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Karst morphology and cave sediments as indicators of the uplift history in the Alpi Apuane (Tuscany, Italy)

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Abstract

In the Alpi Apuane (Tuscany, Italy), Late Pliocene to Pleistocene karst landforms are preserved as relict phreatic caves, which were formed in a geomorphic setting very different from that of the present day. The largest karst drainage basin in the region, the Frigido, hosts cave systems with a vertical development totalling 1600 m. Abandoned phreatic cave passages preserved within this and neighbouring basins indicate that former base-levels were situated at up to ~1000 m above the modern valley floors. The passages constitute morphostratigraphic markers that can be used to reconstruct the uplift history of the Apuane. Their vertical distribution suggests two major phases of base-level standstill—one at 1000–1200 m a.s.l. and one at 600–700 m a.s.l. Some of the passages situated at the latter level contain >5 m thick flowstones whose top-beds have an age exceeding the limits of U/Th alpha spectrometric dating (>350 ka). Cave morphology and chronological constraints obtained from speleothems suggest that an important uplift event occurred during the Middle Pleistocene following a period of tectonic standstill of probable latest Early Pleistocene age. Active spring caves close to present-day valley floors contain speleothems whose ages exceed 100 ka, implying that no significant downcutting of the seaward valleys, and consequently no tectonic uplift, has occurred during Late Pleistocene.

1. Introduction

The Alpi Apuane are situated in northern Tuscany (Italy), where they rise abruptly from the Tyrrhenian coastal plain (Fig. 1). The region is one of the most spectacular high-relief areas in Europe, with several peaks exceeding 1800 m in elevation. The timing of both the uplift of the Apuane and the exhumation of its metamorphic core has stimulated much research over the last few decades (Carmignani and Kligfield, 1990; Abbate et al., 1994), and has major implications for regional tectonic history and landscape evolution (Bartolini et al., 1982). However, the uplift history is not well understood. The geomorphology and chronology of karst caves is one source of evidence that can help resolve issues of uplift history and landscape development (Palmer, 1991). In this paper, we use elevation and age data from dewatered phreatic cave passages to constrain periods of tectonic standstill, rates of incision and minimum ages of former valley-floor elevations.

2. Regional geomorphology and geology

The Alpi Apuane massif consists principally of a NW–SE trending ridge extending for 32 km approximately parallel to the Northern Appennines, which is part of the main mountain chain that runs the length of the Italian peninsula. The massif consists of three tectonic units that were overthrusted, one upon the other, during the Upper Oligocene (Carmignani and Kligfield, 1990). Two of these units make up a single metamorphic complex of carbonate to terrigenous formations, which have been overlapped by the third unit, the Tuscan Nappe (Fazzuoli et al., 1985). Metamorphism occurred as three folding phases, which have been dated between 27 and 10 Ma (Kligfield et al., 1986). The Apuane Unit, the lowest, is a continental-to-marine sedimentary sequence that rests on an Ercinian basement of phyllites and porphyritic vulcanite. The sequence began in the late Permian with continental

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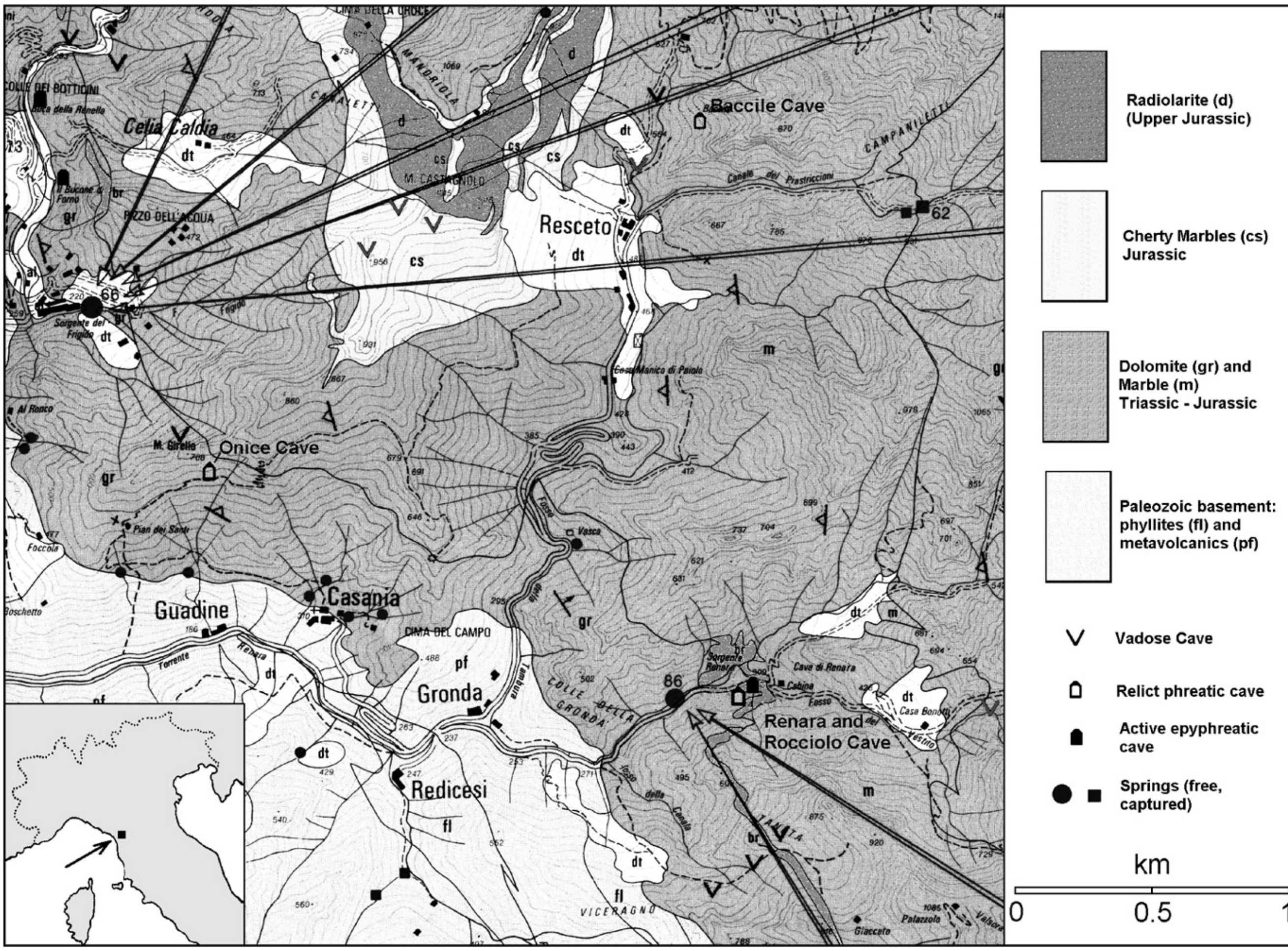

Fig. 1. Geologic sketch map of Frigido Basin with the location of investigated caves (from Piccini and Pranzini, 1989).

clastic rocks, on which developed a carbonate shelf of Carnian to Lower Jurassic age. The shelf consists of metadolomite (''Grezzoni''), dolomitic marble and marble (''Marmo di Carrara'') overlain by pelagic siliceous limestone. At the end of the Cretaceous, the sedimentation became progressively hemipelagic, with shales and calcarenites followed by sandstones of upper Oligocene age (Coli and Fazzuoli, 1992). Extension tectonics in the Late Miocene–Pliocene triggered the uplift of the Apuane massif along peripheral fault systems with ''appenninic'' (NW–SE) and ''antiappenninic'' (NE–SW) strikes. This phase was responsible, first, for the formation of the Lucca and Viareggio Basins, and, subsequently, the collapse of the Magra and Serchio Basins, during the Late Pliocene (Bartolini et al., 1982; Raggi, 1985; Bernini et al., 1990).

The alpine-like relief of the Apuane is the result of differential erosion on a complex structural setting, with metamorphism enhancing lithologic differences. The main ridgeline comprises a series of sharpened crests with steep slopes and high scarps, and with several peaks exceeding 1800 m. Deep valleys incise the SW-facing seaward flank and form secondary watersheds that connect the main ridgeline with a NW–SE lineament of minor peaks located close to the coastal plain. In contrast, the NE flank consists of more gentle ridgelines and longer, lower-gradient valleys. This morphological setting suggests that the present relief is the result of intensive deepening of streams on an ancient subdued low-relief surface, remnants of which are still preserved as low-gradient crests at altitudes of 1000 m or more (Bartolini, 1980; Piccini, 1994a).

3. Apuane karst, cave levels and landscape evolution

Surface karst landforms are not well developed in the Apuane because the high relief and regional climatic conditions (i.e. high temperature excursions and rainfall up to 3500 mm/year) enhance mechanical-denudation processes. In particular, mechanical erosion must have been very active during the last glacial and postglacial phases, destroying most of the pre-Würm surface karst landforms. Only in some restricted low-relief areas are small to medium-scale karst landforms (e.g. karren) found (Marcaccini, 1964; Federici et al., 1981; Piccini, 1994a). On the contrary, karst caves represent one of the most important morphological features of Apuane. Five caves are deeper than 1000 m, 40 caves have a depth of more than 300 m, and 12 caves are longer than 3000 m (Caves Inventory of Tuscany, unpublished). Most of the caves are percolation-vadose in origin with a predominance of vertical development. The deepest caves reach local piezometric surfaces at elevations between 400 and 550 m a.s.l.

Based on the vertical distribution of the phreatic and epiphreatic passages in the caves, three major generations of base-level caves can be identified in the Alpi Apuane (Piccini, 1997). In the largest cave system, the Monte Corchia Complex, at least four are preserved, each cut vertically by a succession of percolation (vadose) caves (Piccini, 1994a). In the central part of the massif, the uppermost level is preserved at an altitude of 1600–1700 m a.s.l., whilst the second and most widely developed generation occurs between 1000 and 750 m a.s.l.. In the Corchia Complex, the situation is slightly different, with the first generation lying above 1450 m a.s.l., and the second between 1000 and 1200 m a.s.l. The latter form a wide anastomosing network that was subsequently affected by a major phase of vadose entrenchment. Below 1000 m, most of the Apuane caves are located on the seaward side, and possess phreatic passages that drain towards the SW. Most of the third generation of phreatic caves is located at an altitude of 650–500 m. Phreatic tubes are also present at the bottom of the major vertical caves, adjacent to the modern piezometric level. Spring caves are still active on the NE side of Apuane, whilst on the seaward side they have been abandoned by valley downcutting. Here, a new generation of phreatic caves is now forming at elevations between 250 and 350 m a.s.l.

There are few chronological elements by which to mark the age of the different stages of karst development in the Alpi Apuane. However, we can assume that the oldest relict caves, including the upper level of Corchia cave, were formed during the early denudation stage of the metamorphic carbonate rock. Apatite fission-track dating provides a first constraint of exhumation timing. According to the data of Abbate et al. (1994) and Bigazzi et al. (1988), the metamorphic rocks were still buried to a depth of at least 3 km ca. ~4.5–5.0 Ma. A second chronological constraint is the age of the alluvial-fan deposits in the basins surrounding the Apuane, where pebbles comprising lithologies belonging to the metamorphic core rest on Late Pliocene–Early Pleistocene lacustrine deposits (Calistri, 1974; Raggi, 1985; Bertoldi, 1988; D'Amato Avanzi and Puccinelli, 1988). The metamorphic core must have been exhumed by this stage. On this basis, we can take 3.0–2.5 Ma as a reasonable age estimate for the initial karstification of the metamorphic carbonate rock.

A more detailed, but more speculative, chronology of karstification and landscape history was reported by Piccini (1997) using relationships between cave levels, low-relief surfaces and the morphotectonic evolution of the Val di Magra and Serchio Basins. In any case, during the Late Pliocene, karst processes must have been very active largely due to the low relief of the area and the favourable climatic conditions (high rainfall and warm temperatures) (Fauquette et al., 1999). It is probable that the oldest relict caves and the upper complex phreatic levels of the Corchia System were formed during this important phase of karst development (Piccini, 1994a).

During the Early Pleistocene, a period of tectonic standstill is a likely cause for the formation of the main levels of phreatic and epiphreatic caves at 1000–750 m a.s.l. Evidence from the sedimentary sequences of the surrounding continental basins suggest that a further standstill in the uplift of the Apuane occurred in the Middle Pleistocene (Bernini et al., 1990). At this time, the phreatic passages at ~500–650 m a.s.l. were probably formed (Piccini, 1997).

4. The use of speleothem age dating as a chronostratigraphic constraint in the apuane

It is widely accepted that phreatic passages form below the local piezometric surface and that they evolve to large tubes close to the karst water table (e.g. Ford and Williams, 1989; Palmer, 1987, 1991, and references therein). If the local base level remains stable, cave systems develop into a complex and hierarchical network of epiphreatic tubes just above the altitude of springs (Palmer, 1991). During a tectonic standstill or a stage of low uplift rates, tubiform passages can evolve to low-gradient canyons characterized by alluvial fills.

Uranium-series (U/Th) dating of speleothems in relict phreatic passages can give significant chronological constraints regarding the age of caves (Ford et al., 1981; Williams, 1982; Gascoyne et al., 1983). Speleothem growth only occurs in caves that have been dewatered or which are, at most, only occasionally active. This is because phreatic waters are usually either undersaturated or just saturated with respect to calcite, and are therefore incapable of precipitating calcite as speleothem deposits. Thus, as local base level falls, phreatic passages become abandoned and secondary deposition of calcite as speleothems from vadose seepage waters can proceed (Ford and Williams, 1989). Speleothem U–Th dates provide minimum age estimates of a cave's dewatering, and therefore minimum ages of former base-level elevations (Ford et al., 1981). Using elevation differences between relict cave passages and modern valley bottoms, maximum incision rates (or maximum uplift rates) can be estimated.

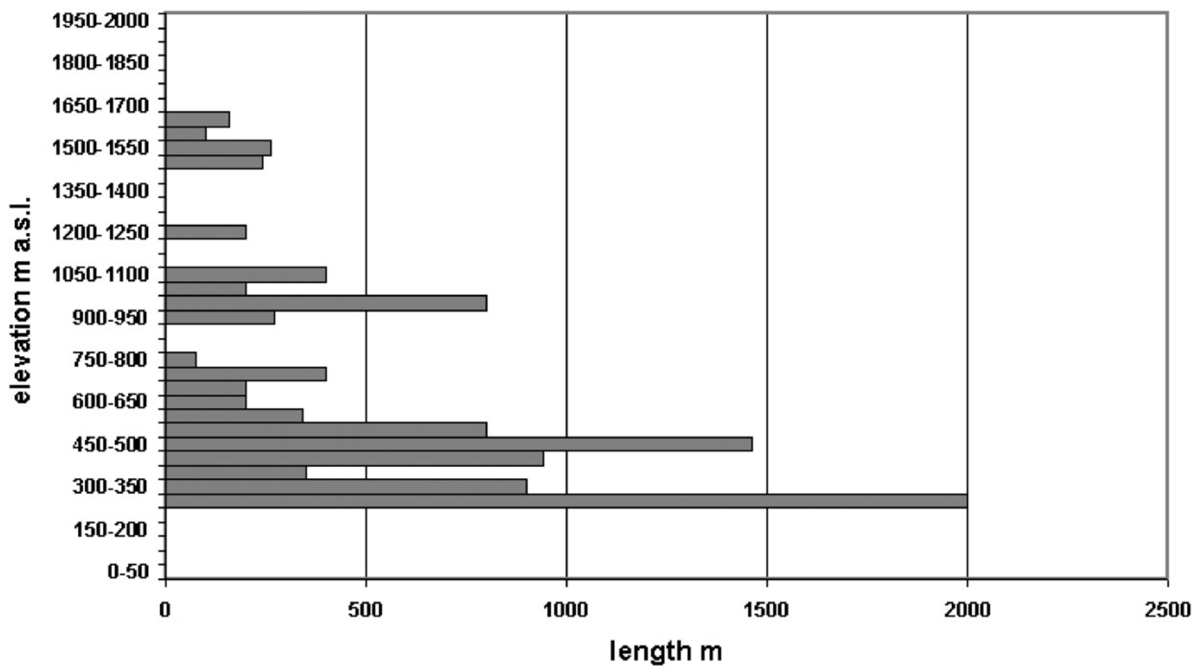

Fig. 2. Vertical distribution of phreatic and epiphreatic cave passages in Frigido Basin.

Samples of speleothems were collected for alpha spectrometric dating (Smart, 1991) from seven caves in the Alpi Apuane. Where possible and practical, speleothems representing the oldest calcite deposits in a given cave were targeted. The most significant results, in terms of uplift history, were obtained from caves located in the lower part of the Frigido drainage basin (Fig. 1), the largest karst hydrologic system of Alpi Apuane (Piccini and Pranzini, 1989, Piccini, 1994b). This system contains more than 100 caves, many of which display several generations of phreatic passage development over >1600 m of elevation. However, the best-developed level of relict phreatic caves occurs between 750 and 400 m a.s.l. (Fig. 2).

Grotta del Baccile (Fig. 3, Table 1) is one such cave. It probably acted in the past as a secondary ''vauclusian'' emergence of an underground flow route that drained to its host valley. The cave consists of two levels of conduits. These cut across the local rock structure and are connected by steep phreatic conduits. The lower level experienced extensive downcutting under vadose conditions. In the last active stage, the underground stream was fed by a sump, which is now completely filled by carbonate sands (Drysdale et al., 2001). A sample of flowstone from the upper level of this cave has been dated to $200+64/-40$ ka (Table 2).

The most intensively investigated cave in the study area is Buca dell'Onice (Fig. 4), a 150 m long segment of an ancient large phreatic tube, which opens at 573 m a.s.l. near a secondary crest of the Frigido Basin. This cave hosts a flowstone of at least 5 m thickness that was quarried in the past for ornamental stone. The top bed of the flowstone has an age exceeding the limits of alpha U-Th dating (>350 ka), whilst the core of a stalagmite growing on the flowstone dates to 290 ka (Table 2). We can thus assume that the flowstone ceased growing not much earlier than 350 ka. Assuming a typical grow-rate of 30 mm ka^{-1} (Baker and Smart, 1992, and references therin) we can infer an age of at least 500 ka for the base of the flowstone. According to these data, we can assert that Onice was active as a phreatic conduit in the Middle Pleistocene, probably before 500 ka BP.

Close to the present karst base level of the Frigido basin is the most recent generation of spring caves, which are presently evolving to vadose caves (Fig. 5). Two of these caves are still acting as overflow springs, but speleothems are already forming in the their uppermost abandoned passages. Buca del Rocciolo is an almost completely inactive cave, although during the most intense floods the lower part of the cave is sometimes water-filled. The central sections of two thick stalactites from this cave returned ages of 105 ± 10 and 90 ± 10 ka. In Buca di Renara, situated just a few tens of metres lower in the valley, similar ages were derived from two small stalagmites (see Table 2).

The speleothem radiometric ages from these four caves, which are located in the same valley, agree with the probable timing of de-watering based on their altitude and their position with respect to the present valley profile (Fig. 5). Furthermore, on the seaward slopes of Alpi Apuane, the karst base level is controlled by incision of the steep (and locally overturned) contact between carbonate rocks and the impermeable basement. Under these conditions, base-level lowering is

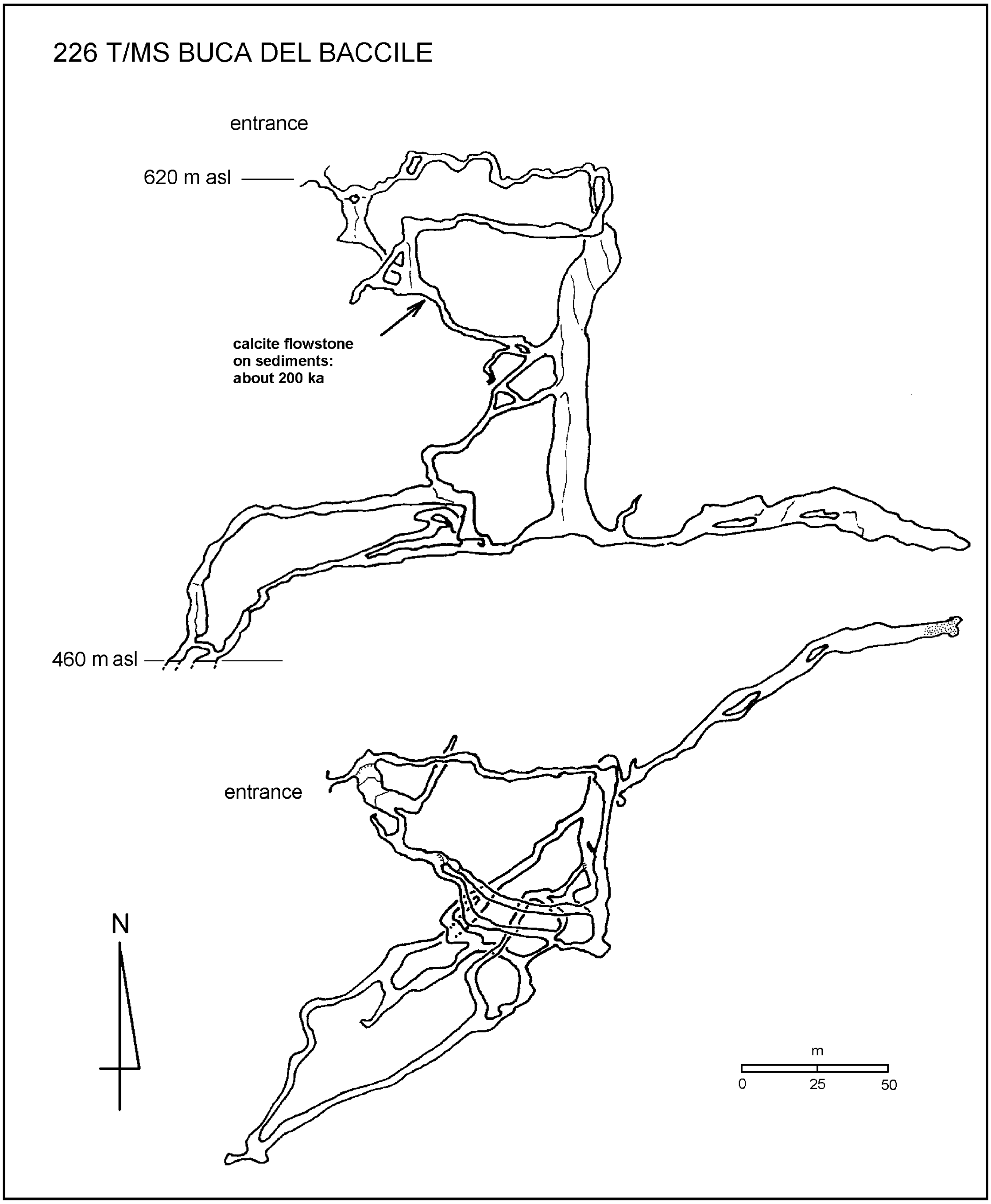

Fig. 3. Profile of Baccile cave with the location of the dated sample.

Table 1
Sample sites

Inventory number	Cave	Entrance m a.s.l.	Elevation above valley floor	Depth	Total length	Geology	Hydrogeological setting
226 MS	BUCA DEL BACCILE	655	100	160	1700	Dolomitic marble	Relict deep phreatic
334 MS	BUCA DELL'ONICE DI M. GIRELLO	573	400	35	150	Dolomitic marble	Relict phreatic
229 MS	BUCA DEL ROCCIOLO	340	40	30	400	Dolomite	Epiphreatic
228 MS	BUCA DI RENARA	305	5	19	400	Dolomite, marble	Active epiphreatic

Table 2
Radiometric (U–Th) ages of speleothem samples

Sample	Type	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Age (ka)	Error (ka)
Baccile B2	Flowstone	1.2998	0.8906	3.7	200	+65/−40
Onice 1	Stalagmite	1.0389	0.9408	1453.3	290	+85/−55
Onice 2	Stalagmite	0.8999	0.6864	307.6	130	+15/−10
Onice 3	Stalagmite	0.8754	0.9308	2348.1	>350	n.a.
Onice 8A	Flowstone	0.8727	0.6507	253.7	120	±10
Onice 8B	Flowstone	0.9401	0.8021	3326.0	185	±25
Onice 9	Stalagmite	0.9703	0.9632	563.3	400	+160/−70
Onice 20	Stalagmite	0.9625	0.9737	101.5	>350	n.a.
Rocciolo 1	Stalactite	0.9198	0.6192	22.5	105	+15/−10
Rocciolo 2	Stalagmite	0.8726	0.1330	16.3	16	±2
Rocciolo 3	Stalactite	1.0413	0.5636	8.2	90	±10
Renara 2B	Stalagmite	1.0148	0.5934	17.9	100	±10
Renara 2A	Stalagmite	1.0370	0.6201	9.6	105	±10
Renara 3	Stalagmite	0.9311	0.9269	8.1	325	+125/−60

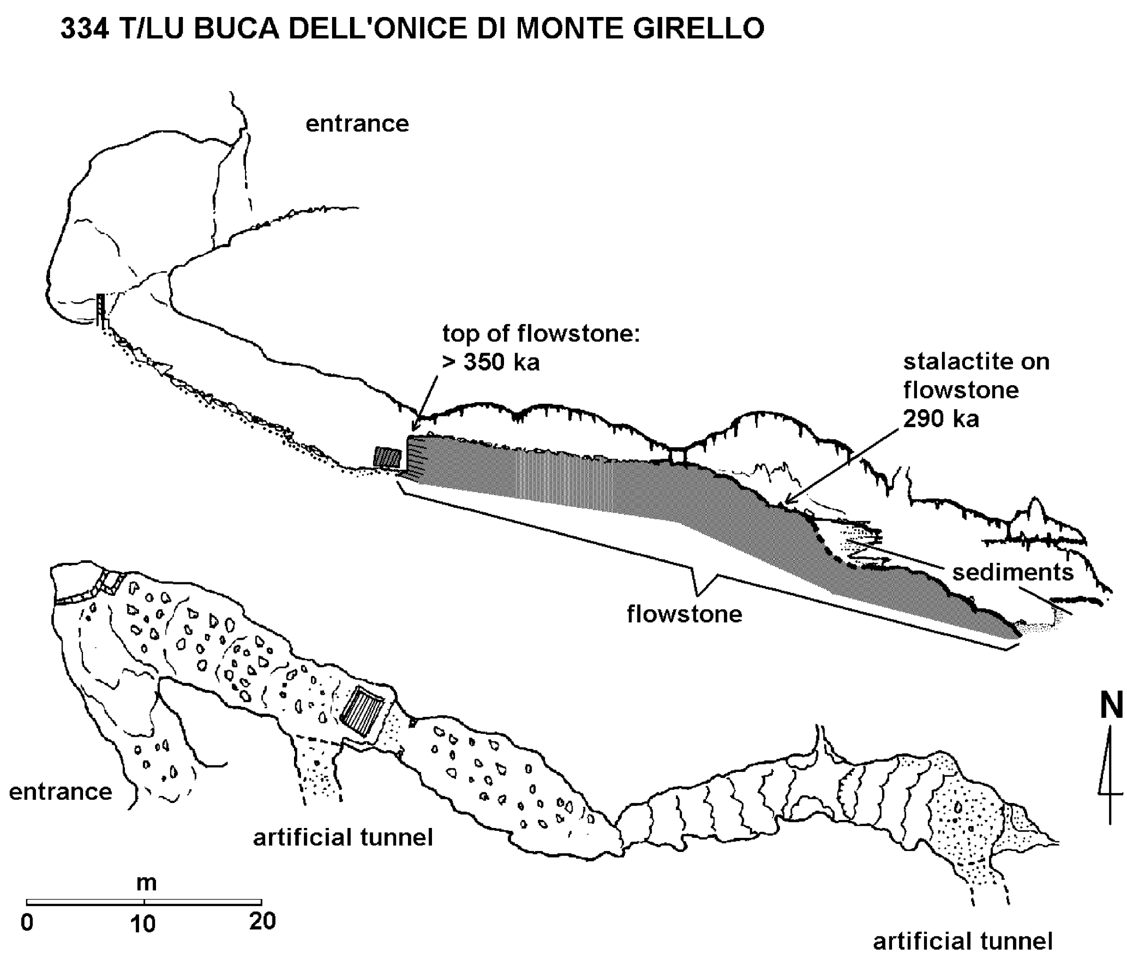

Fig. 4. Profile of Onice Cave, with the location of the dated samples.

driven by stream erosion because the contact between karst rock and basement reaches the minimum altitude only along major streams. Since in high relief regions river downcutting should quickly follow the major uplift stages of the massif (Burbank and Anderson, 2001), and assuming that the dewatering of a cave can begin only when the local stream base level is lower than the altitude of the cave, we presume that the maximum long-term incision rate of the karst base-level, based on speleothem dating, is comparable to the maximum

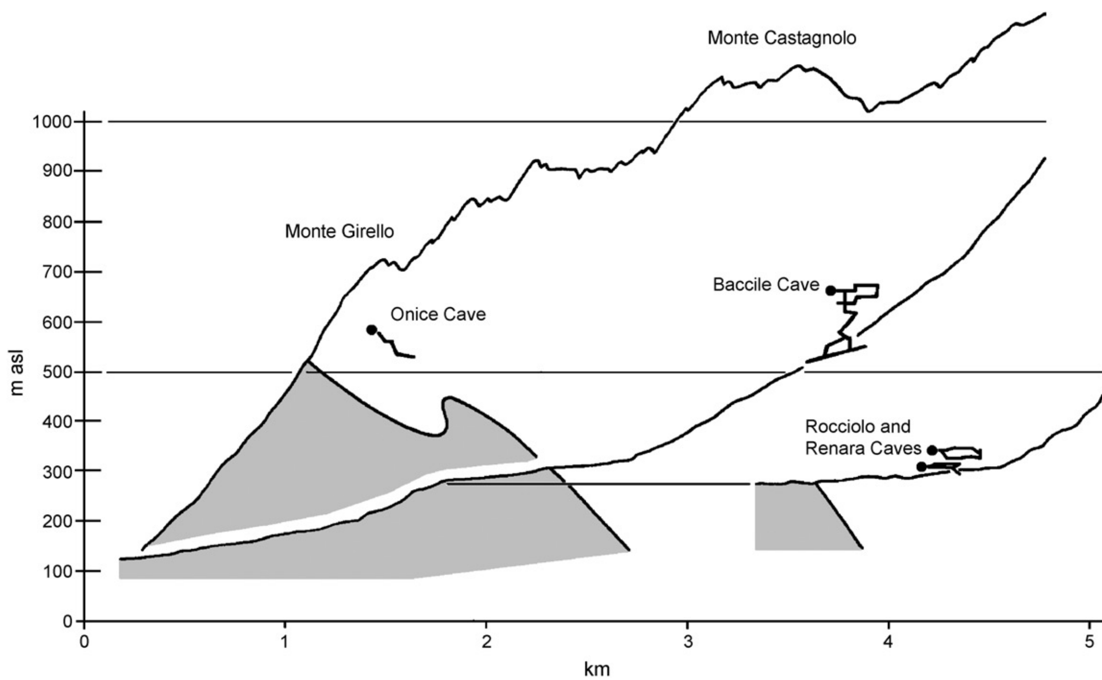

Fig. 5. Sketch profile of Frigido valley with the location of the investigated caves. Note that the incision of valley has led to an upstream retreat of hydrogeological base-level.

Table 3
Valley deepening rate obtained from speleothem dating

Cave	Entrance altitude, m asl	Sampling altitude, m asl (*a*)	Present local base level, m (*b*)	Difference ($a-b$)	Age, ka (*c*)	Deepening rate ($(a-b)/c$) mm a^{-1}
BACCILE	655	620	550	70	$200+65/-40$	0.29–0.26
ONICE	573	540	175	365	>350 (500?)	1.04–(0.73)
ROCCIOLO	340	330	300	30	105 ± 15	0.33–0.25
RENARA	305	310	300	10	105 ± 10	0.11–0.08

effective mean uplift-rate during Middle-Late Pleistocene times (Table 3).

In the Frigido basin, the time gap between the deactivation of Buca dell'Onice (>350 ka) and the present base-level caves (Renara and Rocciolo caves, ~100 ka) is at least 250 ka, but almost twice that time seems to be more realistic because the base of the Onice flowstone is probably ~500 ka or older. Since the elevation difference between the two caves is 230 m, it is possible to infer a mean maximum hydrogeologic base-level lowering of 0.9 mm a^{-1} in the case of a 250 ka age difference and about 0.6 mm a^{-1} in the more probable case of a 400 ka age difference.

These lowering rates cannot be taken as indicators of true stream incision rate, because valley deepening leads to an upstream retreat of the contact between basement and carbonate rock (see Fig. 5). In other words, local valley deepening in this case can be different (i.e. larger) from the lowering of true hydrogeological base-level. Nonetheless, comparing the altitude of speleothem samples with the local altitude of stream beds, we get an estimate of local stream deepening rate (Table 3).

5. Conclusion

The morphological features of the upper cave-levels (above 1400 m a.s.l.), which are certainly older than the main uplift stage of the Alpi Apuane, probably developed during a stage of tectonic standstill or moderate uplift-rate when the prevailing landscape was of low relief. Remnants of this landscape are currently preserved as horizontal ridges and small summit plains along the secondary crests of Alpi Apuane (Piccini, 1994a). The structural setting of the Alpi Apuane suggests that the carbonate aquifers during this stage were still dammed on the SW side by the reverse flank of impermeable basement (Fig. 6). In this hydro-geomorphic context, no significant underground flow was possible toward the seaside basins at this time.

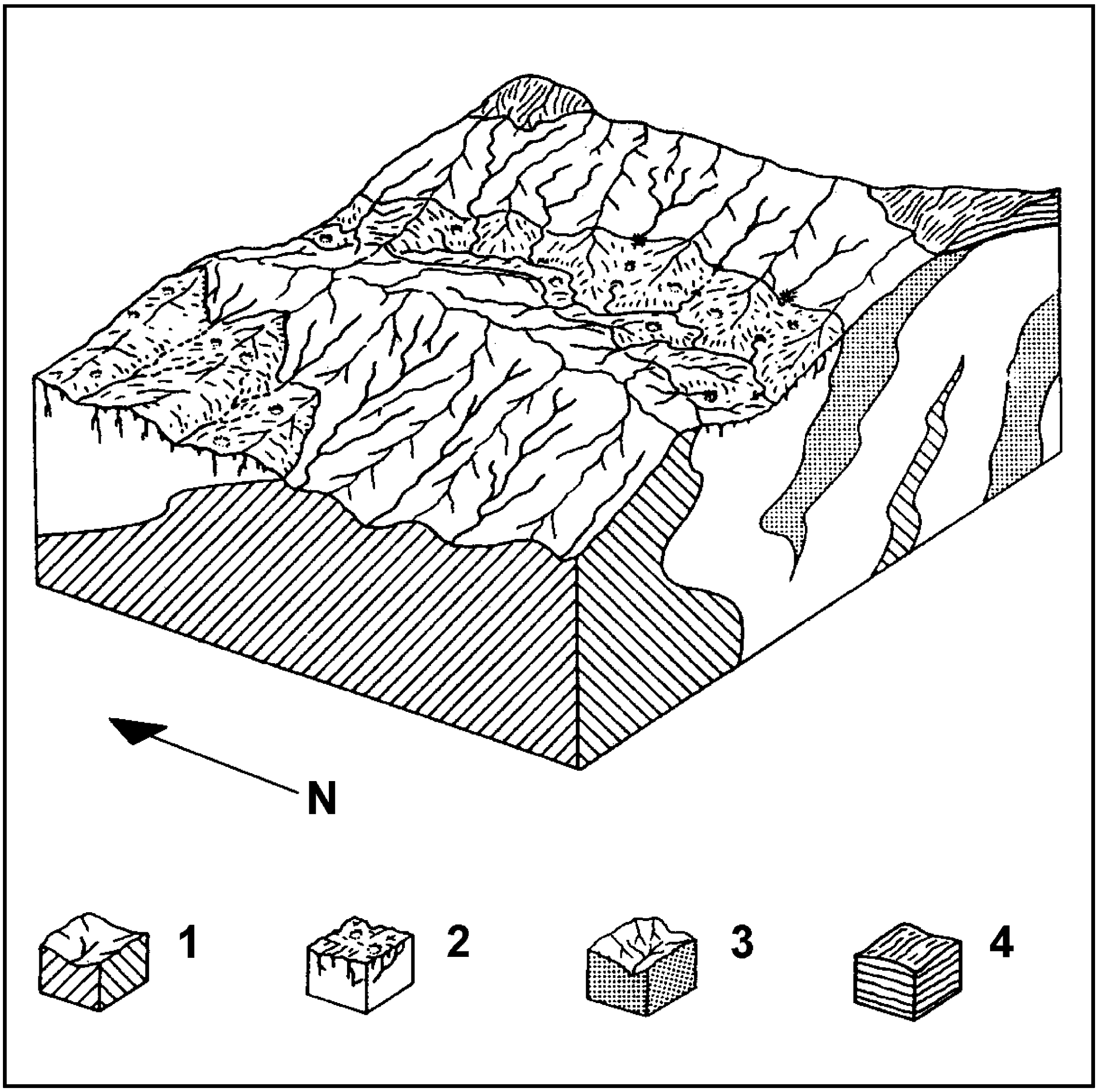

Fig. 6. Hypothetical geomorphic setting of Frigido Basin during Late Pliocene–Early Pleistocene. (1) Paleozoic basement, (2) carbonate rock, (3) pelagic to terrigenous rocks, (4) Tuscan Nappe (modified from Piccini, 1997).

This important stage of karst development can be constrained to the Late Pliocene, because it should precede or be contemporaneous with the first phase of denudation of metamorphic rocks, as suggested by sedimentological evidence in the Apuane-fed alluvial fans of the Magra and Serchio Basins (Calistri, 1974; Raggi, 1985; Bertoldi, 1988).

A significant base-level standstill is likely to have occurred during the Early Pleistocene. In this stage, we envisage the development of new karst cave levels that can be identified in the phreatic systems at altitudes of around 900 m in Frigido basin. An intense uplift of the massif during Middle–Late Pleistocene times, and subsequent incision of the basins on the seaward flank, caused the rapid lowering of the impermeable basement, which had previously dammed the overlying carbonate aquifers.

In the Frigido River basin, the age gap between the deactivation of relict phreatic caves and the present spring-caves allows us to estimate the local lowering-rate of the hydrogeologic base-level, while the elevation of caves in respect of present river bed provides a maximum stream incision rate (Table 3). Although the evolution of caves is controlled by downward migration of springs, which may not necessarily be due to local incision of the trunk valley, we can infer that the last major incision of streams in the Apuane occurred during the Middle Pleistocene. This implies that no significant uplift occurred during the Late Pleistocene. Due to the lack of datable continental deposits (e.g. stream terraces), these preliminary results provide the first chronological constraints on the geomorphic and tectonic evolution of Apuane massif during Pleistocene.

Acknowledgements

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