po Plain stratigraphy by the R surface. This climatic-forced sequence boundary marks the onset of the first major Pleistocene glaciation in the Alps, when ice sheets invaded both the Central Europe uplands (Penck and Brückner, 1909) and the Southalpine foothills, and elsewhere in the Northern Hemisphere (e.g., North America), when the continental ice caps increased in volume.

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