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Middle and late Pleistocene glaciations in the Campo Felice Basin (central Apennines, Italy)

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ABSTRACT

The present paper refers to research conducted in the tectonic-karst depression of Campo Felice in the central Apennines (Italy), in which glacial, alluvial and lacustrine sediments have been preserved. Stratigraphic interpretations of sediments underlying the Campo Felice Plain are based on evidence obtained from nine continuous-core boreholes. The boreholes reach a depth of 120 m and provide evidence of five sedimentation cycles separated by erosion surfaces. Each cycle is interpreted as an initial response to a mainly warm stage, characterized by low-energy alluvial and colluvial deposition, pedogenesis, and limited episodes of marsh formation. In turn, a mainly cold stage follows during which a lake formed, and glaciers developed and expanded, leading to deposition of glacial and fluvioglacial deposits. The chronological framework is established by eleven accelerator mass spectrometer ^{14}C ages and three ^{39}Ar–^{40}Ar ages on leucites from interbedded tephra layers. These age determinations indicate five glacial advances that respectively occurred during marine oxygen isotope stages 2, 3–4, 6, 10 and 14.

Introduction

The Apennine chain, which forms the backbone of the Italian peninsula, extends in a NNW–SSE direction between latitudes 44°40′ N and 37°57′N and is surrounded on three sides by the Mediterranean Sea. The northeast slope of the highest peak (Gran Sasso, 2912 m) supports the Calderone Glacier. This glacier currently is experiencing major ablation (Giraudi, 2005).

The mountain chains of the central and western Mediterranean basins have been studied relatively little from the viewpoint of glacial traces prior to the last glacial maximum (LGM). Limited studies reflect in large part that these mountains poorly represent conditions favourable for dating glacial features. In Spain, France and Greece, moraines older than LGM have been dated (Fernandez Mosquera et al., 2000; Calvet, 2004; Woodward et al., 2004; Hughes et al., 2006, 2007; Hughes and Woodward, 2008, 2009). Mt. Tymphi in Greece (Woodward et al., 2004; Hughes et al., 2007), ca. 600 km southeast of Campo Felice, is the nearest site with a few available ages.

The highest mountains of the Apennines show traces of three glaciations (Giraudi, 2004, and references therein), which occurred in the middle and late Pleistocene. Of these, only the most recent glaciation is reasonably well-dated (Giraudi and Frezzotti, 1997). Uranium series dating carried out on calcite crystals included within moraine deposits at Campo Imperatore allowed Kotarba et al. (2001) to assume that the oldest glaciation occurred during marine oxygen isotope stage (MIS) 6.

Study of the glacial evidence (summarized by Giraudi, 2004) indicates that the most extensive glaciers were in the northern and central Apennines. The greatest quantity of glacier-related phenomena is found in the central Apennines, where the mountains are the highest. Here, many enclosed tectonic basins are also found with endorheic drainage. This internal drainage favored a slower rate of erosion that enabled glacial deposits older than the LGM to be preserved.

One of the depressions on the Campo Felice Plain, on the northern edge of the Mt. Velino massif in Abruzzo (42°13′N, 13°25′E), was chosen for the present study (Fig. 1). The plain is well-known in the literature due to the presence of deposits from at least two glaciations

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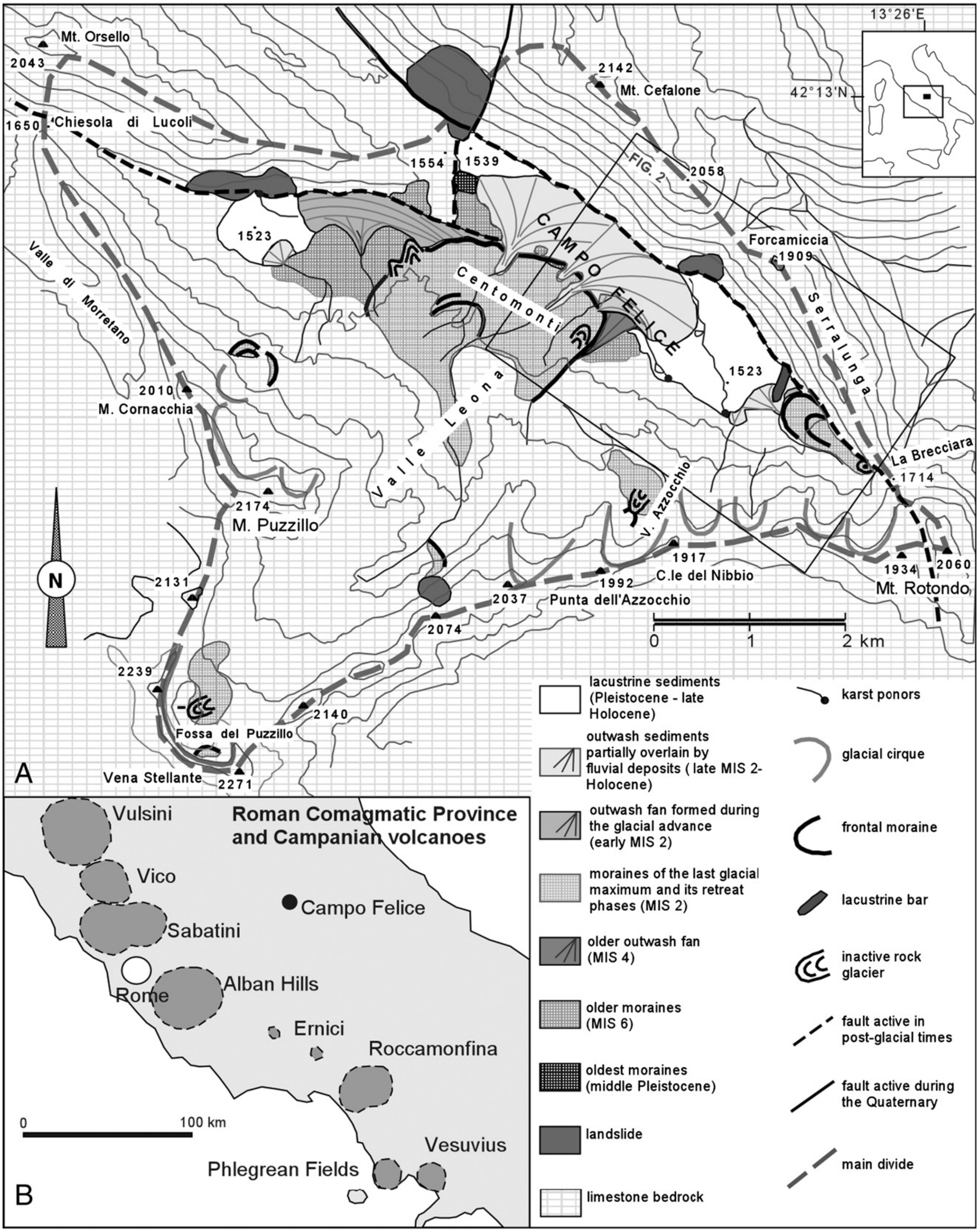

Figure 1. Geological map of Campo Felice and its catchment basin (A), and (B) the Roman Comagmatic Province, and Campanian volcanoes.

(Cassoli et al., 1986; Jaurand, 1998; Giraudi, 2001, 2004). The lithological and mineralogical study of the sediments and the dating reported in the present paper provide evidence for a number of environmental variations that occurred over 500 ka involving five cold periods.

The Campo Felice Plain

The Campo Felice Plain is a small plain located in a closed tectonic-karst basin surrounded by Meso-Cenozoic limestone ridges (Bosi and Manfredini, 1967; Accordi et al., 1986). The plain occurs at altitudes between about 1520 and 1600 m. Thick lake sediments bordered by deposits of glacial, fluvioglacial, alluvial, detrital and aeolian origin occur in the lowest portions of Campo Felice. Some small ponors act as water outflows (Giraudi, 1998, 2001).

The catchment basin (Figs. 1 and 2) extends over large tracts above 2000 m and includes peaks above 2200 m. A large portion of the mountainous zone and the plain were occupied by glaciers during the Pleistocene, and glacio-karstic landforms are present. Moreover, there are traces of the existence of discontinuous permafrost in the past. Because of its geological and geomorphological features, the Campo Felice Basin shows great potential for the dating of past glacial and periglacial events.

The origin of the depression of Campo Felice is due to the formation of a half-graben that displaced a limestone monocline sloping to the NE, and forming the present northern edge of the Plain (Fig. 3). The Forcamiccia pass, located between Mt. Cefalone and Mt. Serralunga (Figs. 1 and 2), is situated at the head of a valley that was truncated headwards by the movement of the fault which produced the half-graben. The fault is oriented NW–SE in the eastern portion (the Mt. Cefalone fault) and WNW–ESE in the western portion (the Mt. Orsello fault). The incision of the Forcamiccia valley truncated by the fault took place before the formation of the half-graben. The stream that produced the incision probably came from the area of Vena Stellante-Punta dell'Azzocchio and flowed towards the northeast. Part of this valley (on the downthrown side of the fault) was covered by the sediments of Campo Felice.

The half-graben structure therefore seems to have been divided into two parts by a roughly N–S fault. Some faults were active also during the late Pleistocene and Holocene (Giraudi, 1995; Giaccio et al., 2002).

Field and laboratory methods

The sediments underlying the Campo Felice depression were sampled by means of 9 continuous-core boreholes, the deepest of which reached 120 m below ground level. These borings were conducted as part of the Special Project “Lacustrine Sedimentation-Palaeoenvironment-Palaeoclimate” of the National Research Council (CNR). Stratigraphy in the upper part of the cores was correlated against glacial and lacustrine deposits outcropping at the surface or observed in shallow excavations.

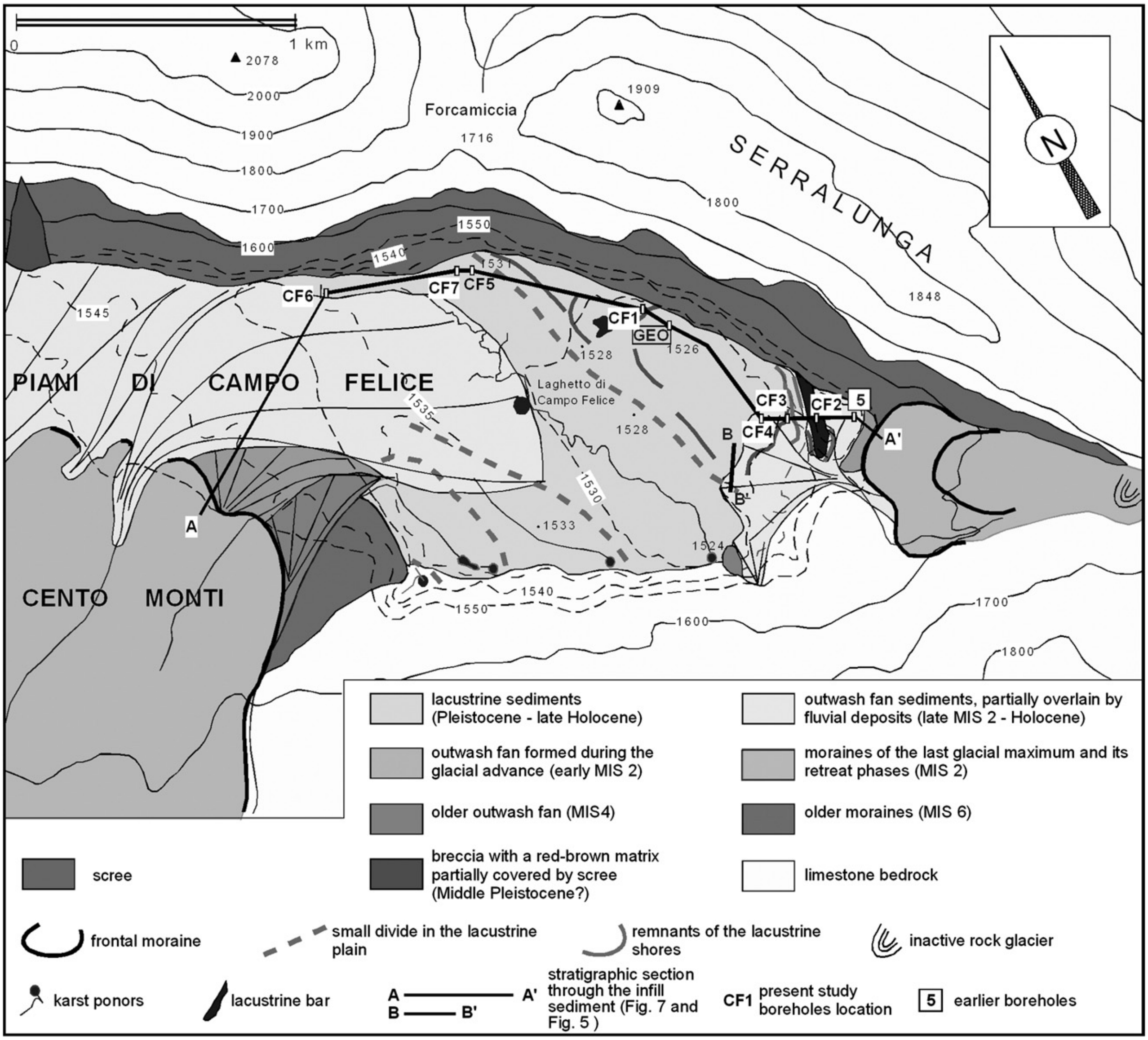

Figure 2. Geological map of the eastern portion of Campo Felice, location of the boreholes CF1–CF7, 5 and GEO, and geological sections reported in Fig. 7 (A–A′) and 5 (B–B′).

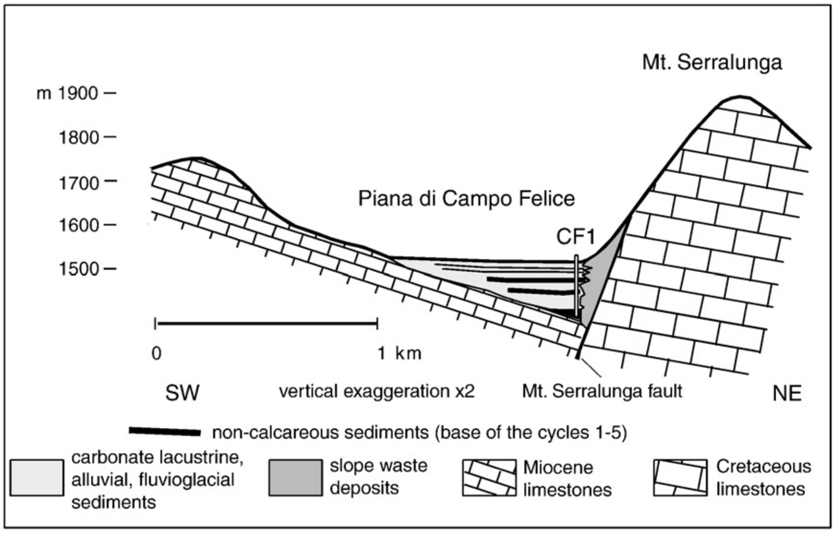

Figure 3. Geological sketch through eastern Campo Felice.

The boreholes were drilled at a distance of 0.1 to 1 km from the younger moraines and a maximum of 2 km from the older moraines. The diameter of the core was 10 cm and the recovery rate was between 75 and 95%. The lower recovery rate was due to the presence of cobbles within the sandy gravel sediments in the easternmost boreholes.

Grain size analyses were performed on the sediments of the CF1 and CF5–7 boreholes. The grain size for the sandy and gravelly sediments was obtained using sieves. For the silt and clay fraction, the grain size was determined using the sedimentation method. The sedimentary stratigraphy of the other boreholes was based on qualitative field descriptions. The total carbonate content was obtained with chemical analyses carried out using a Dietrich–Fruhling calcimeter on CF1 and CF5–7 sediments. Mineralogical analyses were carried out with microscope observations on the sediments of the CF7 borehole.

The chronological framework of the sediments forming the Campo Felice Plain is based on direct dating of sediments (Table 1) obtained with radiocarbon methods (AMS). Peat layers, organic soils and, in the cores, the organic matter present in bulk sediment samples, 10 cm thick, have been dated. The ^{14}C (AMS) dates are reported in the two-sigma calibrated range, obtained using INTCAL98 (Stuiver et al., 1998; Stuiver and van der Plicht, 1998; Talma and Vogel, 1993). The dates older than 20,000 ^{14}C yr BP have been calibrated with the CalPal calibration programme (http://www.calpal-online.de).

The age of the sediment was also established by ^{39}Ar–^{40}Ar dating of tephra levels in older lower sections of the cores. Leucite crystals were separated, irradiated and analyzed by ^{39}Ar–^{40}Ar stepwise heating at the University of Berne using the procedures in Belluso et al. (2000). Uncertainties are given at 95% confidence level.

Geochemical recognition of two tephras of known age provided additional control for dating the sedimentary sequence. The tephra layers chosen for dating and for the geochemical study were interbedded with calcareous lacustrine sediments (see below), presented sharp contacts both at the base and at the top, and were between 0.15 and 1.5 cm thick.

The Quaternary sediments

The unconsolidated sediments underlying the Campo Felice Plain appear to be composed mainly of till, fluvioglacial, alluvial, and lacustrine deposits (Cassoli et al., 1986; Giraudi, 1998; 2001), but there are also aeolian, detrital, and colluvial deposits (Figs. 1 and 2). The present paper focuses mainly on the glacial, fluvioglacial, and lacustrine sediments.

Glacial and fluvioglacial sediments

Moraines occupy a large portion of Campo Felice. The underlying till is represented by sub-rounded limestone cobbles and boulders in a fine-grained calcareous matrix. The moraines are related to at least three glaciations and are differentiated according to degree of preservation, morphological features, pedogenesis, and their different coverings of colluvial and aeolian sediments. Remnants of the oldest moraine occur in a small area north of the Cento Monti (Fig. 1). These remnants are represented by low, badly preserved small hills underlain by till. The intermorainic depressions are nearly filled by pedogenically altered aeolian deposits derived mainly from volcanic materials. Other better-preserved and less pedogenically altered moraines (Fig. 4) are overlain

Table 1
AMS dates.

Age ^{14}C yr BP	Age cal yr BP	Material	Site	Lab. code
30,260 ± 190	34,590–34,260	Organic-rich colluvial sediments (bulk material)	Exposure East Campo Felice	Beta-145527
26,300 ± 600	31,515–30,735	Carbonate lacustrine sediments (bulk material)	CF1 core	Beta-167084
24,810 ± 150	30,155–29,525	Carbonate lacustrine sediments (bulk material)	CF5–7 core	Beta-110183
15,290 ± 50	18,680–17,900	Peat layer 1 cm thick	Exposure East Campo Felice	Beta-145528
15,270 ± 50	18,655–17,880	Peat layer 1 cm thick	Exposure East Campo Felice	Beta-134783
13,870 ± 40	16,970–16,310	Carbonate lacustrine sediments (bulk material)	CF5–7 core	Beta-156395
7760 ± 40	8605–8425	Non-calcareous lacustrine sediments (bulk material)	Exposure East Campo Felice	Beta-138954
3680 ± 90	4260–3730	Organic-rich colluvial sediments (bulk material)	Exposure East Campo Felice	Beta-134785
3480 ± 70	3915–3460	Organic-rich colluvial sediments (bulk material)	Trench East Campo Felice	Beta-134784
3310 ± 40	3640–3460	Organic-rich colluvial sediments (bulk material)	Trench East Campo Felice	Beta-167081
1880 ± 60	1965–1945	Organic soil (bulk material)	Exposure East Campo Felice	Beta-129541

by volcanic mineral-rich aeolian deposits with an interbedded paleosol. These deposits have yielded a Mousterian chert artefact. As reported in Giraudi (2001), in Central Italy Mousterian cultural remains occur from at least MIS 5e and until MIS 3. Since the moraines predate aeolian deposits, the palaeosol, and the artefacts, it is highly improbable that the ice advance occurred during MIS 4. These moraines, formed by a glacier larger than the late Pleistocene one, have been dated to the late middle Pleistocene (Giraudi, 2004) and correlated to the MIS 6 moraines in the Gran Sasso Massif reported by Kotarba et al. (2001).

The local LGM moraines are the best preserved and cover extensive areas within Campo Felice at the locality of Cento Monti (Fig. 4), and at the extreme eastern edge of the Plain. In both localities, the frontal moraines are characterized by a clear, fairly continuous rampart. In spite of the absence of direct dating, the freshness of the forms and the slight degree of pedogenesis, support the idea that these moraines were formed during the LGM (Jaurand, 1998; Giraudi, 1998, 2004). Many ridges occur behind the frontal moraines and enclose depressions that developed during melting of dead ice. In the Cento Monti area (Fig. 1), there are other recessional moraines corresponding to the first re-advance of the glacial front during the general retreat following the maximum expansion (Giraudi, 1998). There are remains of other recessional moraines in the intermediary part of Valle Leona (Fig. 1). A more recent moraine is present on the threshold of the cirque of Fossa del Puzzillo, while the most recent recessional moraine in the catchment basin of Campo Felice is present at the base of the slope of Vena Stellante. The retreat of the glacial tongue following the local LGM must have therefore been interrupted by at least four phases of re-advance.

The fluvioglacial sediments, forming aprons around the local LGM frontal moraines and well-preserved fans, were deposited in two phases. Sediments of the first phase were covered by till during the local LGM glacial advance; the sediments of the second phase cross-cut the LGM moraine, and were formed during the glacial retreat. In the eastern part of Campo Felice, at the contact between the fluvioglacial fan and the lacustrine sediments and at the base of a lacustrine bar, fluvioglacial sediments cover pedogenically altered colluvial deposits, rich in organic matter and dated at approximately 35 cal ka BP (30,260 ± 190 ^{14}C yr BP; Giraudi, 2001). The fluvioglacial sediments are interbedded with lacustrine sediments (Fig. 5) older than 18.68–17.9 cal ka BP (15,290 ± 50 ^{14}C yr BP). The LGM at Campo Felice is therefore bracketed between these ages. This interpretation is consistent with findings of Frezzotti and Giraudi (1992), who bracketed LGM fluvioglacial sediments of Valle Majelama on the southern slope of the Velino Massif, between 38 and 34 cal ka BP (30,700 ± 1700 ^{14}C yr BP) and ca. 16–17 cal ka BP.

Lacustrine sediments

Part of the Campo Felice low-lying areas is underlain by lacustrine sediments, mainly calcareous silt and clay covered by colluvium, mainly formed by volcanic material. The top of the sediments is altered by pedogenesis. The soil on the calcareous sediments is 15 to 20 cm thick and the upper organic horizon is generally 5 to 10 cm thick. In softer non-calcareous sediments the soil reaches a thickness of about 30–40 cm and appears more organic.

A lacustrine bar is also present in the eastern part of Campo Felice. The bar occurs a few meters higher than the surrounding plain and is formed by decimeter-thick strata, slightly dipping towards the center of the plain. The bar consists of clasts that are a few centimeters in size, fairly flattened, and very little sandy matrix. The bar has been correlated with the local LGM, as the sediments forming it cover the fluvioglacial deposits associated with the last major glacial advance and are cut by the fluvioglacial sediments associated with glacial retreat.

Outcrops of fine lacustrine sediments have been dated to the final phases of the late Pleistocene (between 18.68 and 17.9 cal ka BP and 8.605 and 8.425 cal ka BP; Table 1) and to the Holocene (Giraudi, 2001). In particular, in the course of the Holocene, only brief lacustrine episodes occurred, which were interrupted by the sedimentation of colluvium and aeolian sediments, formed mainly of volcanic minerals, and altered by pedogenesis phases.

The stratigraphy of the Campo Felice sediment cores

In order to obtain the stratigraphic data necessary to understand the climatic and environmental evolution, seven continuous-core extractions were made in the eastern portion of Campo Felice (Fig. 2). In addition, the stratigraphy of two sediment cores taken earlier also was examined. The maximum depth reached by the boreholes was about 120 m. In spite of this, in the zone of maximum thickness of the sediments, the base of the sequence of Quaternary sediments was not reached.

The lacustrine sediments include two types of contributions: one dominated by carbonates and the other with a prevalence of silicates (Fig. 6). The silicate fraction contained abundant hydromorphic femic crystals mixed with minerals of volcanic origin.

The litho-stratigraphy of the cores provided evidence that sediments accumulated in conjunction with five different cycles. The base of each sedimentary cycle overlies an erosion surface, or a lacuna, denoted by a clear-cut change in the lithology and facies of the sediments. Also the different thickness of the sediments of the same cycle in different cores seems due mainly to erosion surfaces (Figs. 6 and 7). After the erosion,

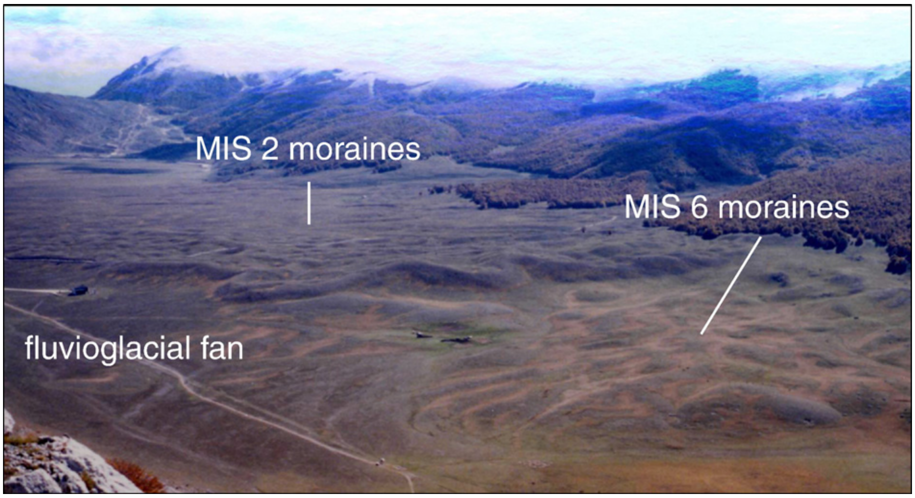

Figure 4. The Cento Monti moraines in the central-western Campo Felice Plain. The younger moraine formed during the local LGM (MIS 2) while the older one formed during MIS 6.

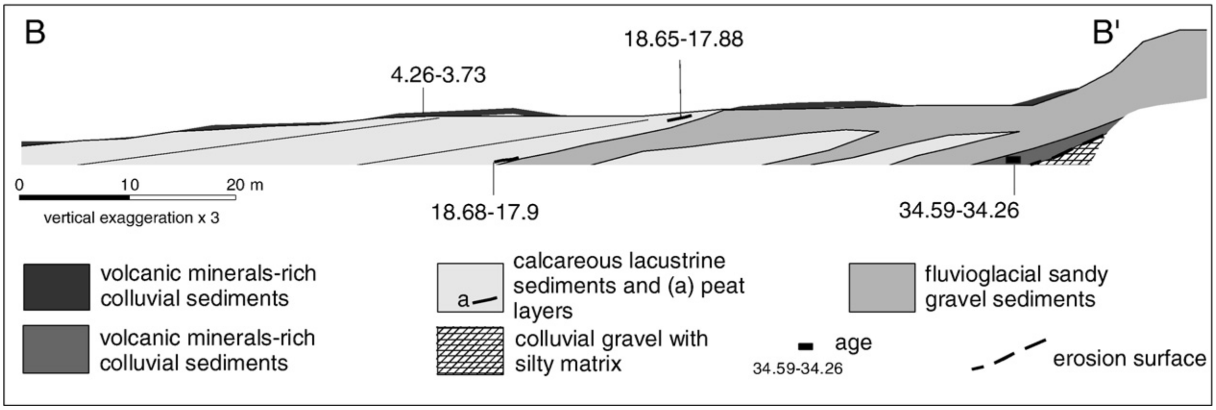

Figure 5. Stratigraphic section of the eastern boundary of the Campo Felice Plain where calcareous lacustrine sediments are interfingered with fluvioglacial sandy gravel sediments. Ages are reported in cal ka BP. See Fig. 2 for B–B′ transect location.

the sedimentation of mainly dark-colored, non-calcareous or weakly calcareous sediments occurred. A typical stratigraphical sequence of these sediments consists of the following: silts and silts with sand, and decalcified gravel of colluvial origin; reworked volcanic material consisting of sand and silt; rare, thin intercalations of gravelly sands of alluvial origin; rare intercalations of thin, light grey or whitish silts and clayey silts of lacustrine origin (Figs. 6 and 7). Discontinuous, 20 to 60 cm thick, yellow–red paleosols developed on silty and sandy gravel, and dark paleosols on thin volcanic material, are preserved. Thin layers of dark silty clay rich sediment in organic matter or peat levels were interbedded with the sediments of the 3rd and 1st sedimentary cycles. The thickness of these sedimentary sequences varies greatly, from more than 10 m to 1.5–2 m. Apart from the thin levels of whitish clayey silts and the gravelly sands, the other sediments are almost completely non-calcareous and the coarse fraction consists mostly of volcanic minerals. In the CF1 and CF5–7 cores, the base of the 4th cycle is the only one formed solely by silty gravels of colluvial origin pedogenically altered.

In general, the non-calcareous or weakly calcareous sediments found in the CF1 and CF5–7 cores have a similar grain size. In the CF5–7 cores a larger number of silty gravel and sandy gravel levels occur and the grain size variations appear more frequent (Fig. 6). The thickness of the prevalently non-calcareous sediments is far less at the base of the 4th and 5th cycles.

Sandy and clayey silts of whitish or light brown color, with a strong carbonate composition (generally more than 60%, at times more than 80%; Fig. 6) overlay the mainly non-calcareous sediments. The thickness of these sediments varies in some boreholes: the maximum thickness is ca. 30 m in the 1st cycle and the minimum is ca. 4 m in the 3rd cycle. The core of the CF1 borehole contains more carbonate than the CF5–7 cores.

The calcareous sediments contain a number of tephra layers and, in some parts, appear laminated. The stratigraphy of some trenches cut into surficial sediments (Giraudi, 2001) shows that the calcareous lacustrine sediments of the last cycle are interfingered with sandy gravels of a fluvioglacial fan linked with moraines of the local LGM (Fig. 5). Similar stratigraphy is present in the boreholes.

Coarse sandy gravels are interfingered with calcareous silts and clayey silts of lacustrine origin in the top four sedimentary cycles (Figs. 6 and 7). However, in the eastern marginal zone of the Campo Felice Plain, near the lacustrine bar and the moraine front, the non-calcareous sediments and the soils of the last four cycles are overlain by the coarse sandy-gravel sediments interfingered with the calcareous lacustrine sediments.

The chronological framework for sediments of the cores was established by radiocarbon AMS datings in the upper part of the cores and by ^{39}Ar–^{40}Ar dating of tephra levels in older lower sections of the cores. The tephra layers are coincident, both in age and mineralogical composition, with some ignimbrites from the Alban Hills Volcanic Complex (AHVC) reported in Villa et al. (1999), Karner et al. (2001) Giordano et al. (2003) and Freda et al. (2006). The tephra levels studied and dated were selected as they are interfingered with calcareous sediments, have sharp contacts with the underlying and overlying lacustrine sediments, and do not contain carbonates of lacustrine origin. Moreover, the tephra were found in the boreholes of the central portion of Campo Felice and not in those at the edges of the plain. It is therefore possible to exclude that they come from any reworking of the volcanic materials already present in the catchment basin. In that case, in fact, levels rich in volcanic materials must have been present, in increasing thicknesses and grain size towards the edge of the plain.

The sediments of the 5th cycle are constrained by several AMS dates on bulk sediment samples (Figs. 6 and 7). The upper part of the 5th cycle contains a layer dated at 16.3–17.0 cal ka BP, while two samples at the base of the lacustrine sediments give ages of 30–32 cal ka BP. At the top of the 4th cycle (Fig. 6), a tephra layer contains leucite dated at 41 ± 9 ka by ^{39}Ar–^{40}Ar. This age overlaps that (ca. 36 ka) of the leucite-bearing eruptions of the Albano Maar (also called Albano 7) from the AHVC (Villa et al., 1999; Freda et al., 2006). The chemical composition of this tephra layer (CF3 in Fig. 8; Table 2) shows affinity with the proximal pyroclastic deposits of the eruption. The Albano Maar ignimbrites have been found in several zones of the central Apennines (Giaccio et al., 2007, and references therein).

A tephra layer was also found interbedded with the lacustrine sediments of the 3rd cycle (Fig. 6). The chemical composition shows that the tephra derives from the Vico volcanic eruption (CF4 in Fig. 8; Table 2) known as "Ignimbrite B" dated 157 ± 3 ka by Laurenzi and Villa (1987).

The lacustrine carbonate sediments of the 2nd cycle contain (Fig. 6) a leucite-bearing tephra layer, which we dated at 376 ± 56 ka by ^{39}Ar–^{40}Ar. This age and mineralogical composition are indistinguishable from that of the leucite-bearing Villa Senni Tuff from the AHVC (dated at 350 ± 2 ka by Karner et al., 2001). The Villa Senni Tuff eruption occurred during MIS 10 (Giordano et al., 2003).

We dated a leucite-bearing tephra layer in the lower part of the carbonate lacustrine sediments of the 1st cycle (Fig. 6) at 504 ± 9 ka by ^{39}Ar–^{40}Ar. Age and mineralogy indicate an attribution to the leucite-bearing Lower Ignimbrite Tuff sequence from the AHVC. The eruptive interval of the Lower Tuffs was from 514 ± 3 to 561 ± 1 ka (Karner et al., 2001) and corresponds to MIS 14 (Giordano et al., 2003).

Correlation of radiometric ages associated with stratigraphic units underlying the Campo Felice Plain indicates the following possible linkages with marine oxygen isotope stages:

- At least part of the lacustrine sedimentation of the 1st cycle occurred during MIS 14;
- the lacustrine sediments lying near the top of the 2nd cycle were deposited during MIS 10;

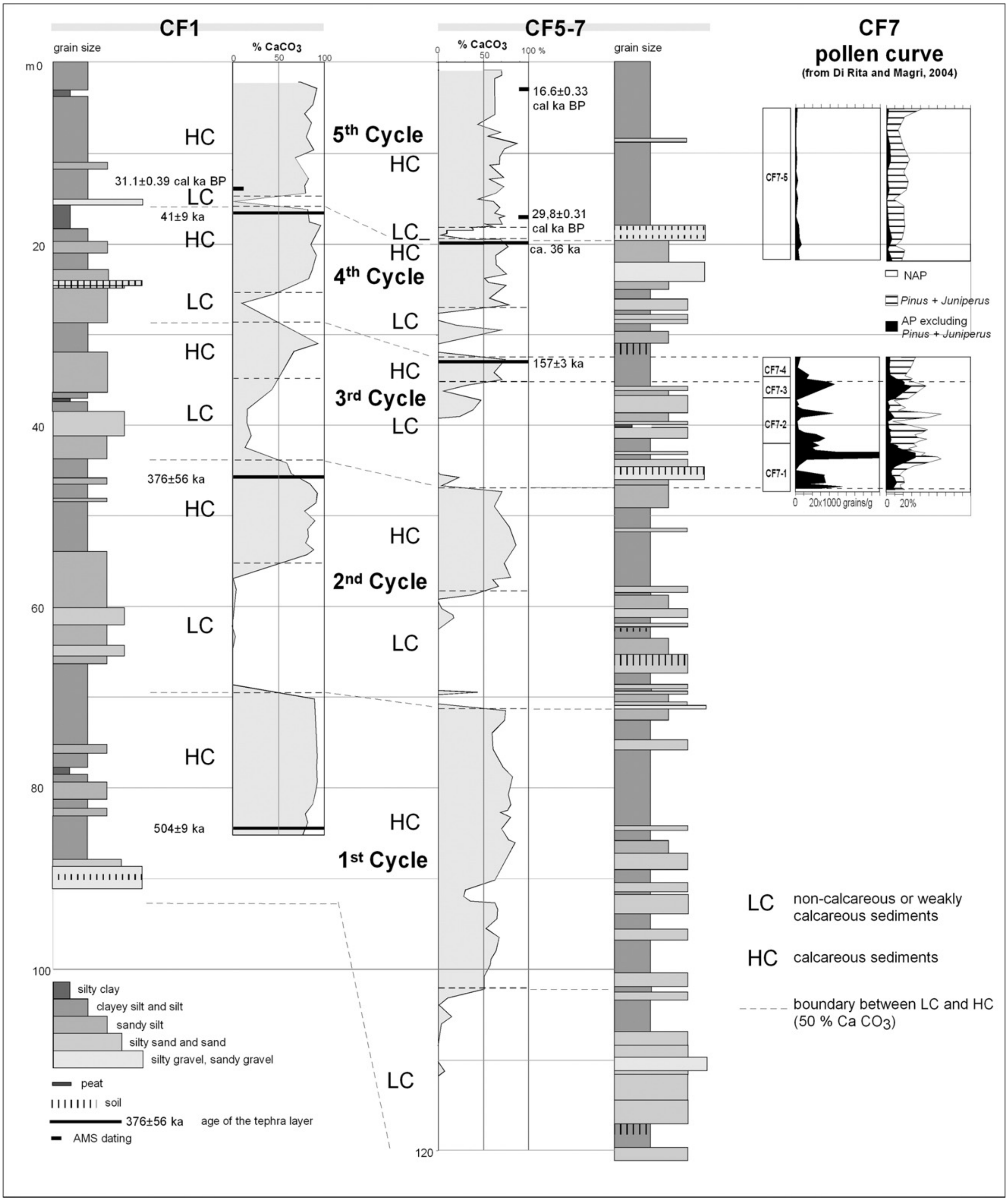

Figure 6. Percentage of carbonate sediments and grain size in the CF1 and CF5–7 cores, and pollen content in the CF7 core. The total carbonate content was obtained with chemical analyses carried out using a Dietrich–Fruhling calcimeter. The grain size of the sandy and gravelly sediments was obtained using sieves. The grain size of the silt and clay fraction was determined using the sedimentation method. The pollen data are from Di Rita and Magri (2004).

- at least the upper part of the lacustrine sediments of the 3rd cycle accumulated during MIS 6;
- the upper lacustrine sediments of the 4th cycle accumulated during MIS 3; and
- the lacustrine sediments of the 5th cycle were deposited during MIS 2.

Analyses of fossil pollen by others suggest palaeoenvironmental changes that are broadly consistent with the results reported herein. Insufficient pollen preservation in the 1st and sedimentary cycles has prevented reliable interpretations of corresponding vegetation (D. Magri, personal communication, 2007). However, Di Rita and Magri (2004) carried out pollen studies on sediments associated with the

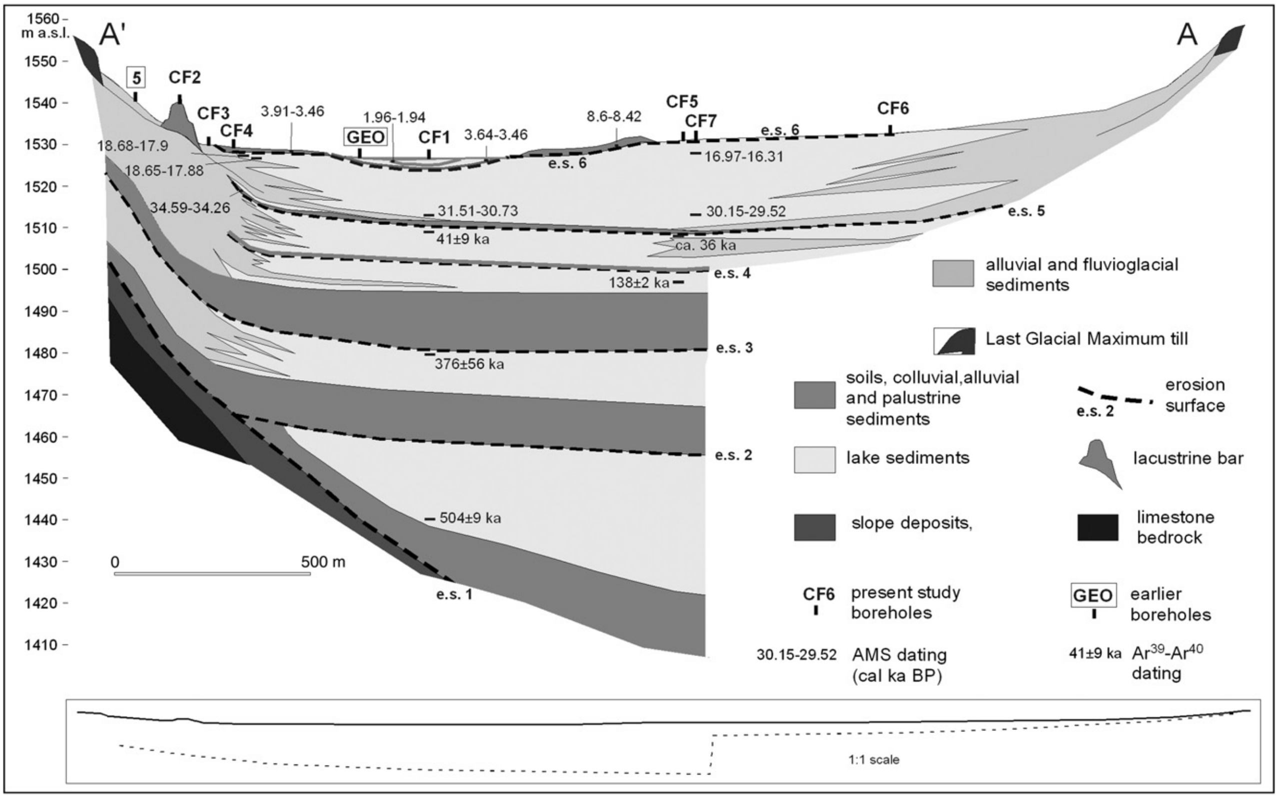

Figure 7. Stratigraphic section through the infill sediment of the Campo Felice Basin. See Fig. 2 for A–A′ transect location.

3rd to 5th sedimentary cycles in borehole CF7. Their results show four different pollen zones within the 3rd depositional cycle (Fig. 6). This include:

- Zone CF7–1. Wood expansion. Several arboreal taxa are represented: *Abies*, *Alnus*, deciduous oaks, *Ulmus*, *Corylus*, *Fagus*, and *Picea*. The pollen succession is interpreted as indicating forest dynamics with elements of mixed oak forest at the beginning, followed by montane tree taxa (beech and fir) and finally by spruce. The authors report that similar dynamics are commonly observed in many European pollen records in the course of an interglacial cycle.
- Zone CF7–2. Progressive diffusion of mountain arboreal taxa ending with an open vegetation. *Pinus* is the predominant tree, while *Juniperus*, *Picea*, and *Ephedra fragilis* reach appreciable

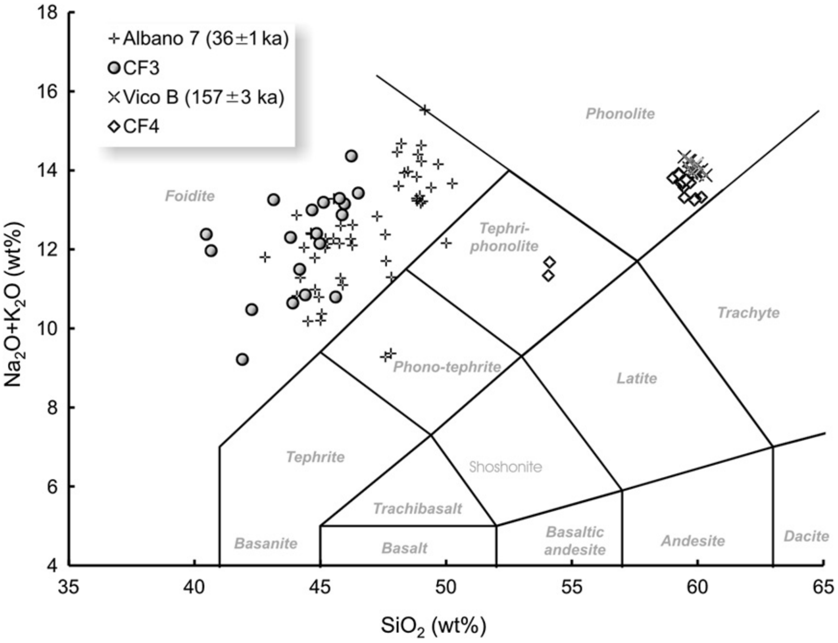

Figure 8. Total alkali silica (TAS, Le Bas et al., 1986) diagram of micro-pumices and glass fragments (EDS-WDS microprobe analyses; data and their source in Table 2) from the tephras Campo Felice 3 and 4 (CF3 and CF4) and from the proximal pyroclastic deposits of Albano 7 (Colli Albani Volcanic District) and Vico B (Vico volcano) eruptive units.

Table 2
Major-element chemical composition of glass shard from Campo Felice 3 and Campo Felice 4 tephras.

Tephra	Campo Felice 3		Albano 7		Campo Felice 4				Vico D	
Age (ka)			36 ± 1						157 ± 3	
Population					a		b			
Number of analyses	*19*		*28*		*14*		*2*		*13*	
SiO_2	**44.23**	*1.81*	**45.57**	*1.28*	**59.51**	*0.32*	**54.09**	*0.04*	**59.87**	*0.23*
TiO_2	**0.85**	*0.15*	**0.85**	*0.11*	**0.44**	*0.03*	**0.73**	*0.04*	**0.46**	*0.07*
Al_2O_3	**19.58**	*1.37*	**19.15**	*0.73*	**20.50**	*0.14*	**19.96**	*0.01*	**19.66**	*0.11*
FeO	**7.97**	*0.96*	**8.35**	*0.79*	**2.81**	*0.12*	**5.90**	*0.04*	**2.86**	*0.06*
MnO	**0.30**	*0.06*	**0.31**	*0.06*	**0.18**	*0.03*	**0.19**	*0.05*	**0.16**	*0.04*
MgO	**1.72**	*0.84*	**1.31**	*0.41*	**0.43**	*0.03*	**1.88**	*0.04*	**0.42**	*0.03*
CaO	**11.84**	*1.88*	**11.29**	*1.07*	**2.34**	*0.08*	**5.29**	*0.19*	**2.38**	*0.05*
Na_2O	**5.18**	*1.27*	**5.53**	*0.91*	**5.12**	*0.18*	**4.11**	*0.10*	**5.39**	*0.09*
K_2O	**6.99**	*1.52*	**6.22**	*1.28*	**8.50**	*0.14*	**7.39**	*0.14*	**8.68**	*0.18*
P_2O_5	**0.26**	*0.14*			**0.04**	*0.03*	**0.32**	*0.09*	**0.05**	*0.04*
F	**0.75**	*0.17*			**0.51**	*0.09*	**0.17**	*0.16*	**0.43**	*0.11*
Cl	**0.23**	*0.08*			**0.22**	*0.02*	**0.42**	*0.04*	**0.22**	*0.03*
SO_3	**1.32**	*0.94*	**0.97**	*0.46*	**0.11**	*0.04*	**0.10**	*0.06*	**0.09**	*0.03*
Cr_2O_3	**0.01**	*0.01*	**0.05**	*0.21*	**0.01**	*0.02*	**0.03**	*0.04*		
SrO			**0.30**	*0.15*						
BaO			**0.10**	*0.05*						
Original total	**97.38**	*1.16*	**96.09**	*1.22*	**96.66**	*0.86*	**96.65**	*0.36*	**94.71**	*1.34*

Average major-element composition (EDS–WDS microprobe analyses, wt.% normalized to 100%; mean value, in bold; standard deviation, in italic) of glass shards from the tephra layers Campo Felice 3 and Campo Felice 4, sampled in CF5 borehole sediments, and from the proximal pyroclastic deposits of Albano 7 (Colli Albani Volcanic District) and Vico B (Vico volcano) eruptive units. A significant chemical affinity between CF3 and Albano 7 and between CF4 (population a) and Vico B, respectively, is evident. Data source: chemical composition of the glasses from Albano 7, Giaccio et al., (2007); $^{40}Ar/^{39}Ar$ age of Albano 7, Freda et al. (2006); chemical composition of the glasses from Vico B, this study; $^{40}Ar/^{39}Ar$ age of Vico B, Laurenzi and Villa (1987).

values. Herbs are very abundant, *Artemisia* being the most important, followed by Cichorioideae, Gramineae, Asteroideae, Chenopodiaceae, and *Thalictrum*.

- Zone CF7–3. Moderate wood expansion. *Abies* is the most important tree taxon, *Picea*, *Fagus*, *Quercus*, and *Zelkova* are other significant tree taxa. Among the herbs, Cichorioideae, Gramineae, and Artemisia are very abundant.
- Zone CF7–4. Open vegetation. *Pinus* and *Juniperus* are the only arboreal taxa continuously present, but tree pollen do not reach 3% altogether. *Artemisia* predominates in the lower part, accompanied by Cichorioideae, while in the upper part an increase of Cichorioideae corresponds to a decrease of *Artemisia*.

The calcareous sediments of the 3rd cycle correspond to the uppermost CF7–3 and to the CF7–4 pollen zones. The tephra of the Vico volcano, dated at 157 ± 3 ka ago, indicate that the CF7–4 pollen zone corresponds with MIS 6. Therefore the underlying forest phase possibly correlates with MIS 7.

There is virtually a total absence of pollen in the calcareous lacustrine sediments of the 4th sedimentary cycle, except next its termination. CF7–4 and CF7–5 pollen zones are dominated by herbaceous taxa, corresponding to cold periods. The CF7–5 pollen zone represents a period dominated by herbaceous taxa with a considerable abundance of *Artemisia*, Gramineae, and Chenopodiaceae. This association corresponds with the LGM (Di Rita and Magri, 2004).

The radiocarbon age of ca. 35 cal ka BP for the non-calcareous sediments at the base of the 5th cycle was determined from a level rich in organic matter exposed in a trench excavation (Giraudi, 2001). The organic horizon was contained within pedogenically weathered colluvium. Analogous ages have been obtained for soils underlying fluvioglacial sediments on the southern slope of the Velino Massif (Frezzotti and Giraudi, 1992). Furthermore, palynological studies carried out on sediment cores taken from an intermontane basin on the northern slope of the Velino Massif indicate that around 35 cal ka BP (about 30,000 ^{14}C yr BP) an arboreal expansion occurred in the area (Chiarini et al., 2007). The non-calcareous sediments at the base of the 5th cycle at Campo Felice thus appear coeval with this arboreal expansion.

Interpretation of the data

The dating of the deposits from which cores have been taken, the continuity between the sediments observed as outcrops and those in the upper part of the cores, and the chronological correlation with morainic and fluvioglacial deposits, enable the environmental evolution of Campo Felice to be interpreted.

Among the prevalently calcareous sediments of the last four cycles, gravelly–sandy sediments increase towards the edge of the plain, towards former glacial valleys. The clear interfingering of moraines and fluvioglacial sediments with the deposits of the 5th cycle provides confirmation that the coarse materials, also in the 2nd, 3rd and 4th cycles, came from past glaciated valleys (Fig. 7). The lacustrine sediments of the 1st cycle, dated at MIS 14, are not interfingered with sediments of fluvioglacial origin. The boreholes that reach the deposits of the basal cycle are, however, located at a distance of 2 and 2.5 km from the oldest moraines, and the absence of coarse deposits in this unit is probably a consequence of this distal geographic location.

The core sediments of the deepest boreholes (CF1 and CF5–7) show, in general, very similar sedimentary sequences, although in detail some differences can be observed. The non-calcareous or weakly calcareous sediment cores have similar grain size, but in the CF5–7 cores we found more silty–gravel and sandy–gravel layers, and grain size variations are more frequent (Fig. 6). A difference exists also for carbonate sediments. The sediments contain more carbonate in CF1 than in CF5–7. The weak differences between the sediments seem quite normal and due to the location of the boreholes. The CF1 borehole lies in the eastern part of the plain not far from the foot of a quite regular slope, about 350 m high. The CF5–7 boreholes lie not far from the foot of a slope that is less regular and 200–500 m high, and near the confluence of the Valle Leona stream (the main tributary valley with the highest mountains — Fig. 1) in the Campo Felice Plain.

As observed before, the thickness of the sediments forming a single cycle can change in different boreholes: the difference is possibly due to the changing sedimentation rate in various places of the Campo Felice depression and to later erosions. The thickness of the prevalently non-calcareous sediments at the base of the 4th and 5th cycles is far less than that of the non-calcareous sediments at the base of the older cycles. The difference could be due to the evolution of the Campo Felice Plain. The gradual filling-in of the depression (Fig. 3) results in a larger area on which the younger sediments are laid down. Therefore, although equal volumes of materials are deposited, the thickness of the more recent sediments is less because they are distributed over a larger area.

The decrease in the thickness of the non-calcareous sediments of the 4th and 5th cycles at Campo Felice may also be due to the smaller quantity of tephra produced by the volcanoes in the nearby Roman Comagmatic Province. These volcanoes (Mt. Volsini, Vico, Mt. Sabatini, Alban Hills, Ernici and Roccamonfina), located at a distance of between 70 and 120 km from Campo Felice (Fig. 1), were very active in the course of the Middle Pleistocene, but their activity ceased or strongly diminished in the last 90–100 ka (Marra et al., 2004, and references therein). In the last 90 ka only a few secondary volcanic centers have been active in the Sabatini Hills (about 40–50 ka) and in the Alban Hills (about 70 and 25–50 ka). In the central Apennines, in the course of the Late Pleistocene and the Holocene, some thin tephra levels were deposited from volcanoes in southern Italy, namely the Phlegrean Fields, Vesuvius and Mount Etna (Narcisi, 1993; Frezzotti and Narcisi, 1996).

Late Pleistocene and Holocene erosion and sedimentation phases recorded on Campo Felice Plain are very similar to those indicated by the non-calcareous sediments present at the base of the sedimentary cycles.

After the end of the sedimentation of the lacustrine deposits of the 5th cycle (age<than 16.97–16.31 cal ka BP and>than 8.605–8.425 cal ka BP), various erosion phases developed (Giraudi, 2001). The erosion phases occurred, therefore, near the end of the glacial period and during the early Holocene. Macklin et al. (2002) also noted many parts of the Mediterranean region indicate evidence of stream incision during interglacials period. The Holocene record shows an accumulation of sediments formed mainly of volcanic materials and reworked by the wind and by colluvial processes including pedogenic weathering. Limited amounts of mainly fine alluvial sediments also were deposited. The oldest preserved Holocene sediments have been dated at about 8.605 to 8.425 cal ka BP. Later, brief episodes of sedimentation in small, shallow lacustrine basins took place. Colluvial layers, interbedded with lacustrine sediments have been documented as being deposited about 1.965 to 1.945 cal ka BP and 3.64 to 3.46 cal ka BP (Giraudi, 2001). Pedogenic development prevailed throughout the late Holocene.

We therefore interpret the late Pleistocene and early Holocene erosion as analogues to the erosion phases developed before the start of each sedimentary cycle. The Holocene record of sedimentation and weathering is interpreted as analogous to sedimentation of alluvial, colluvial and marsh deposits and weathering phases developed at Campo Felice at the base of each sedimentary cycle, and characteristic of the interglacial or interstadial periods. This interpretation is in agreement with expansions of woody vegetation indicated by pollen within the sediments at the base of the 3rd and 5th cycles.

The sedimentary cycles were completed by sandy gravel deposits that interfinger with calcareous lacustrine sediments, containing tephra levels. The calcareous lacustrine sediments of the 5th sedimentary cycle are interfingered with local LGM fluvioglacial sediments (MIS 2) and contain pollen evidence of steppe vegetation. The calcareous lacustrine sediments of the 3rd sedimentary cycle contain a tephra layer dated at MIS 6 and pollen evidence of steppe vegetation. The moraines of the intermediate glaciation present at Campo Felice (dated at MIS 6) may be correlated chronologically with the 3rd cycle. Similar sediments from the 1st and 2nd cycles contain tephra layers dated at MIS 14 and MIS 10.

The above evidence support our assumption that calcareous lacustrine and sandy gravel sediments were prevalently deposited during glacial stages. This interpretation agrees with the data relating to the syn-glacial deposits in the Mediterranean area. Woodward et al. (1992) documented an increase of the carbonate percentage in glacier-fed fluvial sediments, derived from Mt. Tymphi, Greece, where remnants or three glaciations have been found, and a glacio-karst landscape is present. According to the same authors, Mediterranean glaciers exerted an important influence on sediment supply related to enhanced flood magnitudes during meltwater events. In the Mt. Tymphi area, the sediment load in the river decreased and erosion occurred during warmer periods. Elsewhere in other Mediterranean regions, Macklin et al. (2002) found that a large volume of sediments reached the valley floors during cooler climate phases.

The dramatic lithological difference between cold and warm period sediments is due to the environmental variations in the catchment area. We hypothesize that during glacial periods, the glacier meltwater could not penetrate the limestone because the karst features in the bedrock were mainly covered by ice or obstructed by frozen ground. As a consequence, the water flowed towards the Campo Felice Plain, supplying a large volume of fluvioglacial sediments and till. The debris produced by the glacial action was formed of sub-rounded limestone cobbles and boulders in a fine-grained calcareous matrix, as shown by the till. Rivers fed by meltwater and glacial debris deposited sandy gravel in the fluvioglacial fans, while silt, sandy silt, and clayey silt accumulated in lakes.

During warm climatic phases, limestone outcropping at the glacier-free head of the valleys absorbs water and, at lower elevations, the vegetation produces morphological stability. As a consequence the runoff is limited. The low stream energy could produce only erosion of thin, volcanic mineral-rich aeolian, colluvial sediments, and soils.

The erosion surfaces at the top of the lacustrine deposits of the 5th cycle and the small successive erosional episodes were produced by incisions and hillslope degradation in small tributaries that drain to the karst ponors (Giraudi, 2001). The erosion surfaces between the older cycles could also have been produced by analogous causes, but at present we cannot verify the validity of this hypothesis.

During the cold periods, when the lakes formed, the drainage to the karst ponors was probably limited. At least during the last glaciation, mountain permafrost was present in the Campo Felice, and the frozen ground could have played a role limiting water absorption.

Surface and core data supports the following interpretations. The moraines of the last two glaciations at Campo Felice, already dated to MIS 2 and 6, formed in the course of the cold periods and are affiliated with the calcareous fluvioglacial and lacustrine sedimentation of the 5th (MIS 2) and 3rd (MIS 6) cycles. The oldest moraines of Campo Felice formed during cold periods corresponding to the calcareous lacustrine sedimentation of the 1st or 2nd cycle (MIS 14 or MIS 10). The calcareous lacustrine sediments of the 4th cycle are more recent than a warm phase subsequent to MIS 6 and are dated at the top to MIS 3. These lacustrine sediments have similar lithological characteristics to those of the cycles contemporaneous with the glacial expansions. Hence, the environment of Campo Felice and of the surrounding mountains must have been similar to that present during the calcareous sedimentation in the other cycles. Therefore, the calcareous sediments of the 4th cycle probably also indicate a period of glacial expansion. Chronologically the bottom sediments could correspond to MIS 4, while the top sediments are dated to MIS 3. On the Campo Felice Plain moraines datable at MIS 4 have not been recognized, but remains of fluvioglacial fans older than the moraines of MIS 2 and more recent that those of MIS 6 have been recognized by Giraudi (1998). The moraines could have been destroyed by the glacial expansion of MIS 2. Nonetheless, during MIS 3 and 4 glaciers should have been present at least at the heads of the valleys. In the context of the chronological frame of the Alpine glaciations reported by Hughes et al. (2006), the Campo Felice sedimentary cycles involve a pre-Mindel glacial phase, two Riss glacial phases, and two Würm glacial phases.

Correlations with the phases of glacial expansion reported in the central and western Mediterranean basins

The Apennines, which extend across the central Mediterranean area, appear, together with the Pindus Mountains, to be one of the best areas for assessing the glaciations in the area of typical Mediterranean climate. Glaciated Mediterranean mountains were evaluated by Hughes et al. (2006, 2007), and by Hughes and Woodword (2008; 2009), who reported that one of the best age-controlled chronologies for glacial events in the Mediterranean region is associated with Mt. Tymphi in the Pindus Mountains of Greece where moraines of three different glaciations are recognized. The first Pindus Mountains glaciation is older than 350 ka; the second is older than 127 ka; and the third corresponds with MIS 5d-2. Evidence for three different glaciations also has been found in the Apennines (Italy), in the Iberian Peninsula (Spain) and in the Pyrenees (Spain–France), (Jaurand, 1998; Fernandez Mosquera et al., 2000; Calvet, 2004; and Giraudi, 2004). Hughes et al. (2006) hypothesize that the glaciations of the Apennines and of Mt. Tymphi were possibly contemporaneous. In the Iberian mountains, three glaciations are reported and dated using cosmogenic ^{21}Ne (Fernandez Mosquera et al., 2000). The glaciations have been dated at periods older than 15, 130 and 230 ka, and correspond with MIS 2, 6 and 8. In the Pyrenees, Calvet (2004) dated the glacial expansions at MIS 2, MIS 3–4, and MIS 6. In the Apennines (Italy), ages for two glaciations have been reported. The first one is older than 130 ka and corresponds with MIS 6 (Kotarba et al., 2001). The second one occurred during MIS 2 and reached its maximum before 26–28 cal ka BP (Giraudi and Frezzotti, 1997).

We note that the glaciation ages assigned by Fernandez Mosquera et al. (2000), Kotarba et al. (2001) and Hughes et al. (2006, 2007) are only minima. The Campo Felice sediments include glacial phases that are older than the limits of U–Th datings as illustrated by the ^{39}Ar/^{40}Ar method coupled with the use of tephra.

Radiocarbon dating indicates that the local LGM that occurred between 30 and 18 cal ka BP at Campo Felice was apparently more recent than in Greece, where local LGM is dated between about 30 and 25 ka (Hughes and Woodward, 2008). The Campo Felice glacial expansion dated at MIS 3–4 apparently correlates to the local maximum extension of the glaciers in the Pyrenees. The Campo Felice moraines attributed to MIS 6 apparently correlate with the moraines attributed to the intermediate glaciation in Greece and Spain. The glacial expansion dated at MIS 8 in the Iberian peninsula is not recorded at Campo Felice due to a general hiatus in sedimentation between the 2nd and 3rd cycles.

The oldest glacial phase previously reported for the mountains of the Mediterranean basin is older than 350 ka (Woodward et al., 2004; Hughes et al., 2006, 2007). Hughes et al. (2007) correlate it to a prominent cold stage recorded in the Joannina lake sequence in Greece (Tzedakis et al., 2003) assuming that the said glacial phase occurred during MIS 12. Although we have directly dated two middle Pleistocene glacial phases, at Campo Felice the older correlated within MIS 14 and the younger within MIS 10, we also note that at Campo Felice there is a sedimentation gap between the 1st and 2nd cycles and that MIS 12 is apparently not recorded by sediments. Therefore, region-wide correlation of Quaternary glaciations for the mountains in the Mediterranean basin remains difficult because the glacial remnants are discontinuous and sufficient age control is not available.

Conclusions

The tectonic-karst depression of Campo Felice is surrounded by mountains consisting completely of carbonate rocks. The depression contains a sedimentological record of past glaciations which are hard to date by means of surficial expressions. Stratigraphic examination of the sediments underlying the Campo Felice Plain was undertaken from information provided by nine continuous-core boreholes. These boreholes contain evidence representing five sedimentation cycles.

Each cycle involves an initial sedimentation of low energy fluvial, colluvial and marsh deposits, separated by modest erosion surfaces. The sediments are pedogenically altered and are sometimes very rich in organic matter. The sediments also include reworked volcanic minerals. On the whole, the composition of the sediments is prevalently non-calcareous. The sedimentation of non-calcareous deposits took place in periods characterized by phases of arboreal expansion. The geomorphic and sedimentation processes that occurred during the Holocene indicate a similar environmental evolution of this type.

The non-calcareous sediments in each of the cycles are overlain by mainly silty–clayey lacustrine deposits of high carbonate composition and extremely low organic matter content. In the marginal area of the plain, the lacustrine deposits of the last four cycles are interfingered with the sandy gravel sediments. Each cycle has thus been interpreted as the succession of a prevalently warm stage, characterized by the absence of any widespread lake development although limited episodes of small lakes or marsh formation may have occurred. In turn, a prevalently cold stage followed, during which a lake formed in conjunction with the development and expansion of the glaciers.

The chronological framework of the Campo Felice cycles was obtained using radiocarbon AMS and the ^{39}Ar/^{40}Ar dating. A noteworthy contribution of this investigation is an improved understanding of glacial activity older than 300 ka in the Mediterranean region. The composite chronology of the Campo Felice sediments supports the recognition of five glacial advances. The earliest recorded glacial advance took place, during part of the prevalently cold period recorded by the uppermost sediments of the 1st cycle, dated, at least in part, to MIS 14. In turn a second glacial advance recorded by sediments lying in the middle-upper part of the 2nd cycle, and correspond with MIS 10. The oldest visible moraine of Campo Felice was deposited either during this period, or during the MIS 14. The glacial period recorded by the sediments near the top of the 3rd cycle is dated to MIS 6. The MIS 6 event also is recorded by an old, weathered, moraine. Subsequently, another glacial advance is recorded by the lacustrine sediments of the 4th cycle during MIS 3 and probably MIS 4. And finally, the local LGM occurred during MIS 2. Present results combined with research results of others elsewhere on other Mediterranean mountain chains, provide evidence for at least seven glacial expansions during the last 500 ka. Therefore, development of glaciers on the highest mountain peaks in the Mediterranean area was neither a rare nor an unusual event.

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References

Accordi, G., Carbone, F., Civitelli, G., Corda, L., De Rita, D., Esu, D., Funiciello, R., Kotsakis, T., Mariotti, G., Sposato, A., 1986. Lithofacies map of the Latium-Abruzzi and neighbouring areas. C.N.R. Quaderni della Ricerca Scientifica 114 (5) 223 pp.

Belluso, E., Ruffini, R., Schaller, M., Villa, I.M., 2000. Electron-microscope and Ar isotope characterization of chemically heterogeneous amphiboles from the Palala shear zone, Limpopo Belt, South Africa. European Journal of Mineralogy 12, 45–62.

Bosi, C., Manfredini, M., 1967. Osservazioni geologiche nella zona di Campofelice (L'Aquila). Memorie Società Geologica Italiana 6, 245–267.

Calvet, M., 2004. The Quaternary glaciations of the Pyrenees. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations—Extent and Chronology, Part. I: Europe. 119–128. Amsterdam. Elsevier.

Cassoli, A., Corda, L., Lodoli, C., Malatesta, A., Molaroni, M.V., Ruggeri, A., 1986. Il glacialismo quaternario del gruppo Velino-Ocre-Sirente. Memorie Società Geologica Italiana 35, 855–867.

Chiarini, E., Giardini, M., La Posta, E., Papasodaro, F., Sadori, L., 2007. Sedimentology, palinology and new geochronological constrains on Quaternary deposits of the Corvaro intermontane basin (central Italy). Revue de Micropaléontologie 50, 309–314.

Di Rita, F., Magri, D., 2004. Pollen analysis of Upper Pleistocene sediments at Campo Felice, Central Italy. Il Quaternario-Italian Journal of Quaternary Sciences 17 (1), 117–127.

Fernandez Mosquera, D., Marti, K., Vidal Romani, J.R., Weigel, A., 2000. Late Pleistocene deglaciation chronology in the NW of the Iberian Peninsula using cosmic-ray produced 21Ne in quartz. Nuclear Instruments and Methods in Physics Research B172, 832–837.

Freda, C., Gaeta, M., Karner, D.B., Marra, F., Renne, P.R., Taddeucci, J., Scarlato, P., Christensen, J.N., Dallai, L., 2006. Eruptive history and petrologic evolution of the Albano multiple maar (Alban Hills, Central Italy). Bulletin of Volcanology 68, 567–591.

Frezzotti, M., Giraudi, C., 1992. Evoluzione geologica tardo-pleistocenica ed olocenica del conoide complesso di Valle Majelama (Massiccio del Velino — Abruzzo). Quaternario 5 (1), 33–50.

Frezzotti, M., Narcisi, B., 1996. Late Quaternary tephra-derived paleosols in Central Italy's carbonate Apennine range: stratigraphical and paleoclimatological implications. Quaternary International 34–36, 147–153.

Giaccio, B., Galadini, F., Sposato, A., Messina, P., Moro, M., Zreda, M., Cittadini, A., Salvi, S., Todero, A., 2002. Image processing and roughness analysis of exposed bedrock fault planes as a tool for paleoseismological analysis: result from the Campo Felice fault (central Apennines, Italy). Geomorphology 49, 281–301.

Giaccio, B., Sposato, A., Gaeta, M., Marra, F., Palladino, D.M., Taddeucci, J., Barbieri, M., Messina, P., Rolfo, M.F., 2007. Mid-distal occurrences of the Albano Maar pyroclastic deposits and their relevance for reassessing the eruptive scenarios of the most recent activity of the Colli Albani Volcanic District, Central Italy. Quaternary International 171–172, 160–168.

Giordano, G., Esposito, A., De Rita, D., Fabbri, M., Mazzini, I., Trigari, A., Rosa, C., Funiciello, R., 2003. The sedimentation along the Roman coast between Middle and Upper Pleistocene: the interplay of eustatism, tectonics and volcanism. Il Quaternario-Italian Journal of Quaternary Sciences 16 (1bis), 121–129.

Giraudi, C., 1995. Considerations on the significance of some post-glacial fault scarps in the Abruzzo Apennines (Central Italy). Quaternary International 25, 33–45.

Giraudi, C., 1998. The Late Quaternary geologic evolution of Campo Felice (Abruzzo — Central Italy). Giornale di Geologia 60, 67–82 sez. 3.

Giraudi, C., 2001. Nuovi dati sull'evoluzione tardo-pleistocenica ed olocenica di Campo Felice (L'Aquila, Abruzzo). Quaternario 14 (1), 47–54.

Giraudi, C., 2004. The Apennine glaciations in Italy. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations—Extent and Chronology, Part. I: Europe. 215–224. Amsterdam. Elsevier.

Giraudi, C., 2005. Middle to Late Holocene glacial variations, periglacial processes and alluvial sedimentation on the higher Apennine massifs (Italy). Quaternary Research 64, 176–184.

Giraudi, C., Frezzotti, M., 1997. Late Pleistocene glacial events in the Central Apennine, Italy. Quaternary Research 48 (3), 280–290.

Hughes, P.D., Woodward, J.C., Gibbard, P.L., 2006. Quaternary glacial history of the Mediterranean Mountains. Progress in Physical Geography 30 (3), 334–364.

Hughes, P.D., Woodward, J.C., Gibbard, P.L., 2007. Middle Pleistocene cold stage climate in the Mediterranean: new evidence from the glacial record. Earth and Planetary Science Letters 253, 50–56.

Hughes, P.D., Woodward, J.C., 2008. Timing of glaciation in the Mediterranean mountains during the last cold stage. Journal of Quaternary Science 23, 575–588.

Hughes, P.D., Woodward, J.C., 2009. Glacial and periglacial environments. In: Woodward, J.C. (Ed.), The Physical Geography of the Mediterranean. Oxford University Press, Oxford, pp. 353–383.

Jaurand, E., 1998. Glaciers disparù de l'Apennin: géomorphologie et paléoenvironments glaciaires de l'Italie peninsulaire. Monographie de l'Universitè de La Sorbonne: Geographie, vol. 10. 382 pp.

Karner, D., Marra, F., Renne, R., 2001. The history of the Monti Sabatini and Alban Hills volcanoes: groundwork for assessing volcanic–tectonic hazard for Rome. Journal of Volcanological and Geothermal Research 107 (1–3), 185–215.

Kotarba, A., Hercman, H., Dramis, F., 2001. On the age of Campo Imperatore glaciations, Gran Sasso Massif, Central Italy. Geografia Fisica e Dinamica Quaternaria 24, 65–69.

Laurenzi, M.A., Villa, I.M., 1987. ^{40}Ar/^{39}Ar chronostratigraphy of Vico ignimbrites. Periodico di Mineralogia 56, 285–293.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B., 1986. A chemical classification of volcanic rocks based on the total Alkali–Silica diagram. Journal of Petrology 27, 745–750.

Macklin, M.G., Fuller, I.C., Lewin, J., Maas, G.S., Passmore, D.G., Rose, J., Woodward, J.C., Black, S., Hamlin, R.H.B., Rowas, J.S., 2002. Correlation of Late and Middle Pleistocene fluvial sequences in the Mediterranean and their relationship to climate change. Quaternary Science Reviews 21, 1633–1644.

Marra, F., Taddeucci, J., Freda, C., Marzocchi, W., Scarlato, P., 2004. Recurrence of volcanic activity along the Roman Comagmatic Province (Tyrrhenian margin of Italy) and its tectonic significance. Tectonics 23, TC4013 doi:10.1029/2003TC001600.

Narcisi, B., 1993. Segnalazione di un livello piroclastico di provenienza etnea nell'area del Fucino (Italia Centrale). Quaternario 6 (1), 87–92.

Stuiver, M., van der Plicht, H., 1998. Calibration database editorial comment. Radiocarbon 40 (3), XII–XIII.

Stuiver, M., Reimer, P.J., Bard, E., Beck, W.J., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J., Spurk, M., 1998. INTCAL98 radiocarbon age calibration, 24, 000–0 cal BP. Radiocarbon 40 (3), 1041–1083.

Talma, A.S., Vogel, J.C., 1993. A simplified approach to calibrating C14 dates. Radiocarbon 35 (2), 317–322.

Tzedakis, P.C., McManus, J.F., Hooghiemstra, H., Oppo, D.W., Wijmstra, T.A., 2003. Comparison of changes in vegetation in northeast Greece with records of climate variability on orbital and suborbital frequencies over the last 450 000 years. Earth and Planetary Science Letters 212, 197–212.

Villa, I.M., Calanchi, N., Dinelli, E., Lucchini, F., 1999. Age and evolution of the Albano Crater Lake (Roman Volcanic Province). Acta Vulcanologica 11, 305–310.

Woodward, J.C., Lewin, J., Macklin, M.G., 1992. Alluvial sediment sources in glaciated catchment: the Voidomatis basin, northwest Greece. Earth Surface Processes and Landforms 16, 205–216.

Woodward, J.C., Macklin, M.G., Smith, G.R., 2004. Pleistocene glaciation in the mountains of Greece. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations—Extent and Chronology, Part. I: Europe. 155–173. Amsterdam. Elsevier.