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MIDDLE PLEISTOCENE TO HOLOCENE APENNINE GLACIATIONS (ITALY)

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ABSTRACT
Knowledge of the Apennine glaciations may be summarized as follows: it is certain that in the Apennines there are traces of at least one glacial expansion older and more extensive than that of the Last Glacial Maximum (LGM). Its age is not known in detail, but it is highly likely that it dates from the final part of the Middle Pleistocene. An additional earlier glacial phase might also be represented. The Late Pleistocene glaciation has left few traces relating to Marine Isotope Stage 4, but abundant sediments and features relating to the LGM and to its recessional phases are found. Radiometric dating of these glacial oscillations is still rather scanty. In the last few years tephra layers and some eolian deposits have been found which, being isochronous, make it possible to obtain a chronological setting and a precise correlation even between the moraines situated at latitudes and elevations very different from one another.
The Late Pleistocene LGM glaciers started to expand earlier than 22,680±630 ^{14}C years BP (Campo Imperatore Stadial), and began to retreat slowly around 21,500 ^{14}C years BP, and then more rapidly until about 17,000 ^{14}C years BP. After 17,000 years BP there was a readvance. This Fontari Stadial was followed by recessional phases lasting until after 11,760 ±160 ^{14}C years BP. Another readvance followed, the Mount Aquila Stadial, which may be correlated with the Younger Dryas. The recessional phases of this stadial are probably represented by the earliest Holocene moraines: later the glaciers melted. They reformed in the second half of the Holocene (Calderone Stadial) after 3890±60 ^{14}C years BP, and re-expanded after ca. 2650±60, 1450±40, 670±40 ^{14}C years BP and reached their maximum length during the Little Ice Age. The Calderone Glacier, the only one that now exists in the Apennines, has strongly melted back in the 20th century.

RIASSUNTO
Le conoscenze relative alle glaciazioni dell'Appennino possono essere sintetizzate nel modo seguente. E' sicuro che sull'Appennino vi sono le tracce di almeno una espansione glaciale più estesa di quella dell'Ultimo Massimo Glaciale: la sua età non è nota in dettaglio, tuttavia è molto probabile che risalga al Pleistocene Medio, forse alla sua parte finale. Potrebbe essere documentata anche una fase glaciale precedente, per la quale risulta difficile una attribuzione cronologica. La glaciazione del Pleistocene Superiore ha lasciato poche tracce relative allo stadio isotopico 4, ma moltissimi depositi e morfologie relativi all'Ultimo Massimo Glaciale ed alle sue fasi di ritiro. I ghiacciai della fase finale del Pleistocene Superiore si sono espansi a partire da un momento precedente a 22,680±630 anni ^{14}C BP (Campo Imperatore Stadial), ed hanno cominciato a ritirarsi lentamente attorno a 21,500 anni ^{14}C BP, e poi, più velocemente, fino a circa 17,000 anni ^{14}C BP. In un periodo poco più recente di 17,000 anni ^{14}C BP vi fu la riespansione glaciale denominata Fontari Stadial, seguita da fasi di ritiro che durarono fino ad un momento più recente di 11,760±160 anni ^{14}C BP. Si verificò poi la riespansione glaciale denominata M. Aquila Stadial, correlabile al Younger Dryas: le fasi di ritiro di questo stadio dovrebbero essere rappresentate dalle prime morene oloceniche. Per quel che riguarda le espansioni glaciali oloceniche e la Neoglaciazione occorre tenere presente che i dati sono scarsi poiché le località studiabili sono pochissime e ristrette alle porzioni più elevate dei due massicci più elevati dell'Appennino.
I ghiacciai presenti nella fase iniziale dell'Olocene scomparvero e si riformarono poi nella seconda metà dell'Olocene in un periodo più recente di 3890± 60 anni ^{14}C BP, furono soggetti a varie fasi di espansione dopo 2650±60, 1450±40, 670±40 anni BP (Calderone Stadial) e raggiunsero la loro massima lunghezza nel corso della Piccola Età Glaciale. Il Ghiacciaio del Calderone, l'unico attualmente presente sull'Appennino, ha mostrato nel corso del XX secolo una forte riduzione di volume ed appare sull'orlo dell'estinzione.

Key words: Apennines, glaciations, Middle Pleistocene, Late Pleistocene, Holocene.

INTRODUCTION

The Apennines form the backbone of the Italian Peninsula, extended into the Mediterranean Sea between 38° N and about 44°30' N (Fig. 1). Traces of former glaciation have been known for the Apennines since the 19th century and have been the subject of many investigations. In the present work, however, only the most recent studies will be taken into consideration.

The highest peaks in the Apennines are found in the central sector, between about 42°50' N and 41°30' N where they include the Gran Sasso (2912 m), Maiella (2793 m), Velino (2486 m), Sibillini (2476 m) and Laga (2458 m) massifs, but numerous other peaks exceed 2000 m. In contrast, the mountains of the Northern Apennines exceed 2000 m only at Mounts Cusna (2121 m), Cimone (2165 m) and Prato (2054 m), and the mountains of the Southern Apennines exceed 2000 m only in Mounts Sirino (2005 m) and Pollino (2266 m).

At present only a single small glacier which is rapidly melting is found in the Apennines: the Calderone Glacier in the Gran Sasso.

Until around 15 years ago, the study of the Apennine glaciations was limited to examination of the glacial features, the weathering of the till and calculation of the equilibrium line altitude (ELA) of the former glaciers. The chronological framework of the glacial phases relied largely on the correlation between the local ELA and those of the Alps. It is only since 1989 that the use of ^{14}C dates and of tephra layers (Frezzotti & Narcisi, 1989, Frezzotti & Giraudi, 1989) has made it possible to date the glacial deposits directly, although as yet only

very few dates are available. In the Apennines there are traces of at least two glaciations: the most ancient ones, while certain, are rather scanty, whereas traces of the most recent glaciation are very abundant and well preserved. The great majority of the glaciers were present in valleys and glacial cirques orientated towards the north, while only a few developed in valleys orientated towards the west and the east, and hardly any occurred in valleys with a southern alignment.

MIDDLE PLEISTOCENE GLACIATION

It is only recently that the traces of an early glaciation were identified with certainty (Federici, 1977). Since the glacial stratigraphy of the Apennines has been correlated with that of the Alps, the oldest moraines have been attributed to the Rissian glaciation or to a generic pre-Würmian event. Pre-Würmian moraines have been reported from the Northern Apennines, in the area of Mount Navert (Federici, 1977; Jaurand, 1994, 1998), and in the Central Apennines, at Sibillini Massif (Coltorti & Farabollini, 1995), at Campo Imperatore in the Gran Sasso Massif (Giraudi, 1994; Jaurand, 1994, 1998; Giraudi & Frezzotti, 1997; Bisci *et al.,* 1999), in various places of the Velino Massif (Cassoli *et al*., 1986; Giraudi, 1998b) and at Mount Greco (Frezzotti & Giraudi, 1989; Cinque *et al.* 1990). According to Damiani & Pannuzi (1991), however, the 'Rissian' moraines at Mount Greco should be attributed to the Early Würmian glaciation. Judging from the distribution of till in the Central Italian massifs, the extension of the glaciers during this period must have exceeded that of the Last Glacial Maximum (LGM) by some 5 - 10%. It is not possible to assess the ELA of the glaciers because the Apennine Chain has been affected by intense neotectonic movements, and it is likely that the characteristics of the catchment areas of the glaciers have changed considerably. Overall the data are so scanty that no glacial limits can be mapped.

According to Kotarba *et al.* (2001), Uranium Series datings have been done on calcite crystals included in

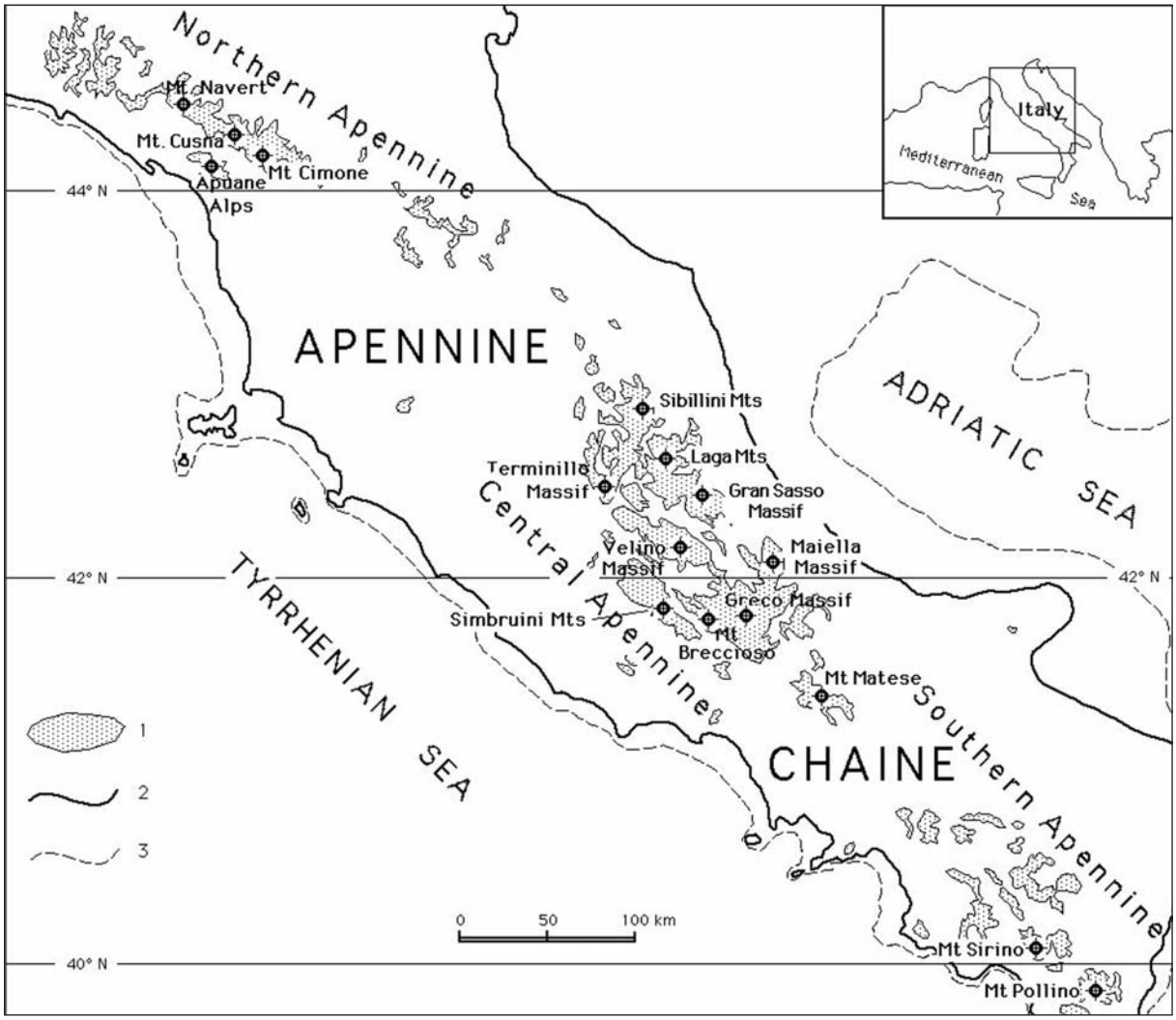

Fig. 1 - Location of the Apennine Chain and of the main mountain massifs. Legend: 1 - areas above 1000 m; 2 - present shoreline; 3 - Last Glacial Maximum shoreline.

moraine deposits at Campo Imperatore: the ages of 121 (+13/-12) and 135 (+10/-9,7) allow the Authors to assume a Late-Middle Pleistocene age for the older glaciation phase.

In a recent study (Giraudi, 1998b) of the Campo Felice area in the Velino Massif (Central Apennines), the relative age of some of the older moraines were determined. These 'Rissian' glaciation moraines are overlain by aeolian deposits which mainly include volcanic minerals. They contain a palaeosol. In addition, these deposits have also yielded a Mousterian chert artefact. In Central Italy Mousterian cultural remains occur from at least Marine Isotope Substage 5e (i.e. Eemian) and until the end of MIS 4 (i.e. Middle Würmian). Since the moraines predate the aeolian deposits, the palaeosol and the artefacts, it is highly improbable that the ice advance occurred during MIS 4 and 5 (i.e. Early or Middle Würmian).

The first major ice advance in the Apennines must therefore date at least from one of the cold stages preceding MIS 5e; it must be Middle Pleistocene. Because the moraines are fairly well preserved, a Late Middle Pleistocene age is most likely (i.e. potentially MIS 6 or 8). According to Jaurand (1994, 1998), the Mount Navert moraine, another pre-Würmian feature that was preserved in a palaeolandscape, may be even older. It might indicate glaciation of the Apennines before the Late Middle Pleistocene.

UPPER PLEISTOCENE GLACIATION, THE LAST GLACIAL MAXIMUM AND ITS RETREAT PHASES

Traces of the Upper Pleistocene Glaciation have been reported in a number of papers, but only the most recent will be considered.

The considered works on the Northern Apennine glaciers are: Bertolini & Trevisan (1984), Braschi *et al.* (1986), Castaldini *et al.* (1998), Federici (l977, 1978, 1981), Federici & Scala (1966), Federici & Tellini (1983), Gabert (1962), Giglia (1967), Gruppo Ricerca Geomorfologia (1982), Jaurand (1994, 1998), Losacco (1982), Nardi (1961), Pelletier (1959), Suter (1950) and Trevisan *et al.* (1971). The works on the Central Apennines glaciers are by Bally (1954), Biasini (1966), Brancaccio *et al.* (1980), Cassoli *et al.* (1986), Castaldo (1965), Catenacci (1974), Cinque *et al.* (1990), Damiani (1975), Damiani & Pannuzi (1976, 1979, 1985-1986 a,b, 1991, 1993), Demangeot (1965), Dramis & Kotarba (1994), Dramis *et al.* (1987), Dramis *et al.* (1980), Federici (1979, 1980), Frezzotti & Giraudi (1989, 1990, 1992), Frezzotti & Narcisi (1989, 1996), Giraudi (1988, 1989a, 1989b, 1992, 1994, 1997a, 1997b, 1997c, 1997d, 1998 a, 1998b, 1998c, 1998d, 2000), Giraudi & Frezzotti (1995, 1997), Jaurand (1994, 1998), Mongini (1970), Palmentola *et al.* (1990), Pfeffer (1967), Praturlon (1968), Raffy (1983), Rasse (1994) and Tagliaferro (1982). The works on the Southern Apennines glaciers are by Boenzi & Palmentola (1971, 1972a, 1972b, 1974, 1975), Giraudi (1998f), Lippmann-Provansal (1987), Palmentola & Acquafredda (1983), Palmentola *et al.* (1990) and Palmentola & Pennetta (1979).

Savelli *et al.* (1995) report the presence of glacial remains on Mount Catria (1700 m a.s.l., north-central Apennines). As the authors point out, the glacial traces on Mount Catria are somewhat problematic and they lack age control. The glacier is said to have developed in a south-facing valley and its front must have reached down to an extremely low level (about 580 m a.s.l.), far lower than the levels reached by the major glaciers of the Northern Apennines with a northern exposure. Glacial landforms are absent from the highest peak of the mountains, which is exposed to the west, and is theoretically best suited to support a glacier. Therefore, this supposed past glacier cannot be discussed until new evidence becomes available.

Upper Pleistocene glacial morphological features and deposits can almost exclusively be dated to the last glacial maximum and its retreat phases. Older outwash sediments have only been identified (Frezzotti & Giraudi, l992) from the margins of the Velino Massif (Central Apennines). These sediments predate a fossil soil on volcanic material, dated to 33,140±1700 ^{14}C years BP and developed, probably, during Marine Isotopic Stage 4.

The most recent summaries of data on the late Pleistocene glaciation of the Apennines were presented by Federici (1979) for the Central and Northern Apennines, Palmentola *et al.* (1990) for the Southern Apennines and Jaurand (1994, 1998) for the whole mountain range.

Federici (1979), using the degree of preservation of the landforms, but without any radiometric dates, correlated the moraines of the maximum ice advance of the Central Apennines to the 'Würm III' of the Alps. This expansion was related by him to between *c.* 21,000 and 18,000 years BP. He also differentiated various successive retreat stages:

- Apennine Stage 1, correlated with the Alpine *Altstadien*, which is marked by a rise of the equilibrium line altitude (ELA) of 110-240 m;
- Apennine Stage II, correlated with the Bühl-Schlern Stages of the Alps, with ELA 300 m higher than 'Würm III';
- Apennine Stage III, correlated with the Gschnitz of the Alps, with ELA about 600 m higher than 'Würm III';
- Apennine Stage IV, correlated tentatively with the Daun of the Alps, with ELA about 700-800 m higher than 'Würm III'.

According to Panizza (1985), the Alpine Bühl-Schlern and Gschnitz Stages are included in the Oldest Dryas, while the Daun corresponds to the Older Dryas.

In the Southern Apennines, Palmentola *et al.* (1990), again in the absence of absolute dates, correlated the maximum ice advance to the Alpine Würm III and distinguished three successive retreat stages: Apennine Stage 1, which they correlated with the Oldest Dryas, with an ELA of about 150-170 m higher than Würm III; Apennine Stage II, which they correlated with the Older Dryas, in which an ELA of about 300 m higher than in Würm III was determined, and Apennine Stage III, which they correlated with the Younger Dryas, with an ELA about 400 m higher than during Würm III.

Later, Frezzotti & Giraudi (1989, 1992) dated the late-glacial climatic phases in the area of Mount Greco and the outwash sediments of Mount Velino (Central Apennines). For the first time they were able to demonstrate that the Apennine LGM was more recent than a

series of depositional and erosional events younger than *c.* 30,000 ^{14}C years BP but older than *c.* 15,000 ^{14}C years BP. Lowe (1992) dated lacustrine sediments behind a number of stadial moraines in the Northern Apennines.

Following study of the glacial events throughout the Apennines, Jaurand (1994, 1998) based his synthesis on a number of radiocarbon dates reported in Frezzotti & Giraudi (1989, 1992) and Lowe (1992).

Jaurand (1994, 1998) attributed the LGM moraines to an ice advance which reached its maximum around 19,000 ^{14}C years BP. He recognized four successive stages: Apennine Stage I, which corresponded to a rise of the ELA of 50-125 m; Apennine Stage IIa, correlated with the Oldest Dryas, older than 13,000 ^{14}C years BP, with a rise of the ELA of 250-300 m; Apennine Stage IIb, which he correlated with the Younger Dryas, with a rise of the ELA of about 400 m and Apennine Stage III, correlated with the Preboreal, with a rise of the ELA of 550-600 m with respect to that of the Last Glacial Maximum (LGM).

Regarding the Southern Apennines, Jaurand (1994, 1998) denies, on the basis of sedimentological and morphological evidence, the glacial origin of deposits in Calabria, south of Mount Pollino formerly postulated by Boenzi & Palmentola (1972b, 1974, 1975b).

More recently, Giraudi (1997a, 1997b, 1997c, 1997d, 1998 a, 1998b, 1998c, 1998d, 2000, in the press) and Giraudi & Frezzotti (1997) carried out more detailed investigations on a number of massifs in the Central Apennines (Gran Sasso; Greco, Terminillo, Velino, Maiella, Breccioso, Matese) and in the Southern Apennines (Sirino and Pollino).

On the Gran Sasso massif, thanks to a series of radiocarbon dates and the Neapolitan Yellow Tuff tephra (recognized by Frezzotti & Narcisi, 1989, 1996), Giraudi & Frezzotti (1997) were able to date various phases of the LGM (Campo Imperatore Stadial). The longest glacier in the Apennines had already reached its maximum extent before 22,680±630 ^{14}C years BP. Its glacier tongue blocked a small tributary valley, damming a proglacial lake. Glacial retreat began around 21,450±250 ^{14}C years BP, when outwash was deposited. A further phase of intense glacial melting is again dated from outwash deposits to a little less than 17,840±200 ^{14}C years BP. Moreover, many recessional moraines are recognized: all of which, except the highest on Mount Aquila, predate the Neapolitan Yellow Tuff tephra, dated at 12,300±300 ^{14}C years BP (Alessio *et al.*, 1973). The authors were able to distinguish two interstadial periods, the Fornaca Interstadial, at 16-17,000 ^{14}C years BP, and the Venacquaro Interstadial, radiocarbon-dated to 13,000 - 11,000 years BP. Giraudi & Frezzotti (1997) summarize the sequence of events as follows:

- In addition to the Last Glacial Maximum (LGM) moraines of the Campo Imperatore Stadial, on the Gran Sasso there are three recessional moraines that predate the Fornaca Interstadial.
- Afterwards these interstadial glaciers readvanced during the Fontari Stadial. A set of three recessional moraines formed prior to the subsequent Venacquaro Interstadial.
- This was followed by a minor glacial readvance in the Monte Aquila Stadial, after 11,760±160 and before 8035±140 ^{14}C years BP, which may be correlated with the Younger Dryas.

Despite having no new ^{14}C dates available, Giraudi (1997a, 1997b, 1997c, 1997d, 1998a, 1998b, 1998c, 1998d, 2000) in his studies of other massifs in the Central-Southern Apennines recognized a number of stratigraphic markers (tephra and aeolian sediments) which are fundamental for the dating and correlation of the glacial events on the different massifs.

Later on, new data about tephra layers found on glacial debris allowed the number of stratigraphic markers, described below, to be improved.

- In all the glaciated areas studied (except for the Gran Sasso and Majella), the most recent moraines (ELA some 400-475 m higher than that of the LGM) are overlain by the Neapolitan Yellow Tuff tephra, radiocarbon dated 12,300±300 ^{14}C years BP (Alessio *et al.*, 1973).
- On the Matese Massif (Central Apennines) a tephra layer predating the Neapolitan Yellow Tuff overlies moraines which indicate a rise of the ELA of c. 300 m with respect to the LGM. The tephra was analyzed by Narcisi (2000, personal communication) using SEM analysis: the chemical composition appears very similar both to the tephra of the "Greenish" and "Basale" eruptions of Mount Vesuvius. Near the volcano, the products of the "Greenish" eruption cover palaeosols dated 15,500±170 and 14,420±160 ^{14}C years BP (Santacroce, 1987), and the tephra of the "Basale" eruption covers palaeosols dated 16,250±130 and 17,050±40 ^{14}C years BP (Delibrias *et al.*, 1979)
- In all glaciated areas, at the bottom of closed depressions on glacial debris, a layer of loess was found. On Mounts Greco and Matese (Central Apennines) and on Mount Sirino (Southern Apennines), this loess consists mainly of quartz. It is the only loess with such a mineralogical composition known in the Central-Southern Apennines in the last 30,000 years BP. Here it overlies moraines which indicate a rise of the ELA of *c.* 200-280 m with respect to the LGM, but is not present on the younger ones. The precise age of this loess, identified for the first time by Frezzotti & Giraudi (1989, 1990), is lacking, but its dating is based on the following criteria:
  - On the Aremogna Plain (Mount Greco - Central Apennines) the loess lies on outwash sediments deposited during the LGM recession. On the basis of the data collected by Giraudi & Frezzotti (1997) on the Gran Sasso Massif, the outwash deposits were, partly, formed after 17,840±200 ^{14}C years BP. At the Fucino Plain, the deposition of outwash sediments from the glacier of the Velino Massif ended around 17,380±160 ^{14}C years BP when the lake covered a soil and produced erosion on such deposits (Giraudi, 1998g). On the Aremogna Plain, the loess, which has been subject to soil formation, was redeposited as colluvium and subsequently overlain by peat dated at 12,850±200 ^{14}C years BP (Frezzotti & Giraudi, 1989).
  - On Mount Matese (Central Apennines) the loess is older than the tephra layer (Giraudi, 1997a). similar to the products of the "Greenish" and "Basale" eruption of Vesuvius, datable at *c.* 14,000-15,000 and 16,000-17,000 ^{14}C years BP.
- The Cerchio Tephra, a tephra of as yet unknown ori-

gin, was identified on the moraines of the first recessional phases after the LGM (with an ELA some 125 m higher than at the LGM) of Mount Breccioso (Central Apennines). The first products of tephra reworking have been dated in the nearby Fucino Plain (Giraudi, 1995) at 19,100±650 ^{14}C years BP.

About the tephra layers that predate Neapolitan Yellow Tuff on the Matese Massif, and overlie the quartz-rich loess, one can observe that, due to the age of the eruption, there is little probability that it corresponds to the "Basale" eruption of Vesuvius. The "Basale" covers palaeosols dated 16,250±130 and 17,050±40 ^{14}C years BP and seems too old to fit in with the chronology of the glacial phases suggested by other datings. Otherwise one must assume that during the short period between 17,380±160 and 16,000 – 17.000 ^{14}C years BP a glacial re-expansion occurred, with the sedimentation of the quartz-rich loess, and a new retreat phase.

It is therefore assumed that the tephra predating the Neapolitan Yellow Tuff on the Matese massif pertains to the "Greenish" eruption of Vesuvius, younger than palaeosols dated 15,500±170 and 14,420±160 ^{14}C years BP .

Following this assumption, one can date the quartz-rich loess, covering moraines of a glacial stadial when ELA was 200-280 m higher with respect to the LGM, to a period around or slightly younger than 16,000 ^{14}C years BP.

Using radiocarbon dating and the chronological data stated above, a chronology of the Apennine last glacial maximum and its retreat phases has been obtained (Fig.2).

The maximum glacial extent, i.e. the Campo Imperatore Stadial, was reached just before 22,680 ±630 ^{14}C years BP and lasted until ca. 21,450±250 ^{14}C years BP.

During LGM, ELA on the Apennines was conditioned by latitude and valley exposures, and varied between 1250 and 1900 m a.s.l. About 21,450±250 ^{14}C years BP the glaciers started the early phases of retreat, that lasted until 17,840±200 ^{14}C years BP. In this period at least two retreat moraines were formed, produced by glaciers having ELA 15-125 and 110-200 m higher than LGM; nevertheless in some massifs the retreat moraines can be three or more because of local topographic reasons.

Around 17,840±200 ^{14}C years BP a very marked retreat phase took place, and a large amount of outwash sediments was produced: such a rapid glacier melting must have been due to a strong climatic change, i.e. to the occurrence of an interstadial (Fornaca Interstadial).

The glacier melting ceased around 17,380±160 ^{14}C years BP, when a new stadial advance took place (Fontari Stadial). During this stadial the last valley glaciers were present on the higher massifs, and ELA was 200-280 m higher than during LGM.

Starting from 16,000 ^{14}C years BP, a glacial reduction took place. Two retreat moraines were formed: the former, dated about 15.000-16.000 ^{14}C years BP, by glaciers having ELA 290-390 m higher than during LGM, and the latter, dated around 14,000 ^{14}C years BP, by glaciers having ELA 400-475 m higher than during LGM.

Between 12,850±200 ^{14}C years BP and at least 11,760±160 ^{14}C years BP, the lack of glacial remnants and the presence of lakes in some former glacial cirques (Giraudi & Frezzotti, 1995) suggest a very small extension of the glaciers. This time lapse is called Venacquaro Interstadial and corresponds to the Bölling-Alleröd interstadial.

Later, between 11,760±160 and 8035±140 ^{14}C years BP, a new small glacial advance took place (M. Aquila Stadial) corresponding to the Younger Dryas chron.

It is clear that the dates obtained generally show an earlier age for the glacial events than assumed before.

HOLOCENE NEOGLACIATION

The presence of glaciers in the Apennines during the Holocene is shown by the Calderone Glacier. This glacier, located on the Gran Sasso Massif, is the southernmost in Europe (Gellatly *et al.*,1994). It is found at an elevation above c. 2670 m in a cirque situated on the northern slope of the Corno Grande (2912 m). Its tongue is rapidly melting and is almost completely covered by debris, but it was still some 15 m thick in its lower part (Gellatly *et al.*,1994; Fiucci *et al.*, 1997). The glacier is situated at the head of the Cornacchie Valley. Here new investigations have begun; in the upper part there are some moraines, which were formed by glaciers with an ELA more than 800-1050 m higher than that of the LGM. They must be of Holocene age, because the Younger Dryas ELA was at least 250 m lower.

There are no precise dates for these oldest Holocene moraines: the only chronological indication is provided by a sequence of colluvial sediments and soils overlying the till that include a tephra layer. The tephra, of uncertain provenance, may be correlated mineralogically with the Duchessa Tephra (Giraudi, 2001). This unit has also been found on other moraines in the Central Apennines, and overlies soils dated to 4390±50 (Beta 117017), 4220±80 (Beta 106450) and 4020±70 (Beta 111004) ^{14}C years BP. The moraines, which indicate a glacier with an ELA about 800 m higher than that of the LGM, may possibly represent the recessional phases of the Mount Aquila Stadial dated to the Younger Dryas Chron.

The moraines situated at the threshold of the Calderone Glacier cirque, with their ELA about 1000-1050 m higher than the LGM, have been attributed to the Little Ice Age (LIA) by various authors (Federici, 1979; Jaurand, 1994, 1998; Gellatly *et al.*, 1994). In the course of new observations on these moraines, three different tills have been recognized (Giraudi, 2000, 2002). The oldest till, almost completely covered by the successive units, has a dark grey matrix of silt rich in organic matter, derived from a soil on volcanic material. Its mineralogical composition is analogous to that of the Duchessa Tephra. The organic matter has been dated to 3890±60 ^{14}C years BP. Consequently, the glacial advance (Calderone 1 stadial) that formed the moraine must be younger than that date and represents the first known Apennine Neoglacial expansion. In view of the very steep sides of the glacial cirque, the soil could only be derived from the cirque, which is currently occupied by the glacier. Therefore, starting from about 4300 ^{14}C years BP and until around 3890 ±60 ^{14}C years BP, the

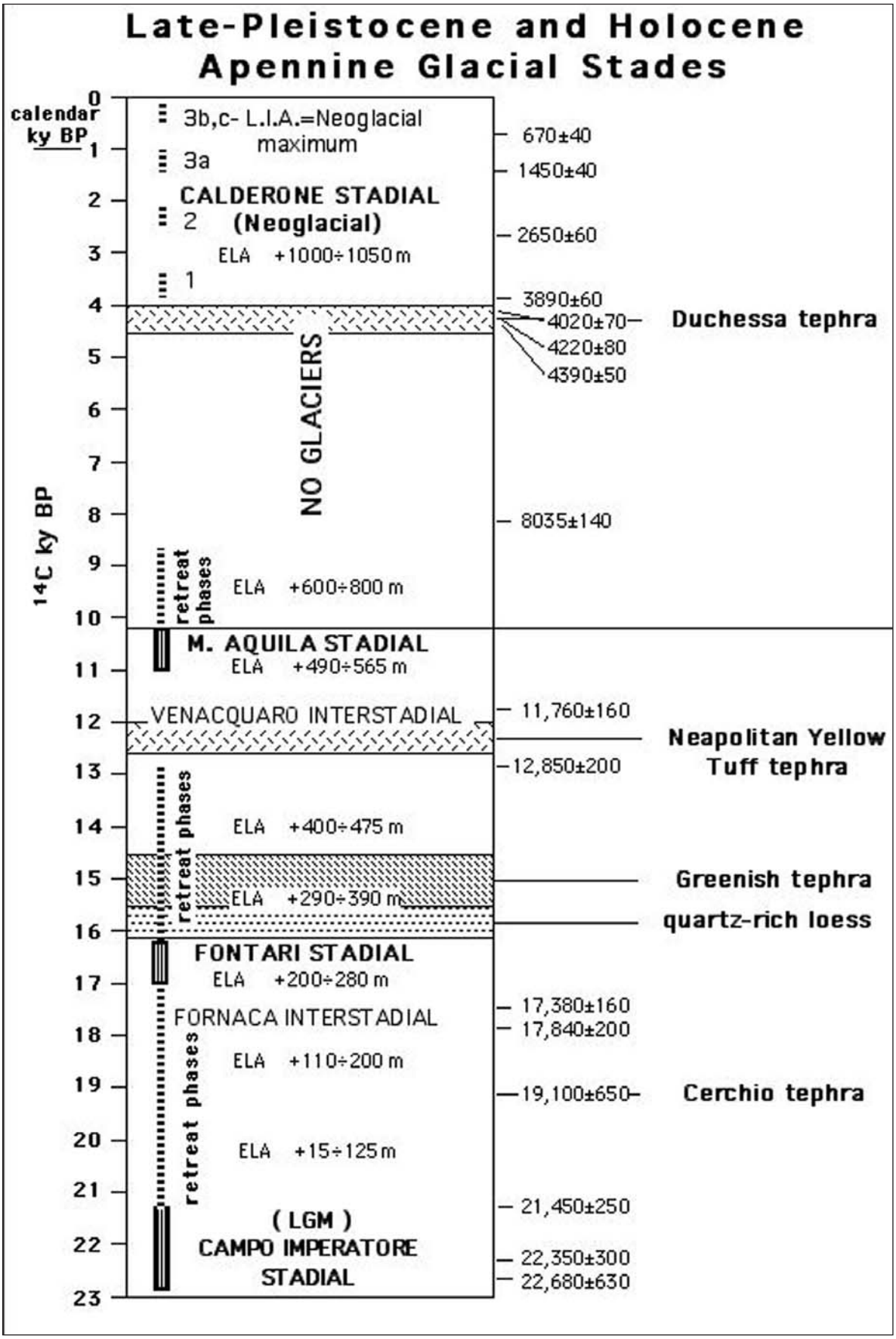

Fig. 2 - Chronological framework of the Last Glacial Maximum, late Pleistocene and Holocene Apennine glacial stadials.

Calderone glacier was absent or was definitely much smaller than at present.

But according to others palaeoclimatic data on the Central Apennines area and the correlations with alpine glacial phases, Giraudi (2000) hypotesized that the glaciers on the Apennines disappeared about 9000 ^{14}C years BP.

In order to detect the age of the debris of glacial origin lying just down-valley of the threshold of the cirque of Calderone Glacier, Giraudi (2002) dated the interbedded soils by means of radiocarbon analysis. The datings point out four more glacial expansions: the first (Calderone 2) following 2650±60 ^{14}C years BP, the second (Calderone 3a) bracketed between 1450±40 and 670±40 ^{14}C years BP, the tird (Calderone 3b) following 670±40 ^{14}C years BP, the last one (Calderone 3c) datable to the XIX century. The Calderone 3b expansion, occurred during the Little Ice Age, can be considered the Neoglacial maximum.

Thus, the following sequence of events has been deduced: the early Holocene saw the recessional phases of the Mount Aquila Stadial glaciers. After 9000 ^{14}C years BP, these glaciers melted completely. Subsequently the Calderone Glacier expanded, after 3890±60, 2650±60, 1450±40, 670±40 ^{14}C years BP and during the XIX century.

Moraines colonized by only very little vegetation, are also preserved at high altitudes at a number of valley heads in the Maiella Massif (Central Apennines). They have been attributed to the Holocene (Giraudi, 1998e). At the head of the Cannella Valley, an extremely small moraine situated at 2540 m is almost completely devoid of vegetation, comparable to the till of the Calderone Glacier attributed to the LIA above-mentioned. It is therefore probable that in this valley a small glacier also formed during the LIA. Traces of neoglaciation are probably found on only the two highest massifs of the Apennines, since the peaks of the other massifs are below the altitude of the Calderone Stadial moraines.

COMPARISON BETWEEN THE APENNINE, ALPINE AND OTHERS MOUNTAIN GLACIATIONS

The comparison between the Apennines and other mountain chain glacial expansions can be reliable only for LGM and Holocene, because the older glaciations lack a suitable chronological framework.

The Upper Pleistocene maximum glacial expansion, dated in the Apennines between 22,680±630 and 21,450±250 ^{14}C years BP, was not synchronous in the European mountain chains. In the Pyrenees LGM occurred in a period older than 38,000 ^{14}C years BP, and a secondary glacial expansion took place ca. 26,000 ^{14}C years BP (Jalut *et al.* 1992; Florinet & Schlüchter, 2000). On the Massif Central, LGM occurred before 28,000 ^{14}C years BP, while a minor expansion took place ca. 18,000 ^{14}C years BP (Etlicher & De Goer de Hervé, 1988; Florinet & Schlüchter, 2000).

On the Jura, LGM is dated between 25,000 and 15,000 ^{14}C years BP (Campy & Richard, 1998).

In the Northern Alpine Foreland LGM was reached in a time lapse between 28,000 e 20,000±1800 ^{14}C years BP (Ivy-Ochs, 1996; Florinet & Schlüchter, 2000), while in the Southern Alpine Foreland it took place between 24,000 and 17,700±360 ^{14}C years BP (Fliri, 1989, Orombelli, 1974; Bini, 1997).

The LGM datings in the Apennines, the Alps and the Jura are essentially similar. Although the beginning of the glacial retreat in the Italian Alps (17,700±360 ^{14}C years BP according to Orombelli, 1974) clashes with the start of the fast retreat of the Apennine glaciers (ca.17,840±200 ^{14}C years BP), in the Apennines a slow glacial melting occurred after ca 21,450±250 ^{14}C years BP. The early Apennine glacial retreat was produced by a climatic change from cold and wet to cold and dry (Giraudi & Frezzotti, 1997). This change probably occurred only in the Italian peninsula, not in the Alps, or the climate change was weak and not able to affect the alpine glacial system having greater inertia.

According to Florinet & Schlüchter (2000) the different chronological framework for the Pyrenees and the Vosges LGM is the consequence of palaeoclimatic conditions linked to some differences in the Upper Pleistocene atmospheric circulation.

About Holocene, Baroni & Orombelli (1996), Orombelli & Mason (1997), Grove (1997), Grove & Gellatly (1997) and Jania (1997) report that between 9000 and 8000 ^{14}C years BP in the Alps, the Pyrenees and the TatraMountains, the largest glaciers were smaller than today and the smallest ones melted: strong glacial expansion took place only after 5000 ^{14}C years BP.

During the same period the Calderone Glacier melted, leaving the Apennines without glaciers. The same glacier, lying at both a lower altitude and latitude than other mountain glaciers, reappeared only in a period more recent than 3895±65 ^{14}C years BP, when ELA went down to a height lower than the Gran Sasso peak.

Grove (1997), in a paper on the Holocene European glacial phases, reports glacial advances in the Alps ca. 3000-3600, 2100-2600 ^{14}C years BP, 800-900 AD, and much glacial expansion since 1350 AD. These glacial expansions can be correlated with the Calderone Stadials 1, 2, 3a, 3b, 3c.

In particular, about the Italian Alps, Orombelli & Pelfini (1985) report an advance of the Forni Glacier (Ortles-Cevedale Massif) older than peat dated 2670±130 ^{14}C years BP, which can be correlated to the Calderone Stadial 1. In the Pisgana Glacier (Adamello Massif) a glacial expansion took place between 3015±75 and 2345±125 ^{14}C BP (Baroni & Carton, 1991) coincident with the Calderone Stadial 2.

The Brenva Glacier (Mt. Bianco Massif) advanced (Orombelli & Porter,1982) and the moraines covered a tree dated 1170±75 ^{14}C years BP (760÷980 cal. AD); Strumia (1997) found some soil dated 1185±80 ^{14}C years BP (734÷980 cal. AD), buried because of the advance of the Lys Glacier (Mt. Rosa Massif). These glacial advances can be correlated with the Calderone Stadial 3a.

In the Alps, starting from the XV Century, i.e. during the Little Ice Age, a great deal of glacier expansions took place (for a synthesis see Baroni, 2000) which can be coeval, on the whole, to the Apennine Calderone Stadial 3b,3c.

CONCLUSIONS

In the Apennines the main phases of glacial expansion occurred in the Middle Pleistocene (probably during the Marine Isotopic Stage 6 or 8) and in the Late Pleistocene LGM. The Middle Pleistocene glaciers were 5-10% larger that the Upper Pleistocene ones

During LGM, some glaciers reached an altitude of 700-800 m a.s.l.. The ELA value was between 1250 and 1900 m a.s.l., changing according to the altitude, latitude, exposition of the glacial valleys, amount of snow precipitation etc., and according to the distribution of land and seas as pointed out by Messerli (1967) for the mountains surrounding the Mediterranean Sea.

ELA varied between 1250 and 1550 m, 1550 and 1900, 1600 and 1800 in the Northern, Central and Southern Apennines. Messerli (1967;1980) calculated the present day snow limits in the Northern (ca. 3000 m

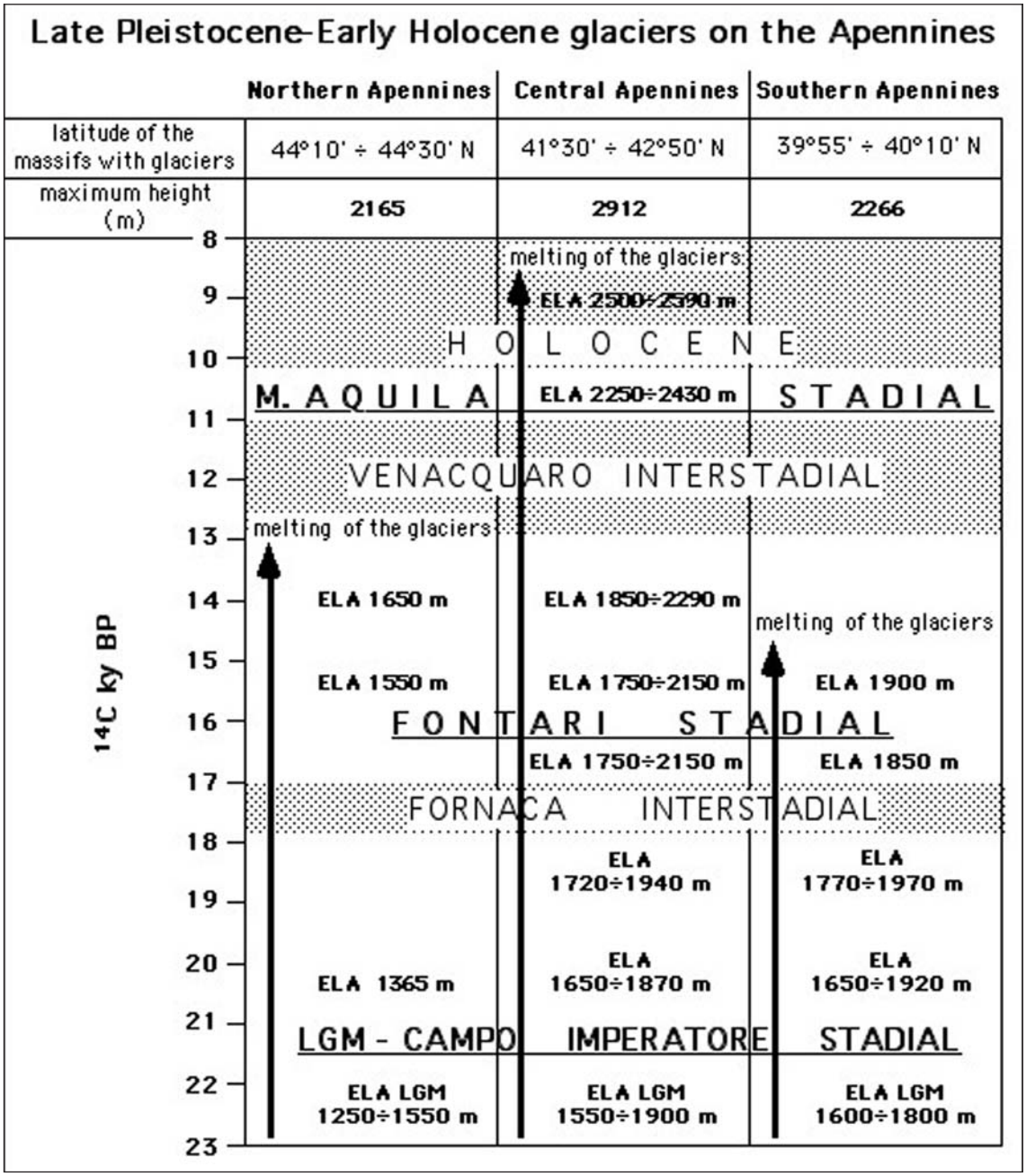

Fig. 3 - Glacial stadials and Equilibrium Line Altitude (ELA) variations from Last Glacial Maximum to the early Holocene. The data from the Northern Apennines stadial ELA's are based on Val Parma glaciers facing North (from Jaurand, 1994, 1998). Maximum and minimum ELA values reported for the Central and Southern Apennines depend on the different massifs and valley orientations. In the Southern Apennines, the glaciers melted earlier than in the Northern Apennines despite the maximum elevation being higher. In the Northern Apennines the ELA is clearly lower than in the Central Apennines, while there is only a small difference between the Central and Southern Apennines.

a.s.l), Central (ca. 3220 m a.s.l), and Southern Apennine (ca. 3330 m a.s.l). As well as during the LGM, the difference between Northern and Central Apennine is bigger than between the Central and Southern Apennine.

The moraines are preserved better in the calcareous Central and Southern Apennines than in the Northern, formed mainly by marly and arenaceous sediments. In spite of the different data-base, a comparison between the sectors of the Apennines chain can be made. In the Central Apennines, reaching the maximum altitude, the glaciers lasted until the early Holocene (Fig. 3); later they disappeared but the Calderone Glacier reappeared and reached its maximum neoglacial length during the Little Ice Age; the same glacier, although very small and completely covered by debris, lies in a portion of the Gran Sasso high cirque even today.

During LGM, the Northern Apennines ELA was lower than in the Central and Southern sectors. In spite of the elevation of the mountains, in the Southern Apennines the glacier melted earlier (about 15,000 ^{14}C years BP) than in the Northern part, where glaciers disappeared about 13,000 ^{14}C years BP (Fig. 3).

According to the published datings, the Apennine Late Pleistocene and Holocene glacial advances and retreats were nearly synchronous with the Alpine ones: the clearest difference is represented by the early beginning of the LGM Apennine glaciers retreat, which started about 21,000 ^{14}C years BP.

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