Journal of Maps

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tjom20

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To cite this article: Paolo Galli, Paolo Messina, Biagio Giaccio & Edoardo Peronace (2024) Quaternary morpho-stratigraphic evolution of the eastern Campo Imperatore basin (Gran Sasso range, central Italian Apennines) and tectonic implication, Journal of Maps, 20:1, 2392853, DOI: 10.1080/17445647.2024.2392853

To link to this article: https://doi.org/10.1080/17445647.2024.2392853

JOURNAL OF MAPS
2024, VOL. 20, NO. 1, 2392853
https://doi.org/10.1080/17445647.2024.2392853

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Quaternary morpho-stratigraphic evolution of the eastern Campo Imperatore basin (Gran Sasso range, central Italian Apennines) and tectonic implication

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ABSTRACT
Geological survey and geochronological analyses were conducted in the Campo Imperatore plain to understand its Quaternary morpho-sedimentary and tectonic evolution. In the Late Pliocene-Early Pleistocene, low relief energy and steady and warm climatic conditions promoted a long phase of areal peneplanation, resulting in the formation of gently sloping landscape. With further regional uplift and changes in frequency/amplitude of the glacial-interglacial cycles (Early-Middle Pleistocene transition) and after establishment of the expansion-contraction cycles of the Apennine glaciers (Middle Pleistocene), the morpho-sedimentary processes become highly dynamic. In Middle Pleistocene, more than 100 meters of breccias deposited all along the slopes of the Gran Sasso range, followed by higher frequency processes of sedimentation, erosion and pedogenesis of Middle-Late Pleistocene to Holocene fluvio-glacial deposits. These have been progressively offset by synthetic and antithetic normal faults belonging to the Gran Sasso fault system, a 40-km-long seismogenic structure which released in the past earthquakes of Mw~7.

ARTICLE HISTORY
Received 15 June 2024
Revised 6 August 2024
Accepted 8 August 2024

KEYWORDS
Quaternary stratigraphy; geomorphology; active tectonics; Gran Sasso massif

1. Introduction

Geological mapping is among the primary source of information for reconstructing and understanding the evolution of the Earth system. In addition, Quaternary geology provides a privileged observatory to understand how some of the most dynamic phenomena, such as climate variability, hydrological processes and landslide, tectonics and volcanism, acted in recent past and thus on how they can continue to act currently and in the future.

In the framework of the ongoing geodynamic evolution of the Mediterranean (Faccenna et al., 2014; Patacca et al., 1990; Scandone & Patacca, 1984; Spakman & Wortel, 2004), which resulted in both diffuse and intense Quaternary tectonic and volcanic activity (Galadini et al., 2000; Peccerillo, 2005), the Italian peninsula has been long considered ideally suited for Quaternary studies. In particular, the Apennine Chain, which extends all along the Italian peninsula, hosts a system of Quaternary intermontane basins that a number of studies proved to be valuable archives of recent tectonic, volcanic and paleoenvironmental-climatic history and evolution, humans included (e.g. Branca et al., 2023; Galadini & Galli, 2000; Galli et al., 2008; Giaccio et al., 2014; Giraudi et al., 2011).

Aware of the wealth of these natural archives, in the wake of these studies, we performed a detailed geological survey in the Campo Imperatore plain, which overlies the highest intermontane tectonic basin among those of the central Apennines. As the existing geological mapping of this area mainly deals with the pre-Quaternary substratum (Cardello & Doglioni, 2015; D'Agostino et al., 1998; Ghisetti & Vezzani, 1986; Ghisetti & Vezzani, 1990; Ghisetti & Vezzani, 1991; Servizio Geologico d'Italia, 2010; Vezzani & Ghisetti, 1998), leaving a knowledge gap about its Quaternary geology, we performed new investigations by applying an integrated stratigraphical, geomorphological and geochronological approach (e.g. Giaccio et al., 2012). This results in an updated geological map bearing new insights and information on the Quaternary tectonic, sedimentary and paleoenvironmental evolution of the basin (see supplementary material).

2. Geological setting

The Campo Imperatore plain extends for an area of approximately 40 km^2 south of the Gran Sasso mountain range, at elevations between 1500 and 1800 m asl (Figure 1). The Gran Sasso basin is the highest and

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Supplemental map for this article can be accessed at https://doi.org/10.1080/17445647.2024.2392853

outermost intermontane depression of the entire system of post-orogenic extensional tectonic basins, which developed along the chain axis (CNR-PFG, 1987). Previous works have shown a progressive eastward migration of tectonic activity and uplift in the central Apennines (Faccenna et al., 2003; Galadini & Galli, 2000; Galadini & Messina, 2004; Patacca et al., 1990; Scrocca et al., 2007 and references therein), which implies that the easternmost basins, including the Campo Imperatore, are the youngest ones and thus may be related to ongoing seismogenic processes.

Specifically, the Campo Imperatore basin originated from the hanging-wall downthrown of the Gran Sasso normal fault system, an active and seismogenic structure responsible for Mw~7 earthquakes in historical times (i.e. in 1349 CE; Galli et al., 2022) and previously, at least in the Late Pleistocene-Holocene (Cardello & Doglioni, 2015; Galadini, Galli et al., 2003; Galli et al., 2002; Giraudi & Frezzotti, 1995). The fault segments responsible for the deepening of the Campo Imperatore basin are the Mandrucce-Vado di Corno, Mt Brancastello, Mt Paradiso and Mt Camicia-San Vito synthetic faults (MVCF, PF, BF, SVF in Figure 1, respectively). The Holocene activity of most of these segments has been previously acknowledged (Galli et al., 2022 and reference therein), and there is no indication of recent tectonic activity along the border fault of Mt Camicia, apart from the existence of rock fault scarps downthrowing the breccias of the Mt Faeto Unit (Middle Pleistocene). Similarly, there are no signs of activity along the Mt San Vito fault, apart from buried rock fault scarps at the bottom of the slope. In the southeastern sector of the eastern alluvial plain, the basin is bounded by the Cocchiarelle antithetic fault (see Geological Map), the important role of which will be discussed in this paper. This fault displaces the Pleistocene and Holocene infilling of the plain, damming the natural southward course of the creek that feeds one of the main alluvial fan descending from the mountain range (i.e. Fornaca fan; Figure 2).

The basin is mainly infilled by alluvial (fluvial, glacial and fluvio-glacial) and lacustrine sediments, which reach 180 m thick, at least in the only existing borehole (i.e. western part of Campo Imperatore: COGEFAR, 1980). Depositional episodes alternate with areal and linear fluvial erosive phases, reflecting a geologic and geomorphologic evolution that has persisted since at least the Middle Pleistocene. At that time, the hydrographic network was partially different from the current one, as the eastern sector had its base level in the Prati di Cretarola plain (hydrographic basin of Tavo River), while the western sector had its base level in the Coppe di Santo Stefano area (hydrographic basin of Pescara-Tirino springs) (Figure 1). Currently, water drainage occurs periodically through a number of sinkholes affecting the southeastern part of the plain (Prati di Cretarola) or, very exceptionally through their natural outlet, i.e. the Pietrattina Valley and the Vallone di Cretarola, both joining eastward into the Vallone D'Angora and then into the River Tavo (see geological map).

Notably, the Campo Imperatore endorheic basin acts as a preferential recharge area of the Gran Sasso karst aquifer (Tallini et al., 2013), which hosts a unique regional-wide groundwater table with a mean hydraulic gradient of 5–20% (Amoruso et al., 2013), and a total discharge ranging from 18 to 25 m^3/s from its springs.

3. Materials and methods

3.1. Geological survey

Stratigraphical and geomorphological surveys in Campo Imperatore area were conducted for over two years. Fieldwork was complemented with aerial photographs interpretations at a 1:33,000 scale using the Istituto Geografico Militare (IGM, 1954–1955) and the Regione Abruzzo (1984) photos, satellite imagery from Google Earth, and digital terrain models derived from topographic maps at 1:5000 and 1:10000 scales of the Regione Abruzzo (http://geoportale.regione.abruzzo.it/). Additionally, digital terrain models (DTM) were generated from aerial surveys conducted with Unmanned Aerial Vehicles (UAV; 0.1 m spatial resolution). We acquired aerial photos using a DJI Phantom 4 RTK drone (L1/L2 RTK/PPK rover antenna) in PPK acquisition mode (e.g. in Cirillo et al., 2022), using an Emlid Reach RS2 system (GNSS/RTK L1, L2, L5) as a base station. To ensure the accuracy of the 3D model, we placed Ground Control Points (GCPs) whose positions were acquired using the Reach RS2 GNSS sensor. We carried out photogrammetric processing using the Agisoft Metashape Pro software, which resulted in a very accurate 3D model of the investigated areas. Finally, we reconstruct a detailed 3D panoramic photo of the central portion of the Fornaca fan by elaboration of 4k videos acquired with the same system described above. The data consists of 4k resolution frames sampled from the videos, in a fixed user-defined framerate, extracted and elaborated with Agisoft Metashape Pro software, to reconstruct a detailed photogrammetric model of Fornaca fan.

3.2. Radioisotopic geochronology

To obtain reliable geochronological constraints for defining the long-term tectonic-sedimentary evolution of the basin, both 9 radiometric and 1 tephrochronological analyses, were performed.

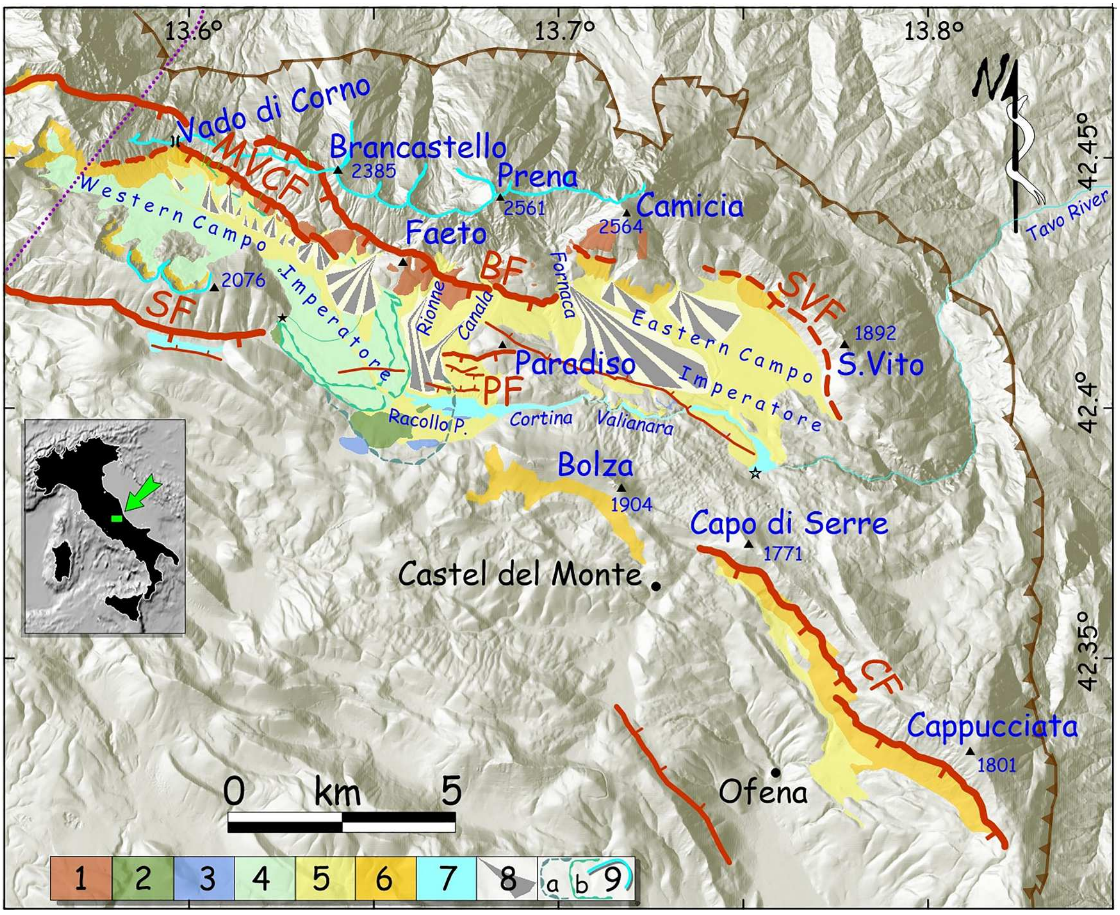

Figure 1. Shaded relief map of the area affected by the eastern segments of the Gran Sasso Fault System (bold red lines; dashed where activity is uncertain). Legend of Quaternary deposits (for detail. refer to geological map in Supplemental material): 1, Middle-Late Pleistocene breccias; 2, Middle Pleistocene till; 3, Middle-Late Pleistocene alluvial deposits; 4, LGM till; 5, Late Pleistocene-Holocene alluvial deposits; 6, Late Pleistocene-Holocene slope deposits; 7, Holocene alluvial deposits; 8, post LGM-Holocene alluvial fan; 9, LGM glacial cirques (a-b Middle Pleistocene and LGM moraine front). Brown triangle-line is the main thrust of the Gran Sasso-Mt Genzana carbonate Units over the siliciclastic Units derived from the deformation of the Marche basin (sensu Vezzani & Ghisetti, 1998). Faults: SF, Mt Scindarella; PF, Mt Paradiso; MVCF, Mandrucce-Vado di Corno; BF, Mt Brancastello; SVF, Mt San Vito; CF, Mt Cappucciata; black star (western Campo Imperatore) are the ruins of St Egidio church; empty star (eastern Campo Imperatore) is the karstic swallow-hole. Modified after Galli et al. (2022).

Organic sediments (all paleosols and related colluvial embedded within alluvial deposits of Campo Imperatore) were collected for ^{14}C dating. Ages were determined for bulk samples and charred wood materials utilizing the accelerator mass spectrometry (AMS) technique at Beta Analytic in Miami, USA. The standards and analytical protocols can be found at http://www.radiocarbon.com/14C Ages of samples reported in previous studies were calibrated or recalibrated using the CALIB 8.2 software (Stuiver et al., 2021). Suitable material for ^{14}C dating was collected, as bulk organic-rich samples, from the paleosol PS2 (sample Forn06), PS3 (Forn02), PS4 (Cort01, Cort2), PS5 (Forn04), PS6 (Forn05). PS4 has been sampled twice from an outcrop facing the head of the Cortina Valley. Results are summarized in Table 1. All datings are within the chronological boundary of the method (~45 ka), except two related to the same paleosol (PS1) sampled in two distant places and dated twice (Forn01, Forn03), that provided an age >45 ka. All datings presented in the following are ^{14}C calibrated ages.

Tephrochronological investigation, including ^{40}Ar/^{39}Ar dating, was performed on one tephra layer at the top of a reddish/brown paleosol (PS1) within the alluvial gravel of the Fornaca fan. ^{40}Ar/^{39}Ar dating was performed on pristine sanidine crystals, and Ar isotopes were analyzed using a VG5400 mass spectrometer at LSCE (Laboratory of Science on climate and Environment, Gif-sur-Yvette, France) following procedures outlined in Nomade et al. (2010).

4. Previous studies on the Quaternary geology of Campo Imperatore

Holocene sedimentation phases and glacial phenomena have been already investigated in several works (Giraudi, 2003a; Giraudi, 2003b; Giraudi, 2015; Giraudi & Frezzotti, 1997; Jaurand, 1996; Kotarba et al., 2001), as well as the activity of the fault that bounds the

Figure 2. View looking north of the Fornaca alluvial fan seen from the Cocchiarelle fault footwall. In background Mts Prena-Brancastello (left), and Mts Camicia-San Vito (right).

southwestern flank of the Gran Sasso relief (MVCF, BF, SVF in Figure 1. Galadini, Galli et al., 2003; Galli et al., 2002, 2022; Giraudi, 1988; Giraudi & Frezzotti, 1995).

Frezzotti and Giraudi (1990), Giraudi and Frezzotti (1997), and Giraudi (2003a) identified six main sedimentation phases in the Quaternary of Campo Imperatore, dated through radiocarbon analyses of paleosols and lacustrine sediments in the 1980s–90s. According to these authors, one of the main and extensive alluvial fans in the basin (Fornaca alluvial fan) consists of gravel deposits containing two paleosols ^{14}C dated at 31500 ± 550 yr BP and 17840 ± 200 yr BP (here recalibrated to 36935–34695 yr BP and 22155–21050 yr BP, as all the following ages). This is followed by successive depositional phases associated with five terraces: the first pre-Holocene alluvial phase occurred between 14410 and 13770 yr BP, followed in the Holocene by another one between 8120–7910 yr BP and 6400–5950 yr BP. The

Table 1. Laboratory ages of samples considered in the study.

Site	Paleosol	Sample	Laboratory	Analisys	Dated material	δ13C	Conventional age (BP)	2σ cal. 95%	References
Fornaca fan	PS3?	UD-385	CRAD Udine	radiocarbon	Organic sediment	–	17840 ± 200	21010–22136 BP	Frezzotti and Giraudi (1990)
Fornaca fan	PS1?	BO-179	ENEA Bologna	radiocarbon	Organic sediment	–	31500 ± 550	34329–36484 BP	Frezzotti and Giraudi (1990)
Valle della Macina	–	BO-254	ENEA Bologna	radiocarbon	Organic sediment	–	21450 ± 250	26114–25213 BP	Giraudi and Frezzotti (1997)
Coppe S. Stefano	–	BO-250	ENEA Bologna	radiocarbon	Organic sediment	–	22350 ± 300	27208–26007 BP	Giraudi and Frezzotti (1997)
Coppe S. Stefano	–	BO-251	ENEA Bologna	radiocarbon	Organic sediment	–	22680 ± 630	28076–25731 BP	Giraudi and Frezzotti (1997)
Valle Cortina	PS4	CORT01	BETA Miami	AMS	Organic sediment	−24.9	15920 ± 50	19413–19061 BP	this paper
Valle Cortina	PS4	CORT02	BETA Miami	AMS	Organic sediment	−24.7	16090 ± 50	19556–19241 BP	this paper
Fornaca fan	PS1	FORN01	BETA Miami	AMS	Organic sediment	−24.2	>43500	–	this paper
Fornaca fan	PS3	FORN02	BETA Miami	AMS	Organic sediment	−24.6	24140 ± 80	28631–27953 BP	this paper
Fornaca fan	PS5	FORN04	BETA Miami	AMS	Organic sediment	−24.4	14080 ± 40	17330–17022 BP	this paper
Fornaca fan	PS6	FORN05	BETA Miami	AMS	Organic sediment	−24.2	7470 ± 30	8365–8193 BP	this paper
Fornaca fan	PS2	FORN06	BETA Miami	AMS	Organic sediment	−24.3	35730 ± 310	41368–40147 BP	this paper
Fornaca fan	PS1	FORN07	BETA Miami	AMS	charred material	−23.7	>43500	–	this paper
Fornaca fan	PS1	FORN03	CEA Paris	$^{40}Ar/^{39}Ar$	Sanidine	–	–	111 ± 4 ka	this paper

Note: The elevation of sampling is around 1600–1700 m asl. Sampling depth is visible in the photomosaic below the main map. AMS, accelerator mass spectrometry (Beta Analytic Inc., Miami, Florida). 2σ calibration with software CALIB 8.2 (Stuiver et al., 2021). $^{40}Ar/^{39}Ar$ age at the CEA-DRF laboratory in Paris.

sediments forming the second terrace range from 8120–7910 yr BP to 4830–4410 yr BP, whereas those forming the third terrace were deposited between 4830 and 4410 yr BP and a later period, spanning from 2190–1990yr BP to 580–689 CE. The sedimentation of the alluvial deposits forming the fourth terrace occurred between 580 and 689 CE and a more recent period (1440–1640 CE). Finally, the alluvial deposits of the fifth terrace are very recent or current.

In addition to this, in other works (Giraudi, 2003a; Giraudi, 2003b; Giraudi, 2015; Giraudi & Frezzotti, 1997; Jaurand, 1996; Kotarba et al., 2001), different phases of sedimentation and erosion related to glacial phenomena during recent cold periods have been described. These phases led to the formation of typical glacial deposits (frontal and lateral moraines) and the creation of related glacial landforms (cirques, abrasion surfaces). In a recent study (Sanders et al., 2022), the presence of carbonate breccias in the area between Colle Caciaro and Cocchiarelle is attributed to huge rock avalanche phenomena, older than 124.25 ± 2.76 ka BP (U/Th age of intraclast calcite). As we interpreted these deposits as local alluvial breccias, cataclasite-breccias or altered/ karstified limestone, they do not appear in our map.

Active tectonics in the area has been recently investigated by Galli et al. (2022) along the eight major fault segments comprising the Gran Sasso fault system. These authors performed paleoseismological analyses at four sites on three different fault segments, reviewing data from previous studies for three other segments (Galli et al., 2002; Galadini, Galli et al., 2003; Giraudi & Frezzotti, 1995). By employing radiocarbon dating and cross-referencing with previously published ^{14}C ages, they determined robust slip rates and established the Holocene seismic history of this fault system. This history includes three consecutive earthquakes since the beginning of the Late Holocene, separated by intervals of 3.3 and 2.2 kyr, respectively. The most recent one occurred during the 13th–14th centuries CE, coinciding with the catastrophic earthquake sequence of 1349 CE in central Italy (~Mw 7.0).

5. Results

5.1. Quaternary deposits and morphology

Eleven different morpho-sedimentary units are distinguished in the investigated Campo Imperatore basin, as schematically shown in Figure 3 and in the main map.

Anzano Paleolandscape – AP (Late Pliocene-early Lower Pleistocene? Before 1.6 ± 0.5 Ma)

It is a widespread belief among many authors that, following the emergence of the central-southern Apennines orogeny, significant phases of areal peneplanation occurred, leading to the formation of extensive low-energy paleolandscapes, typically carved into Meso-Cenozoic marine formations (Blumetti & Dramis, 1992; Bosi, 1989; 2002; Bosi & Messina, 1991; Calamita et al., 1982; Coltorti et al., 1989; Coltorti & Pieruccini, 2000; Desplanques, 1969; Gentili & Pambianchi, 1999; Schiattarella et al., 2009). One of these paleolandscapes is called Anzano (Bosi, 1989) and extends in the southern sector of the Gran Sasso massif and in the southeastern part of the Campo Imperatore plain. Based on stratigraphic and morphological relationships with other sedimentary and erosive episodes, Galadini, Messina et al. (2003) place the age of the Anzano paleolandscape in the Late Pliocene or at the base of the Quaternary. Supporting this, it should be noted that, in the sector between the Gran Sasso ridge and the Aterno River valley (15 km SE to Campo Imperatore), the Anzano paleolandscape is significantly elevated above breccias with a reverse paleomagnetic field (i.e. ~780 ka; Fonte Vedice breccias in Bertini & Bosi, 1993; Bosi et al., 2003; D'Agostino et al., 1997). These breccias intercalate with white lacustrine clays containing tephra layers recently dated to the Early Pleistocene (1.77 ± 0.15 Ma, Cosentino et al., 2024).

In the study area, this paleolandscape is carved into the marine, Jurassic carbonate succession, extending to the southernmost part of Campo Imperatore, between Mt Bolza, Colle Caciaro, and Mt Paradiso, at times covered by modest thicknesses of Quaternary continental deposits (see Figure 4 and main map). On this extensive and articulated erosion surface, there are highly developed karst phenomena, such as dolines and sinkholes. The carbonate succession often appears so altered and tectonized to the extent that surface limestones sometimes take on the appearance of breccias, while frequently preserving their original layering. These alteration phenomena are particularly visible on the summit of Colle Caciaro, the section between Colle Caciaro and the Cocchiarelle fault scarp and between the latter sector and Mt Bolza (see Geological Map).

Monte Faeto Unit – MFU (early? Middle Pleistocene)

Extensively exposed on the slopes between Mt Camicia, Mt Faeto, and Vado di Corno, are breccias reaching thicknesses of 70–80 m in outcrop. These are typically well cemented slope-breccias composed of angular or subangular carbonate clasts, exhibiting well-defined down-hill stratification (Figure 5). This unit has not a clear geometric relationship (such as bedding, basal surface, source area, etc.) with the present-day slopes, being morphologically higher than the fluvial and morainic deposits associated with the Upper Pleistocene and the Last Glacial Maximum deposits. For these reasons, it could be generically

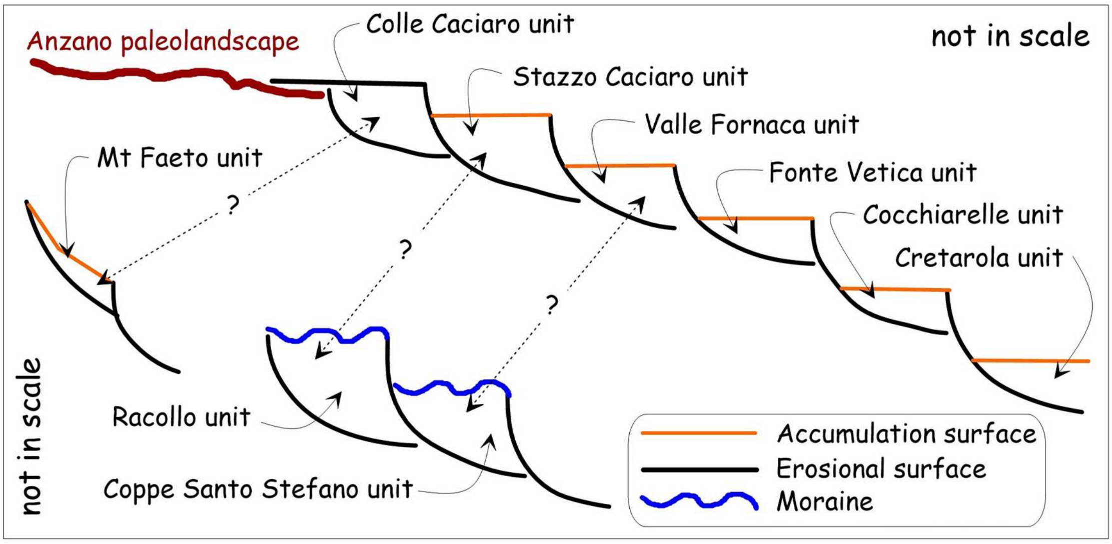

Figure 3. Stratigraphical and morphological relationships among the different units identified in Campo Imperatore area and described in the text. Note that Costa San Vito Unit (slope debris) is not represented here because it may overlap any of these other units.

attributed to the Middle Pleistocene, although it cannot be ruled out that it may be older.

Colle Caciaro Unit – CCU (early? Middle Pleistocene)

Close to the flat summit paleolandscape carved in the marine carbonates at the top and around Colle Caciaro (i.e. paleolandscape of Anzano), there are outcrops of rounded to sub-rounded sub-horizontal conglomerate deposits, heavily cemented and interbedded at places with breccias layers. Clasts are predominantly from Mesozoic carbonates, although sporadically sandstone clasts are also found (Figure 6). On the western slope of Colle Caciaro, some portions of this unit have been tilted due to sliding phenomena caused by local landslides or collapses on a steep slopes.

The deposits of this unit are morphologically suspended relative to the current landscape, making it impossible to trace them back to their source area. Moreover, they crop out only in the footwall of the Cocchiarelle antithetic fault (see Geological map), that juxtapose them to younger units. For these reasons, we guess that they are much older than the Upper Pleistocene units surrounding them, and that they might be related to the late fluvioglacial phases of an earlier glaciation, before the one related to the Racollo Unit (see below), possibly the same glaciation preceding the Faeto Unit.

Racollo Unit – RU (late Middle Pleistocene)

In the area of Piano Racollo and near the ruins of the medieval church of St. Egidio (black star in Figure 1), there are remnants of ancient morainic deposits

Figure 4. View looking southeast of the Valianara canyon. The Valle Fornaca Unit (VFU) mantles the left bank (north) of the karstified Anzano paleolandscape (yellow dashed line), which is almost completely exposed to the south.

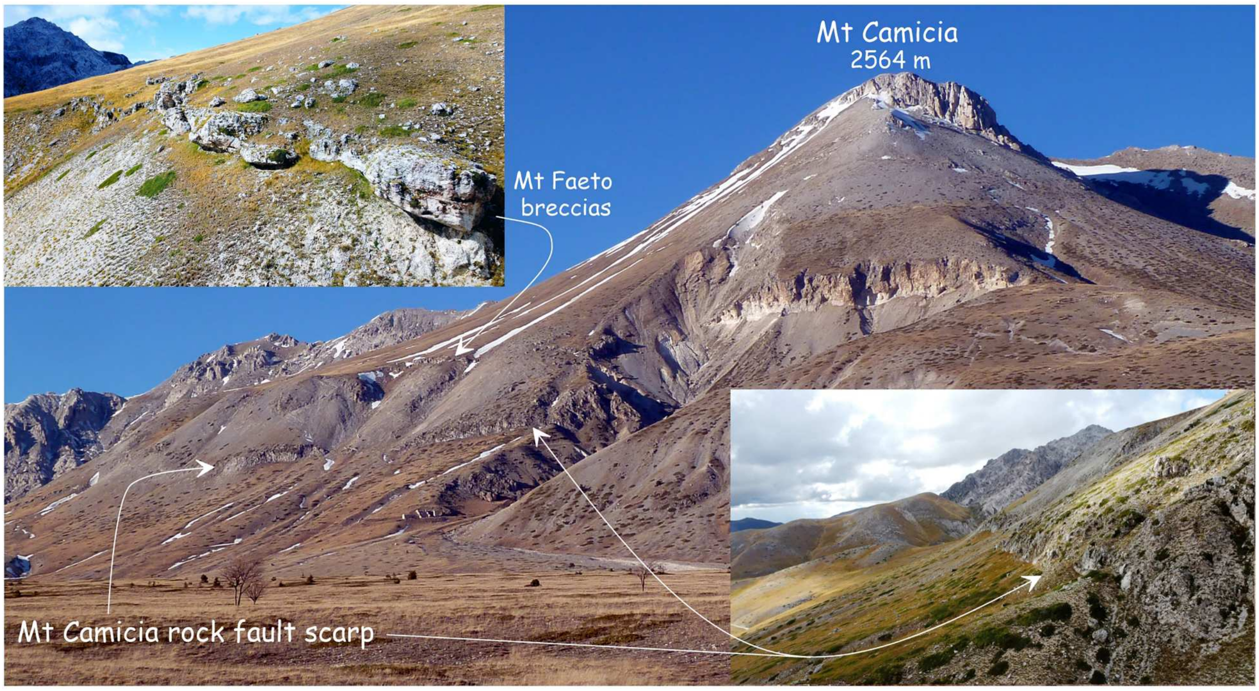

Figure 5. View looking north of Mt Camicia southern slope. Left insets, aerial view of the breccias of Monte Faeto Unit, suspended in the footwall of the Mt Camicia fault (right inset). The plain is about at 1600 m asl.

composed of chaotic breccias with unsorted angular clasts (see Figure 7) that emerge in the current plain, covered by recent fluvio-lacustrine deposits (LCU and VFU). The apparent thickness is around 10–15 m and they are dissected and superimposed by deposits related to LGM glacial and other fluvial phases, suggesting an earlier age (Middle Pleistocene: Bisci et al., 1999; Giraudi & Frezzotti, 1997). U/Th dating of calcite from within these deposits allowed Kotarba et al. (2001) to estimate an age of approximately 131 ka, which matches the penultimate significant glacial episode (MIS 6).

Stazzo Caciaro Unit – SCU (Late Pleistocene; 111–40 ka)

These fluvial deposits are exposed to the north and east of Colle Caciaro (see Figure 8) and are primarily composed of well-rounded, loose-to-cemented pebbles. They are distinctive due to the presence of abundant rounded sandstone clasts, which are not typically found in other fluvial units in Campo Imperatore. These deposits reach a thickness of approximately 20 m in outcrop, with the highest exposure found near the locality named 'Stazzo Caciaro', where the unit preserves its original summit surface. The main source area for this unit is probably located in 'le Toppe' (NE of Mt Paradiso), a tributary valley of the main Fornaca Valley, within whose hydrographic boundaries the late-orogenic formation of the Monte Coppe Conglomerates (Messinian-Lower Pliocene; Ghisetti & Vezzani, 1986) containing the same sandstone clasts as the unit in question, outcrops in strong unconformity over the Meso-Cenozoic carbonates (see also Calamita et al., 2004).

The absence of datable elements makes it challenging to infer the age of these deposits. However, they are older than the Valle Fornaca Unit (see here below) as they are morphologically higher than the top surface of this unit (Figure 8). In detail, entrenching of the Valle Fornaca Unit inside Stazzo Caciaro Unit diminishes as approaching the source area uphill, where the Stazzo Caciaro Unit is buried by more recent units. For this reason, we hypothesized that these deposits may relate to the alluvial fan deposits outcropping just below the Valle Fornaca Unit, between two paleosols (PS1, PS2) with ages of ∼40 and ∼111 ka, respectively, both exposed on the cliff along the right bank of the Fornaca Valley (see Figures 9 and 11). In particular, at the top of PS1, a reddish-brown >1 m thick paleosol (PS1 in Figure 11(E)), we sampled a slightly pedogenized yellowish tephra layer, with sanidine crystals that were dated to 111 ± 4 kyr BP ($^{40}Ar/^{39}Ar$ age). Giving this age, PS1 can be related to the warm and wet phase of MIS 5e (∼129–116 ka), interrupted by the stadial MIS 5d, and thus Stazzo Caciaro Unit could have been deposited since this stadial and during the successive cold MIS 4 (∼70 kyr BP).

Notably, in the same outcrop, two secondary normal faults (Figure 11(E)) displace this succession by about 50 cm (southern fault) and the other by at least 2 m (northern fault). The southern fault affects the entire outcropping succession, while the northern one is sealed by the same erosional surface that truncates PS1 (Figure 11(E)).

To the east of Colle Caciaro, this unit is displaced against the Colle Caciaro Unit by the western splay

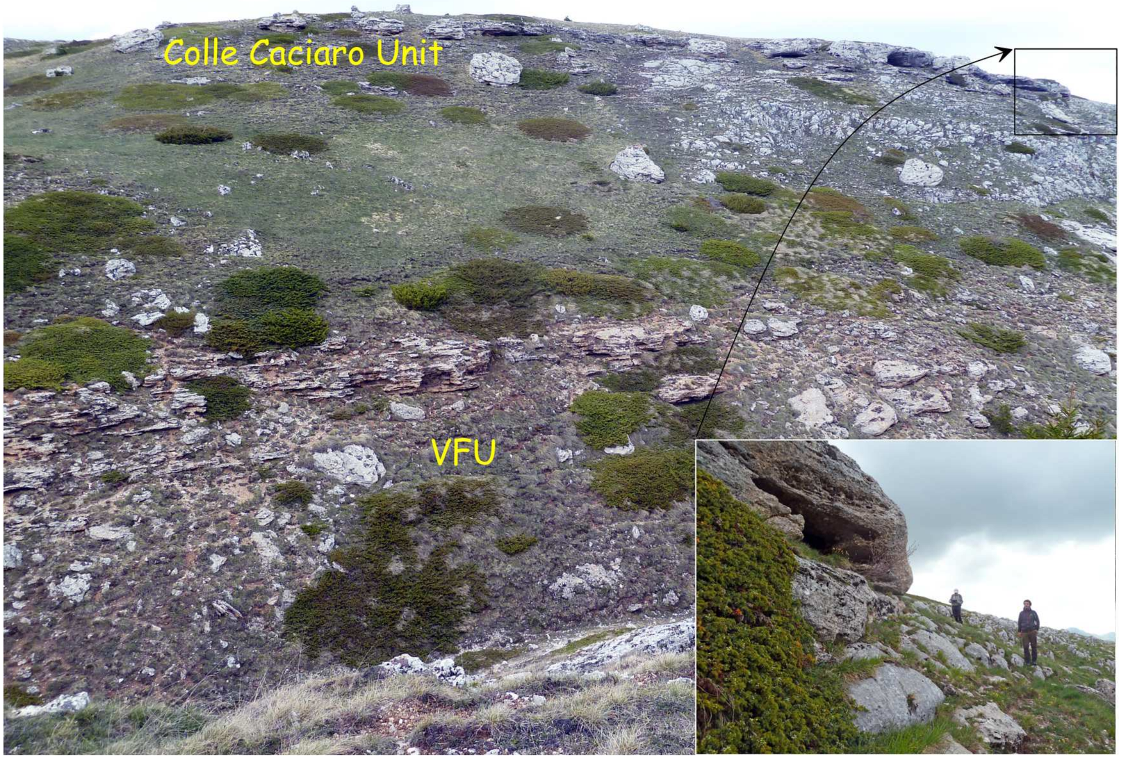

Figure 6. Colle Caciaro seen from west. Note Valle Fornaca Unit (VFU) entrenched within the Colle Caciaro Unit, and the subhorizontal layering of these units, both resting over the carbonate bedrock (center foreground and right inset, respectively), and the big boulders of the Colle Caciaro Unit, toppled and rolled along the slope.

of the Cocchiarelle antithetic fault (Figure 8), testifying the Late Pleistocene activity of the fault.

Coppe di Santo Stefano Unit – CSSU (LGM; ∼28–26 ka)

The western part of Campo Imperatore is mantled by moraine deposits composed of chaotic gravels and blocks with unsorted angular clasts, from pebbles to boulders, related to a 10-km-long piedmont glacier.

Figure 7. Remnant of the cemented Racollo moraine, SW to Piano Racollo. According to Kotarba et al. (2001), this moraine was emplaced around/before 131 ka (U/Th dating). The Corno Grande (2912 m a.s.l.) is in the background.

These moraines extend from the glacial cirques – well visible under the mountain crests to the south and north of the Campo Imperatore plain – and then coalesce in a unique basal moraine with a fossilized front (see Geological map and Figure 9). This unit has a thickness of several tens of meters (up to 150 m according to Giraudi & Frezzotti, 1997), and has been attributed to the Last Glacial Maximum (Giraudi, 2003a; Giraudi & Frezzotti, 1997), with a maximum extent reached at 28–26 kyr BP (Campo Imperatore Stade in Giraudi & Frezzotti, 1997). It presents the typical morphologies associated with lateral, frontal, and basal moraines, featuring a hummocky morphology (also referred to as drumlins; see Benediktsson et al., 2016).

Valle Fornaca Unit – VFU (Upper Pleistocene; 40–15 ka)

These alluvial deposits, which still preserve their depositional top surface, have been fed by torrential streams deeply incised into the southern slope of the Gran Sasso mountain range, mainly Rionne, la Canala (Figure 10), and Fornaca valleys. The deposits of this unit extensively crop out throughout the eastern Campo Imperatore area (alluvial fan facies; Figures 4, 6, 8, 10, and 11), and along the left bank of the Valianara canyon (distal alluvial fan and fluvial facies; Figures 4 and 6). The most prominent exposures of the alluvial succession are found along the east-facing, right bank of the northern sector of the Fornaca alluvial fan. This nearly vertical and straight erosive cliff spans 350 m in length and exhibits a gradual decrease in height above the current stream bottom, ranging from approximately 25 m in the northern part to about 2 m in the southern part (see Figure 11(A)). The northernmost section of the outcrop shows well-stratified fluvial deposits, with loose or faintly cemented subangular to angular pebbles, indicative of multiple alluvial phases. These phases are sometime demarcated by remnants of paleosols, suggesting warmer and wetter periods, alternated with colder rhexistasy phases that either truncated or eroded the paleosols. Two important

Figure 8. Left, view looking south of the sub-horizontal depositional surface of Stazzo Caciaro Unit. In background, top surface of the Valle Fornaca Unit (VFU; left side of the Valianara canyon), entrenched in the Stazzo Caciaro one. Right, Cocchiarelle rock fault scarp, displacing the Colle Caciaro Unit against the Stazzo Caciaro Unit. In the background, Valle Fornaca Unit with its well-preserved depositional top surface (right side of Valianara canyon).

Figure 9. Left, view looking south of the 'drumlin field' related to the post LGM glacier retreat. Right, detail of the top surface of Coppe Santo Stefano terminal moraine, with boulders and pebbles in selective erosion. The Corno Grande (2912 m a.s.l.) is in the background.

Figure 10. View looking south of the La Canala valley outlet, with Mt Paradiso and Mt Bolza in the background (right). The terraced flat area (center) is the top of the Fornaca Valley Unit (VFU in map), here forming the divide between the Fornaca and La Canala valleys (see Geological map). The whitish alluvia are the Cretarola unit (CU in map).

paleosols, exhibiting extensive lateral continuity and vertically spaced 4–5 m apart, were selected for AMS dating. They yielded ages of 28560–27960 yr BP (PS3) and >43500 yr BP (PS1?) (Figure 11(C)). Notably, standard radiometric analyses from the 1980s (Frezzotti & Giraudi, 1990) provided younger ages for a seemingly similar pair of paleosols (22155–21015 yr BP and 36935–34695 yr BP, recalibrated ages).

Valle Fornaca Unit corresponds to the upper part of the exposed succession, which lies in clear unconformity above the lower units. The unit deposited between PS2 (Figure 11(A,E)) and PS5 (Figure 11(A, F)), where PS2 is a relict paleosol overlying an important erosional surface, and provided an age of 41370–40145 yr BP, while PS5, sampled in the southern sector of the cliff, provided an age of 17330–17020 yr BP.

Farther southward, facing the deeply incised Val Cortina head valley, the VFU overlaps directly the marine carbonate bedrock. Here, 15 m below the top surface of the suspended surface of the fan, we exhumed a thick brownish paleosol, developed above the silty colluvium of an older tephra. Two samples (Cort01-02), taken in two distant sites provided two concordant AMS ages of 19560–19240 yr BP and of 19415–19060 yr BP.

Southwest of Monte Paradiso (La Canala alluvial fan), in the alluvial succession paralleling the one in the Fornaca valley, Galli et al. (2002) found inside a paleoseismological trench a quartz-rich loess deposited at the top of the VFU alluvial fan gravels. This loess, likely represents the transition between the Oldest Dryas stadial (or Greenland stadial GS-2) and the Bölling/Alleröd Interstadial (or Greenland Interstadial Gl-1) at around 15 ky BP (Giraudi et al., 2013) and provides an upper chronological boundary of the VFU.

In the easternmost sector of Campo Imperatore, VFU extensively outcrops, mainly as the fluvial infilling of the Valianara canyon, that successively reincised this unit. Here, in the Valle della Macina stream, Giraudi and Frezzotti (1997) dated a paleosol embedded within the cemented gravels near the top surface to approximately 21 ka (bo-254). Conversely, VFU does not crop out in the Cortina Valley, between Coppe di Santo Stefano and the entrance of the Valianara Canyon. This area was the headwaters of a valley originally draining westward, that likely had its base level in the area of Coppe di Santo Stefano (with probable presence of buried karstic swallow-holes), separating hydrologically the western sector from the eastern sector of Campo Imperatore. Only later did the capture of this valley by retrogressive erosion of the stream of the Valianara canyon cause a reversal of drainage towards the plain of Prati di Cretarola (Figure 12).

Fonte Vetica Unit – FVU (Upper Pleistocene – Holocene; ~15–8 ka).

These are loose alluvial fan deposits primarily fed by the streams from the La Canala and Fornaca valleys, and from ephemeral streams originating from the southern slopes of Mt Prena and Mt Camicia. They are generally composed of carbonate angular clasts, passing to sub-rounded clasts in more distal

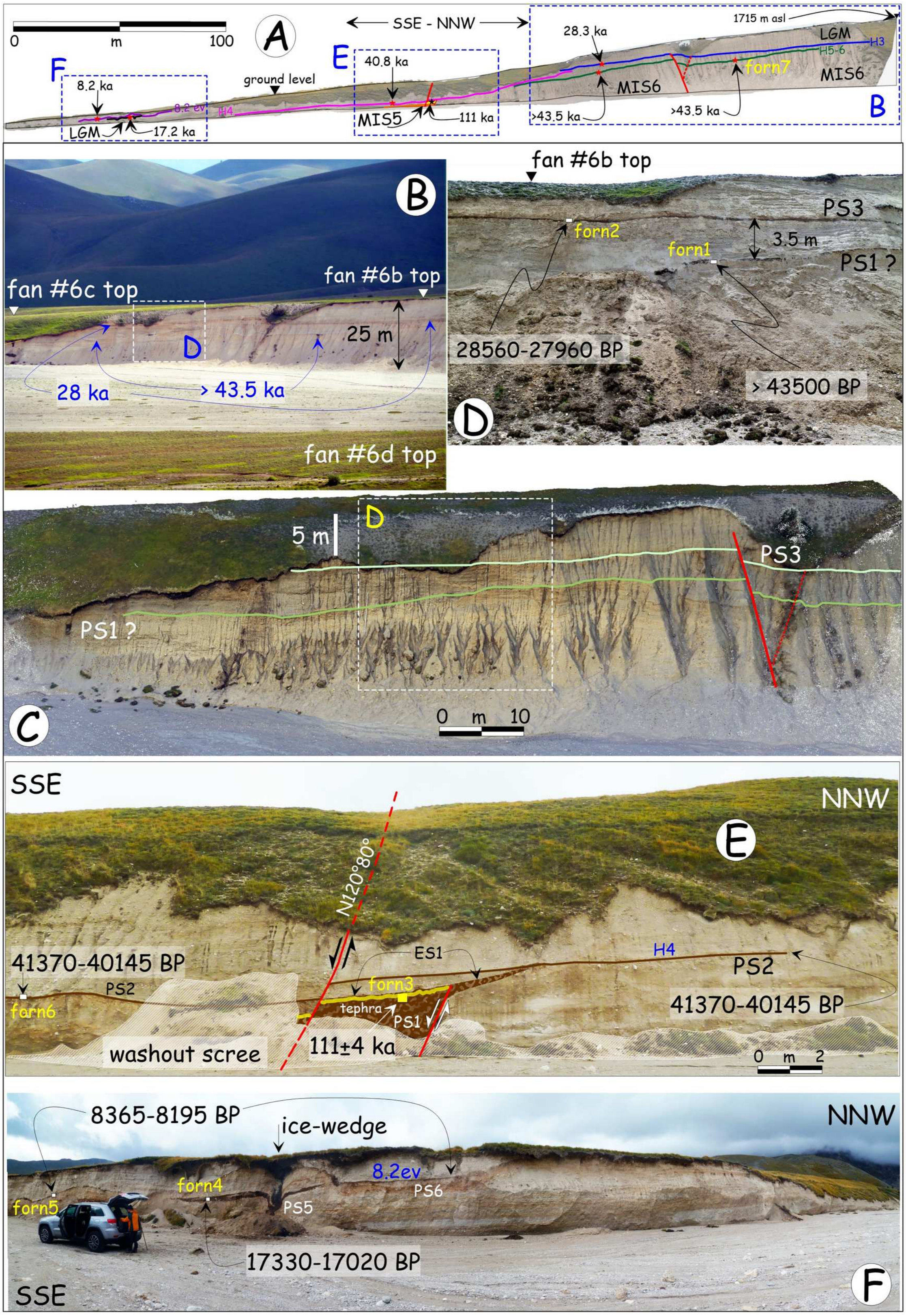

Figure 11. (A-B-C-D) Panoramic views of the central portion of the Fornaca fan, where several secondary, synthetic and antithetic faults affects the Upper Pleistocene alluvial succession. The PS1 paleosol (see insets C-D-E) sampled 200 m away, provided a 14C age >43500 BP (beyond the 14C method), later fixed at ~111 ka by $^{40}Ar/^{39}Ar$ dating of sanidine crystals contained in a yellowish tephra that we recognized at the top of the same (?) paleosol. PS1 is truncated upward by an erosional surface (ES1) that also seals the northern fault. Paleosol PS2, dated ~40 ka, is truncated northward by another erosional surface; both paleosols are offset from the southern fault by 0.5 m. F Fish-eye view of the southern part of the Fornaca Valley fan. Note the deformation induce by the ice-wedge on the hosting deposits, well depicted by the folded paleosols PS5-6, dated ~17 ka and ~8 ka, respectively.

Figure 12. View looking east of the junction point of the Valianara canyon and the Cortina valley, where the former has gradually overtaken the latter's course, redirecting its previous westward flow. Yellow dashed line suggests the ancient head of the Cortina valley.

areas. Except where dissected by ephemeral streams, this unit has preserved its original top-surface, which is clearly entrenched within the VFU (see Geological Map). In the southernmost part of the long outcrop of the Fornaca cliff (Figure 11(F)), alluvial deposits subsequent to the VFU are exposed, separated from it by a paleosol PS5 (17330–17020 yr BP) and capped by another PS6 (8365–8195 yr BP). These deposits correspond to the Fonte Vetica Unit, which are carved both morphologically and stratigraphically within the VFU due to the presence of a prominent 2–3-meter-high scarp evident in the field and in high-resolution DEMs. Before the deposition of the Fonte Vetica Unit and the subsequent Cocchiarelle Unit, the area was affected by erosional phases that allowed these units to be embedded within each other.

Le Cocchiarelle Unit – LCU (post ~8 ka) These alluvial fan deposits were primarily transported by streams from the San Lorenzo Valley and Fornaca Valley. They are morphologically entrenched or overlaid on the Fonte Vetica Unit. As the preceding units, they are generally composed of angular to sub-rounded carbonate clasts, toward the distal areas.

Costa San Vito Unit – CSVU. These deposits (Figure 2, Geological Map) consist of angular carbonate clasts mantling discontinuously, with variable thicknesses – ranging from a few dm to several tens of meters – on the slopes of the Campo Imperatore.

Cretarola Unit – CU. This unit is made by loose fine gravels within whitish carbonate silt, mantling the current valley floors. Clasts are generally poorly rounded, as they are primarily emplaced by flashfloods that have occurred in recent centuries or, in some cases, in recent years (Figure 2, Geological Map). In the Cretarola plain area, this type of deposit is accompanied by finer sediments, sometimes deposited in stagnant water, due to the occlusion of karst conduits that currently regulate the drainage of the Campo Imperatore area.

5.2. Quaternary geological evolution of Campo Imperatore

With the aim of better understand the Quaternary geological evolution of the investigated area, during field survey we also gathered new data on the tectonic activity of the Gran Sasso faults (GSFS in Figure 1), which helped to address the entrenching relationships among various alluvial units. As mentioned earlier, the Campo Imperatore area predominantly lies within the hanging wall of the Mandrucce-Vado di Corno, Mt Brancastello, and Mt San Vito segments (MVCF, BF, and SVF in Figure 1 and Geological Map), with the study area being affected by the latter two, as well as by the secondary faults of Mt Paradiso and Cocchiarelle.

At the intersection of the Mt Brancastello fault and the Rionne stream (Figure 1), we encountered chaotic torrential deposits, either loose or weakly cemented, extensively affected by sub-vertical N150° fault planes exhibiting dip-slip striae, as well as by sub-vertical N70° planes with oblique striae. These faults have offset the cemented bottom of the creek by 0.5 m, indicating recent surface displacement (Figure 13). Further evidence of the Late Pleistocene activity of the Brancastello fault at its easternmost extent is provided by the widespread dm-scale faulting observed in the Fornaca valley alluvial deposits, occurring along both synthetic and antithetic splay faults (Figure 11).

However, the most compelling evidence of Late Pleistocene faulting was found along an antithetic

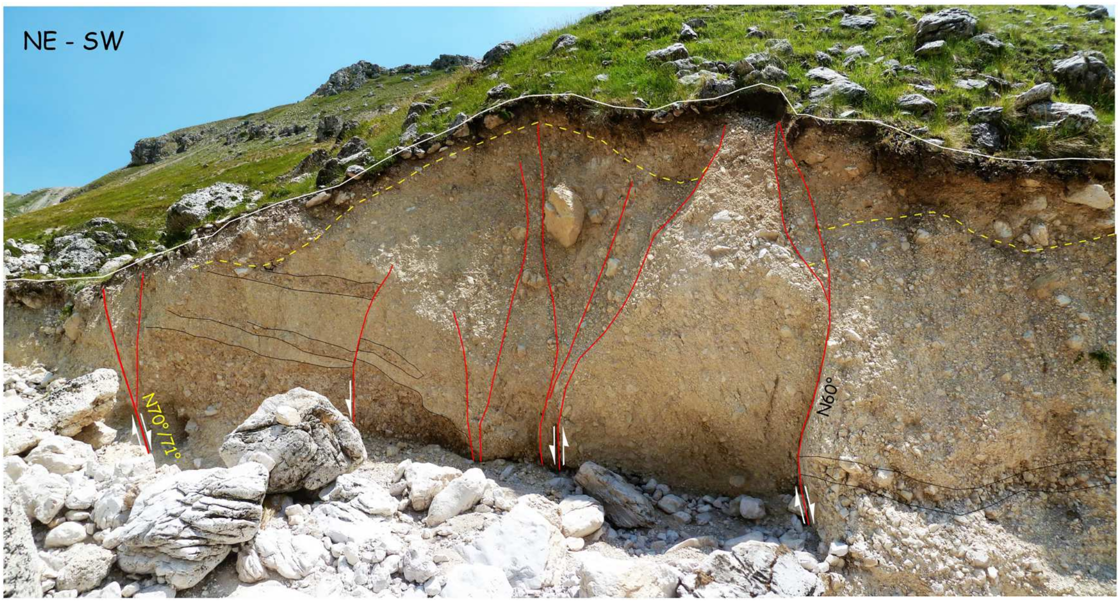

Figure 13. Rionne stream, crossing point with the Brancastello Fault. View looking east of the faulted fluvial gravel and of the cemented bottom of the stream. Red, faults (with strike/dip); dashed black lines, lithological limits; white-yellow, top and bottom of active soil.

fault that dams the natural drainage of all the water flowing south from Mt Prena divide, especially the one within the hydrographic basin of the Fornaca stream. Just 2 km south of the mouth of the deeply entrenched Fornaca Valley, the 5-km-long, N290° striking Cocchiarelle normal fault downthrows the northern sector of the Campo Imperatore basin. Over time, relative coseismic footwall uplift periodically dammed the north–south course of the Fornaca stream, which originally flows towards its base level in the Valianara canyon, forcing it to divert eastward. Here, the uplift of the footwall block prevented it from entering the Valianara canyon through the subsequent catchment area west of Colle Caciaro, instead driving its path farther eastward, into the Valle della Macina. Over time, this fault has significantly influenced sedimentation phases of the eastern Campo Imperatore basin, thereby shaping its geomorphological framework. Currently, erosion of the Fornaca fan has breached the footwall, temporarily restoring a shorter drainage pattern towards the Valianara canyon. Nevertheless, it is possible to estimate that the relative uplift of the footwall since the end of the Last Glacial Maximum (LGM; roughly the top of VFU) has been on the order of 15 m (Figure 14), indicating an average slip rate of approximately 1 mm/yr.

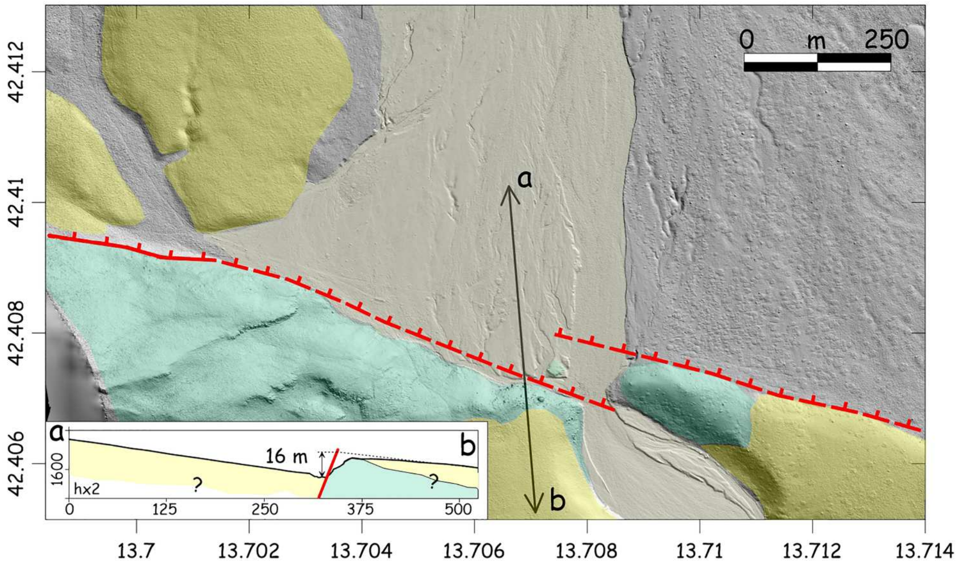

Figure 14. Detail of the intersection between the Cocchiarelle fault (red line, dashed where buried by alluvial fan deposits) and the Fornaca stream. Green, carbonate bedrock (Cretaceous calcirudites with rudists) raised by the fault; yellow, Valle Fornaca Unit (VFU); pale-yellow and gray, very recent alluvial deposits. Despite the southward breakthrough by the watercourse across the footwall, the VFU gravels, dating back to the last 20 ky, are uplifted by more than 15 m (see section a-b).

Considering this tectonic framework, and taking in mind the alluvial units described above and reported on the Geological map, we can summarize the Quaternary evolution of this sector of Campo Imperatore as:

1. During the Late Pliocene and/or the lower part of Early Pleistocene (i.e. before 1.6 ± 0.5 Ma), areal peneplanation originated the paleolandscape of Anzano, which was almost entirely carved within Meso-Cenozoic marine carbonates.
2. In the Early-Middle Pleistocene the eight main segments of the Gran Sasso fault system progressively linked each other, driving the opening and deepening of the whole Campo Imperatore basin. High relief energy and glacial processes prompted the formation of slope breccias, moraines and thick alluvial deposits now buried at depth in the plain. The pattern of the hydrographic network began to take shape with initial meandering incision of the future Valianara canyon, flowing towards the Prati di Cretarola, which already served as the base level of the eastern sector of Campo Imperatore. Conversely, the western sector of Campo Imperatore, between the Vado di Corno area and the Cortina valley, had its base level in the Coppe di Santo Stefano area, where karstic sinkholes were likely present, now buried by subsequent fluvial-glacial processes. At that time, the Cortina valley (the current stretch between the Coppe di Santo Stefano-Racollo area and the entrance of the Valianara Canyon) still had a westward flow and had not yet been captured by the Valianara Canyon.
3. In the late Middle Pleistocene (before ∼131 ka), moraine deposits related to the latest MIS6 glaciation were emplaced (Racollo Unit), preceded by the deposition of significant bodies of slope breccias (Monte Faeto Unit), mainly piled up along the northern slopes of the entire Campo Imperatore ridge, and by alluvium of the Colle Caciaro Unit. Successively, the oldest units exposed along the cliff of the Fornaca Valley deposited before ∼111 ka. The Valianara canyon deepened along with its tributaries, due to a lowering of the base level of watercourses in the Prata di Cretarola area, where karst sinkholes regulated the drainage of eastern Campo Imperatore. Even in its upper course the canyon deepens within the carbonate substrate, causing the progressive capture of the Cortina valley.
4. In the early-mid Late Pleistocene (after ∼111 ka), the Stazzo Caciaro Unit sedimented, with alluvial deposits originating from the Fornaca Valley, followed unconformably by the early phase of the Valle Fornaca Unit that almost entirely filled the Valianara canyon (after 40 ka).
5. At the end of the Last Glacial Maximum, the moraine of Coppe di Santo Stefano Unit (emplaced by ∼28–26 ka) was finally abandoned by the glacial tongue descending from the circles located in the north-westernmost sector of the Campo Imperatore plain. At the same time, there was continued deposition of post LGM alluvial deposits of the Fornaca Valley Unit, mantling the entire investigated area, from Mt Paradiso to the Piano dell'Ospedale. Water and sediment input from the Gran Sasso range occasionally allowed this unit to cross the Cocchiarelle footwall dam and the consequent flooding and burying of the sector of the paleolandscape of Anzano, between the Cocchiarelle fault and the Valianara canyon. Meanwhile, capture of the Cortina valley by the Valianara canyon was completed.
6. After the LGM and during the Holocene, all the successive alluvial units (i.e. Fonte Vetica, Le Cocchiarelle, Cretarola) were progressively emplaced, where they are now entrenched within each other in the Valianara canyon and its tributaries, and in the whole Campo Imperatore plain area. This entrenching is due to the continued lowering of fluvial base level in the Prata di Cretarola area and subsidence of the area between the two faults.
7. With the completion of the capture process in the Cortina valley, the entire northwestern sector of Campo Imperatore now drains towards the Prati di Cretarola. The Valianara stream has reincised its talweg, leaving suspended along its left bank the Upper Quaternary conglomerate of Stazzo Caciaro and Valle Fornaca unit. Occasionally, during significant flood events, such as the one in 2022, flash-floods from the Fornaca valley dam the Valianara canyon, causing overflooding of the Cortina valley.

6. Concluding remarks

Our geological and geomorphological investigation within the central-eastern sectors of the Campo Imperatore plain has yielded an enhanced understanding of the Pleistocene morpho-sedimentary and tectonic evolution of this basin. Several radiometric dating analyses have been instrumental in establishing the chronology of the main alluvial and fluvio-glacial phases, spanning from the late Middle Pleistocene to present. The pronounced uplift of the Apennine chain, alongside fluctuations in the frequency and magnitude of glacial-interglacial cycles since the Middle Pleistocene, as well as tectonic downthrow of the Campo Imperatore basin, has fostered highly dynamic morpho-sedimentary processes in this high-elevation region (1500–2500 m asl).

During the Middle Pleistocene, deposition of over 100 m of carbonate breccias occurred extensively along the slopes of the Gran Sasso mountain range. Concurrently, surface basin processes witnessed heightened rates of sedimentation, erosion, and pedogenesis, yielding Middle-Upper Pleistocene to Holocene glacial, fluvial, and fluvio-glacial deposits.

After the retreat of MIS6 Racollo glacier, at ∼131 kyr BP, a thick brownish paleosol formed on the top surface of the Fornaca alluvial fan. Its presence indicates mild and wet climate conditions during MIS 5e, roughly matching the last interglacial (LIG c. 129–116 ka), which were abruptly interrupted after 111 ky BP. This stadial is likely represented by the Stazzo Caciaro Unit, whose gravels truncate the underlying paleosol and tephra. Following a new period of relative biostasy, a significant erosion phase occurred around 40 ka. This was succeeded by alternating fan deposition, represented by the Valle Fornaca Unit, and new soil development until approximately 28 ka. At this point, the onset of the Campo Imperatore Stadial, corresponding to the local Last Glacial Maximum (LGM), led to glacier advance and widespread gravel transport and deposition, extending into the southeastern sectors of Campo Imperatore. After the LGM and the retreat of the Coppe di Santo Stefano glacial tongue, alternating periods of biostasy, marked by the presence of paleosols at both 17 and 8 ka, were interspersed with episodes of erosion and further gravel deposition.

Landforms and alluvial deposits within the Campo Imperatore plain have also been gradually affected by synthetic and antithetic normal faults associated with the active Gran Sasso fault system. This 40-km-long fault system represents the seismogenic structure responsible for earthquakes of magnitude Mw∼7, with the most recent one occurring in 1349 CE. Amongst its antithetic faults, an important role in the morphogenesis and depositional processes in the area has been played by the active Cocchiarelle fault. Indeed, the relative uplift of its footwall has controlled the flow of water from the Fornaca valley towards the Valianara canyon, occasionally obstructing and diverting it eastward, i.e. during coseismic events of surface faulting.

The new chronological constrains of the units, their stratigraphic arrangement, and the resultant Late Pleistocene geological evolution of the Campo Imperatore plain may be of considerable interest for understanding the geological evolution of the several other intramontane basins that populate the central Apennines.

Software

The data collected have been managed and stored in a georeferenced data-base using Esri ArcGIS, ArcMAP Desktop 10.8. Agisoft Metashape Professional 2.1 has been used to derive high-resolution photomosaics from SfM image-based modeling. Adobe Illustrator 28.5 was used for final map production.

Acknowledgements

We are grateful to Sebastien Nomade for dating the tephra through Ar/Ar analyses. Antonio Galderisi participated in the early field surveys before joining the Royal Navy and keeping the Italian flag flying high. We are also grateful to the Ente Parco del Gran Sasso for his great collaborative spirit. Field survey conducted in the framework of the IGAG P-Faults Project (Coordinated by E. Peronace). The criticisms of M. Shand, L. Cardello, M. Spadi, T. Piacentini and J. Knigth greatly enhanced the first version of our manuscript. We are grateful to all of them. The view and conclusion contained in this paper are those of the authors and should not be interpreted as necessarly representing the official policies, either expressed or implied, of the Italian Government.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and in the attached Map.

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