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Karst Geomorphology

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EVOLUTION OF KARST CAVES IN THE ALPI APUANE (ITALY): RELATIONSHIPS WITH THE MORPHOTECTONIC HISTORY

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The study of the geomorphic features of the karst caves in the Alpi Apuane can give a notable contribution to the understanding of the morphotectonic history of this part of Apennines in the Pliocene and Quaternary periods. The geomorphic analysis of cave systems and relict-caves suggests three major development phases.

The first phase, represented by relict phreatic caves at more than 1400 m a.s.l., developed in a landscape very different from the present-day one, with a base level 800-1000 m higher than now. This phase acted mainly in the M. Corchia Complex, where the occurrence of fluvial in-fills with non-metamorphic sandstone, suggests that this cave began to be formed when the Alpi Apuane were bounded on N and E by highlands of non-metamorphic rocks. Such a morphotectonic framework probably existed in the Late Pliocene, before the tectonic collapse of the intermontane basins surrounding the Alpi Apuane (Serchio and Magra basins). During this phase, a closed basin of 20-30 km^2 drained allogenic waters towards the Corchia Complex, allowing the development of a wide level with large epi-phreatic conduits.

The second and more important development phase gave rise to most of the phreatic caves, which are now located between 750 and 900 m in altitude. These caves can be related with the plain surfaces, now found at an altitude of about 900-1000 m, which can be interpreted as remnants of pediments or base-level plains, developed during an early quaternary phase of tectonic standstill.

The third phase of karst evolution was responsible for the formation of the phreatic conduits now found between 500 and 650 m a.s.l.. On the NE side of Apuane, this generation of caves is still active, while on the seaward side, the karst base level, corresponding to the main karst springs, was affected by a further lowering due to a Late Quaternary regional uplift.

KEY WORDS: Karst morphogenesis, Morphotectonics, Alpi Apuane.

INTRODUCTION

«One of the major difficulties of geomorphic interpretation is that the processes of weathering and erosion, which play such an integral part in the geomorphic evolution of a region, tend to obscure and obliterate the evidence for previous events at the Earth's surface.

In a karst region, however, the record of past events is preserved far longer and in richer details than in other continental settings, largely because these events are reflected in the pattern of subsurface features such as caves.» A.N. Palmer (1984)

In high-relief karst areas, where surface processes of moulding are very active, only caves and cave in-fills can be preserved from denudation processes for a long period. In these circumstancies a cave system acts as a high resolution «recorder» of morphotectonic and environmental changes. The effects of these variations can be observed along the vertical development of the caves, from the upper and oldest relict passages to the lower and youngest active passages.

To use a cave system as a «morphotectonic recorder», we must first recognize the effects of the passive geological factors: lithology and structural setting. This is only possible in the karst areas where a great number of caves are known. In the Alpi Apuane, where more than 1,000 caves have been explored to date, the geomorphic analysis of caves indicates that there is not a statistically significant influence of the large-scale geological structure on their geomorphic setting; in particular, the high angle of bedding planes doesn't allow the lithology to influence the vertical distribution of cave passages.

Finally, if we agree that climatic changes, whose action has been strong on surface landforms during the Quaternary, had a low effect on the pattern of caves, then we can analyse the underground systems in the attempt to reconstruct the morphotectonic history of the area.

GEOGRAPHICAL OVERVIEW

The Alpi Apuane are a small mountain range, about 50 km long and 20 km wide, located in the NW of Tuscany.

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This mountain region has a landscape very different from the typical landscape of the Northern Apennines. The alpine-like morphological framework is the result of differential erosion on the complex structural setting, made up by isoclinal folds with very steep flanks, and where the metamorphism has enhanced the lithological differences.

The ridge is NW-SE elongated and presents peaks, up to 1,947 m high, and sharpened crests with steep slopes and walls. The main watershed runs for 35 km at a mean elevation of 1,400 m.

The seaward flanks (SW) are incised by deep valleys, with secondary watersheds which lose their altitude only next to the coastal plain; the drainage pattern of the basins is dendritic to rectangular, some river captures are present in the northern side.

The NE flanks present long gentle ridges and less deep valleys. The basins are parallel and elongated towards NE with drainage patterns almost regularly dendritic. The extreme northern and southern basins have an asymmetric pattern controlled by the dome structure of the massif.

In the Alpi Apuane the effects of the last glaciation (Wurm) are notable (Federici, 1981; Braschi & *alii*, 1986). Snow-glacial landforms, such as circles and niches, are well developed in the flanks facing N and E of the highest massifs, whereas steep snow-troughs are present in the S-W sides too. Glacial and periglacial deposits occur in several zones; the largest are in the main valleys of the N side and sometimes they still exhibit end and lateral moraines.

On the carbonate outcrops, karst is often the dominant geomorphic process, and even though few large and medium-scale karst landforms are present, small-scale landforms are widely represented. In many zones, the present effect of the karst process is limited since the high local relief enhances the mechanical geomorphic processes. In the past, on the contrary, a lower relief allowed the development of a more advanced surface karst and of large cave systems.

GEOLOGICAL OVERVIEW

In the Alpi Apuane area, several tectonic units, belonging to the Tuscan and Ligurian Domains, has been identified by geologists (Carmignani & Giglia, 1984, cum bibl.) (fig. 1).

The lower units, the Apuane Unit and the Massa Unit (fig. 2), make up a metamorphic core complex exhumed during a Late Miocene extensive tectonic phase (Carmignani & Kligfield, 1990). The core complex is characterised by a green-schist facies metamorphism dated from 27 to 10 Ma (Kligfield & *alii*, 1986).

The Apuane Unit consists of a sedimentary sequence dating from Trias to Oligocene, with a metamorphic basement made up by Ordovician phillytes and porphyric vulcanites of Early Permian. The alpine-type sedimentary sequence began in the Late Permian with the deposition of a metarudite of continental environment («Verrucano») on which a carbonate shelf is found from Carnic to Sinemurian. The carbonate sequence is formed by metadolomite («Grezzoni»), dolomitic marble and marble («Marmo di

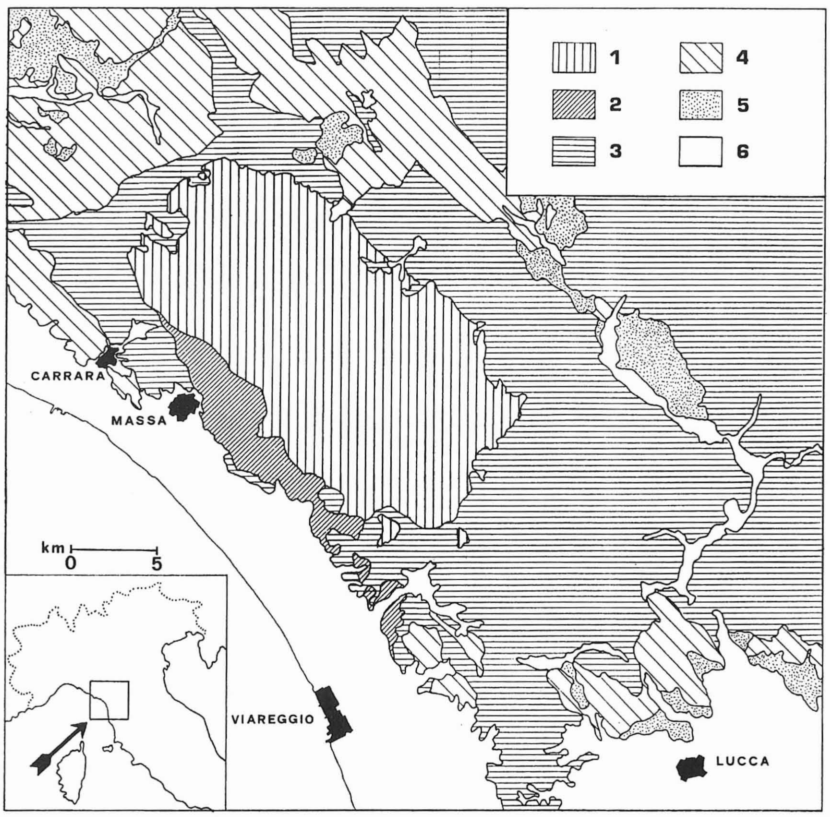

FIG. 1 - Geological sketch map of Alpi Apuane: 1) Alpi Apuane Unit; 2) Massa Unit; 3) Tuscan Nappe; 4) Ligurian Units; 5) Continental deposit of Pliocene and Quaternary; 6) Recent alluvial deposit.

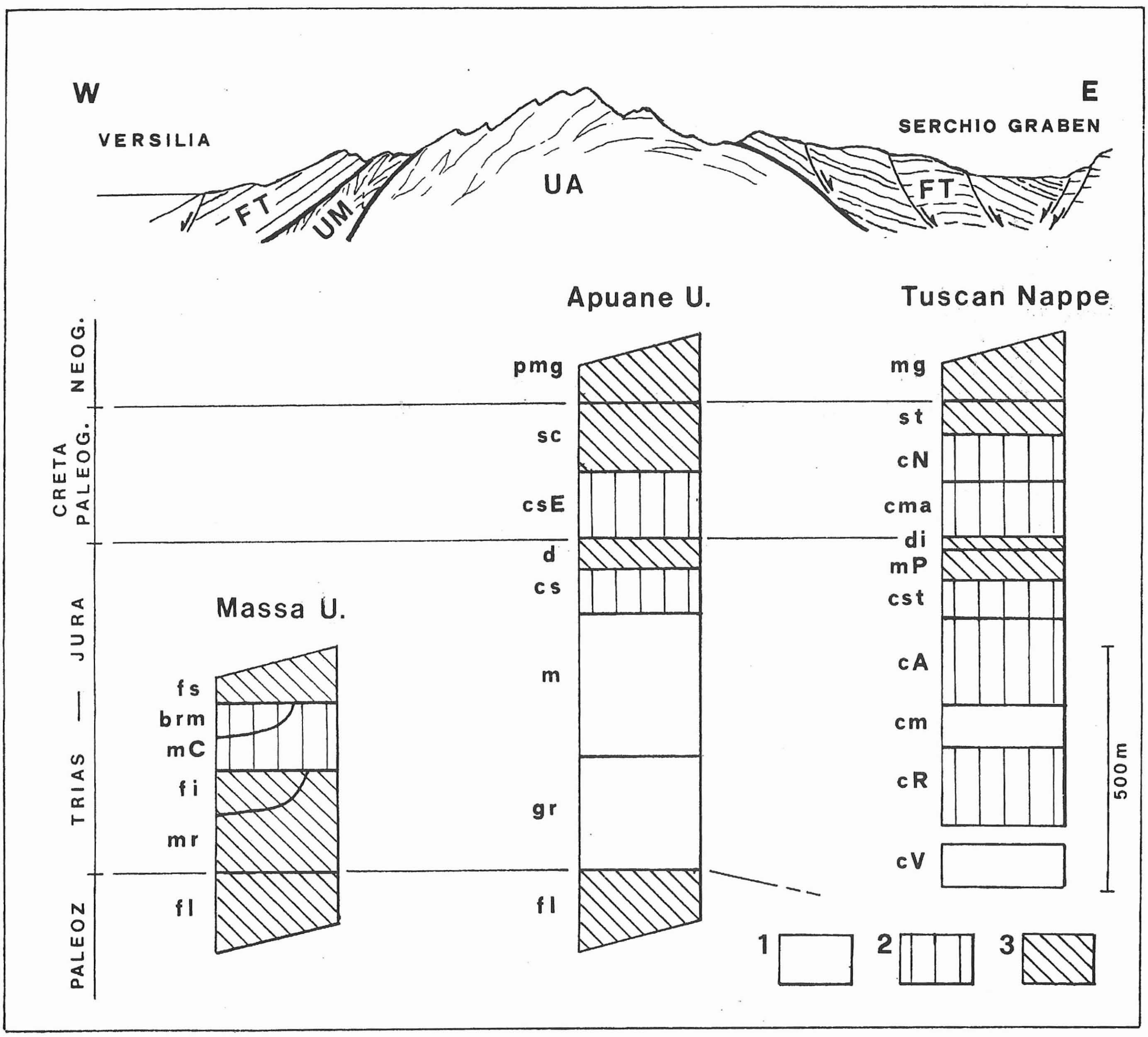

FIG. 2 - Stratigraphic and structural sketch of the main tectonic unit of the Alpi Apuane. *Massa Unit* (UM): fl = Palaeozoic basement, prevalently phyllites; mr = Metarudite; fi = Phyllite and metasandstone of the lower cycle; mC = Marble with Crinoids; brm = Marble Breccia; fs = Phyllite and metarudite of the upper cycle. *Alpi Apuane Unit* (UA): fl = Palaeozoic basement, prevalently phyllites; gr = Dolostone (Grezzoni); m = Marble and dolomitic marble; cs = Cherty limestone; d = Radiolarian Chert (Diaspri); csE = Siliceous limestone with Entrochs (Calcari Selciferi a Entrochi); sc = Seracitic schists; pmg = Metasandstone (Pseudomacigno). *Tuscan Nappe* (FT): cV = limestone breccia; cR = Rhaetavicula rich limestone and marl; cm = Massive limestone (Calcare Massiccio); cA = Angulates rich limestone; cst = Cherty limestone; mP = Posidonia rich marl (Marne a Posidonia); di = Chert (Diaspri); cma = Cherty limestone (Calcare Maiolica)»; cN = Nummuliti rich limestone (Calcareniti a Nummuliti); st = Marly limestone and shales (Scisti Policromi); mg = Turbiditic sandstone (Macigno). Development of karst: 1) High, 2) Medium 3) Absent.

Carrara»). A metamorphosed cherty limestone lies on the marbles, followed by radiolarian cherts («Diaspri»-Tithonian). The Cretacic to Paleogene sequence is made up of phyllites and calcschists on which a torbiditic metasandstone («Pseudomacigno») of Oligocene lies.

The Massa Unit has the same basement as the Apuane Unit, but the sedimentary sequence displays a higher development of low Triassic continental facies. A Noric carbonate shelf lies on the first continental cycle. Carnic phyllite and metasandstone represent a second continental cycle of deposition.

Both metamorphic units are overlapped by the Tuscan Nappe. This tectonic unit has a stratigraphic sequence similar to that of the Apuane Unit, but with a major thickness of Cretacic and Tertiary hemipelagic and torbiditic facies. In the extreme NW and SE of the Alpi Apuane, small portions of Ligurian Units (Caio Unit and Gottero Unit) occur.

The structural setting of the core-complex is characterised by large-scale isoclinal folds, piled one over the other and facing NE. Structural analysis reveals more syn-metamorphic folding phases, either compressive or extensive, with all-scales of interference figures and transposition effects.

The bare metamorphic complex is not affected by significant post-orogenic faulting, whereas an uniformly oriented system of joints can be surveyed on the whole Alpi Apuane; the main joint sets have SW-NE and E-W strikes.

The extensive tectonic phase of Late Miocene-Pliocene caused the uplift of the Apuane massif along fault systems with NW-SE and NE-SW strike. This phase migrates from SW to NE, with the formation of the Lucca and Viareggio basins first, which began in the Late Miocene, and after that with the tectonic collapse of the Sarzana and Serchio basins, in the Middle-Late Pliocene (Bartolini & *alii*, 1982; Boccaletti & *alii*, 1995; cum bibl.).

The stratigraphic sections of the lacustrine deposit of the Serchio and Sarzana basins show two main deposition cycles (Calistri, 1974; Federici, 1973; Raggi, 1985). The first is Late Pliocene-Early Pleistocene and was fed mainly from the Alpi Apuane (W), the second is Middle-Late Pleistocene and is fed from the main Apennine ridge (E). According to the sedimentary sequences of the continental basins, a possible standstill of the uplift of the Alpi Apuane, in respect to the base-level of these basins, can be identified in the Middle Pleistocene.

KARST

Surface karst

The Alpi Apuane region is one of the most important and most studied karst area in Italy, but in spite of this it doesn't exhibit a typical karst landscape.

The surface karst landforms are not so broadly developed because of the high relief and the climatic conditions, with high temperature ranges and very high rainfall (up to 3,500 mm/year), which enhance mechanical-moulding processes such as frost weathering and runoff erosion. Mechanical erosion must have been very active during the last glacial and post-glacial phases, destroying most of the karst landforms developed during pre-Wurm periods. Only in some restricted areas, with a low local relief, we can find a high density of middle-scale karst landforms, dissolution sinkholes and shafts, while small-scale solution sculptures are very diffuse on all carbonate outcrops.

The more developed karst occurs in the outcrops of marble and pure limestone, while dolostone exhibits karst landforms only in some restricted areas. The best examples of exokarst landforms are located in some high altitude areas where marble outcrops. In fact, marble has a low joint density and a high isotropy which allows the development of solution sculptures with a very low lithostructural influence.

Dolines, the most representative landforms of karst landscape, are rare (the mean density on carbonate outcrops is 0.5 dolines/km^2), and concentrated in some restricted areas where morphologic conditions favourable to their development and preservation occur. Most of them are on the NE flank, in correspondence with low gradient surfaces, and at an altitude of 1,400 to 1,700 m a.s.l. (fig. 3-a). Many dolines are found in correspondence with crests and gaps, and they were probably formed in a less steep landscape.

In the Alpi Apuane the most significant and diffuse medium-scale karst landforms are the cave entrances. Cave entrances are not strictly surface landforms because they are the external expression of deep karst processes. Dolines are always infiltration forms, while cave entrance can be infiltration or emergence forms. Many of the cave entrances are «intersection forms» (Mylroie, 1984), they represent caves cut by slope-retreat, or depressions formed by the collapse of subterranean cavities. In the mountain regions of the Alpi Apuane, most of the intersection caves has been opened by the Wurmian glaciers erosion.

The analysis of cave entrances needs some care because they are not necessarily related to the present-day landscape nor to the karst processes now in action. This is always true for the intersection caves, and for the inactive spring-caves now found much above the base level.

Cave entrances are located in the upper part of the mountains and concentrated in the zones where infiltration is very high,. Most of them are at an altitude between 1,400 and 1,600 m, with the maximum from 1,450 to 1,500 m (fig. 3-b). The higher density of cave entrances is in the altitude of 1,650-1,700 m, where 25 entrances/km^2 occur, whereas below the altitude of 1000 m, the entrance density is always lower than 1.

Most of the dolines and cave entrances are located between 1,450 and 1,600 m, where remnants of an ancient planation surface are probably preserved (Kralik & Skrivanek, 1965; Piccini, 1992, 1994-b).

A significant concentration of dolines and cave entrance is between 1,100 and 1,200 m, found in correspondence with valley-side benches, peripheral summit plain and horizontal ridges.

Endokarst

Endokarst represents one of the most important morphological features of the Alpi Apuane. Almost 1,000 caves have been explored. Of these, 40 caves have a depth of more than 300 m and 15 caves are longer than 3,000 m. The largest cave is the famous M. Corchia Complex, the longest cave in the Italy and one of the longest in the world; its depth is 1,190 m and its length is over 50 km. This large system is characterised by the presence of several inactive phreatic levels, vertically cut by percolation caves. The resulting pattern is a very complex underground system where many generation of caves are overprinted; for these reasons the Corchia Complex is probably one of the best examples of a polycyclic cave in the world.

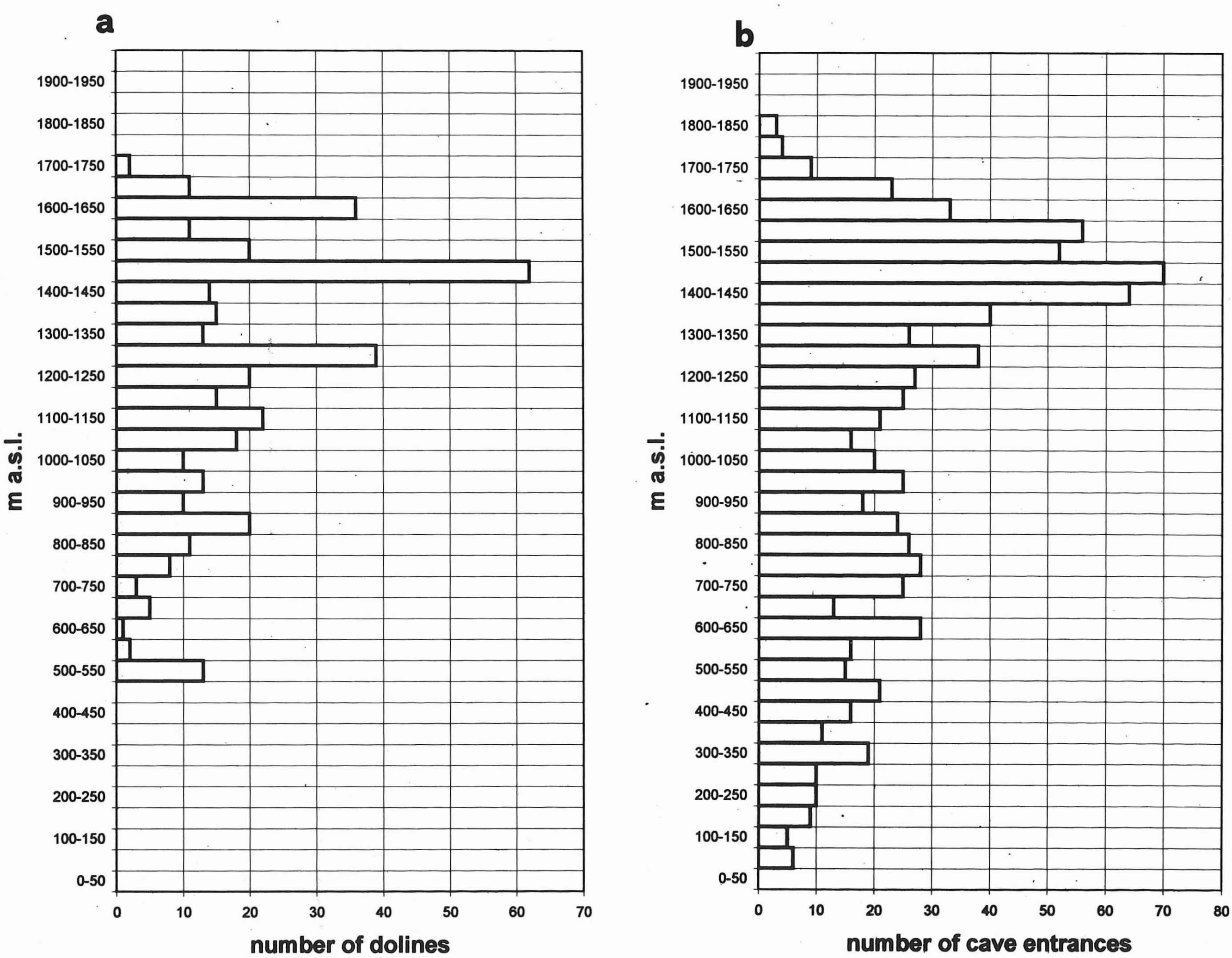

FIG. 3 - a) Vertical distribution of dolines; b) Vertical distribution of cave entrances.

The second longest cave is the Abisso Milazzo, close to the M. Corchia. The depth of this cave, is 700 m and the length is more than 8,000 m; this cave has a wide and complex phreatic network placed at an elevation of 800-850 m a.s.l.

On the NE side of M. Tambura we find two very deep caves. The deepest of these is the Abisso P. Roversi; with a depth of 1,250 m (the deepest in Italy) and a length of 4,000 m. This cave is a typical «alpine cave», mainly vadose in origin, with a pattern made up by a sequence of active shafts (one of which is more than 300 m deep). At a depth of 1,200 m, about 500 m a.s.l., small phreatic tubes are present, just 30-50 m above the present water table.

Close to the Abisso Roversi, the Abisso P. Saragato is located. In this cave, which has a depth of 1,080 m and a length of 7,000 m, a complex phreatic network occurs at an altitude of 600-700 m. In the same area the Abisso dell'Aria Ghiaccia, 800 m deep and about 7,000 m long, is found.

On the seaward side of M. Tambura we find the M. Tambura Complex, 965 m deep and 5,100 m long, while on the NE side of M. Tambura, in the glacial basin named Valle d'Arnetola, 14 caves have a depth more than 400 m on a surface of about 2 km^2, making this area one of the richest of deep caves in the world.

Another very deep cave is the Abisso Olivifer: 1,215 m deep and about 7,500 m long. This cave opens on the seaward side of the M. Grondilice. In its vertical pattern it exhibits the effects of a differential lowering of the water table, influenced by the seaward downcutting of the reverse impermeable threshold that dams the carbonate aquifers.

Most of the caves in the Alpi Apuane are percolation-vadose caves, with a vertical pattern; the deepest of them reach the piezometric surface at a depth of 400-550 m a.s.l., where small epi-phreatic tubes sometime occur. Among the largest caves, only the Corchia Complex and the Abisso Milazzo have a different pattern, with large phreatic networks organized in different levels.

Spatial distribution of caves

For a significant analysis of the spatial and vertical distribution of caves we have restricted the study to the caves with a length more than 100 m. According to our experience, this arbitrary limit permits us to exclude the small caves and the snow-shafts, abundant in mountain karren-fields. We also didn't include the caves external to the metamorphic core, because most of them are active caves located at the interface of limestone with shale, and so their altitude is determined by the structure. On the contrary, in the metamorphic complex the steep layering of the lithologic surfaces between carbonate rock and impermeable rock doesn't permit an important structural influence on the vertical distribution of caves.

The caves with a length more than 100 m number, in the metamorphic outcrop of the Alpi Apuane, about 200. Their total length is 210 km. Taking in account that the extension of the metamorphic carbonate outcrops is about 130 km^2 we obtain a mean cave density of 1.6 km/km^2. This means that the degree of knowledge of sub-surface karst is good enough to show a significant relationship with the morphotectonic evolution of the landscape.

A qualitative analysis of the cave patterns indicates the existence of three kinds of caves: «vertical simple caves», «horizontal simple caves» and «complex caves».

Simple caves are those which have experienced a monocyclic development. They can have a vertical pattern if they are percolation caves, or a horizontal pattern if they are base-level caves. The percolation caves, formed by vertical sequences of shafts, are abundant in the high infiltration areas on the NE side of the Alpi Apuane. Horizontal phreatic caves are concentrated at the base of the karst massif, and next to the present hydrogeologic base level. Many of these caves are water-filled exsurgences and can be explored only by divers.

Some caves, including the two largest caves of the Alpi Apuane (the Corchia and the Milazzo) have a complex pattern and are polycyclic in origin. These caves show an evolutionary history affected by several phreatic-erosion phases, the oldest of which have left phreatic passages at a present altitude from 1,000 up to 1,500 m. Large complex caves are, in other terms, the sum of different generations of caves.

Complex caves are rare and most of the phreatic passages are preserved as small relict caves placed in the upper part of the Alpi Apuane ridges. It is important to observe that the complex caves are concentrated along a narrow axial area which runs from NW to SE to just SW of the lineament of the highest mountain (fig. 4). Because of the ancient origin of these caves, we can speculate that this area is where carbonate rock of the metamorphic complex first outcropped.

TABLE 1 - The longest and deepest cave in the Alpi Apuane (* = cave in exploration)

Name	Altitude m a.s.l.	Depth m	Length m
1 - Complesso Rocca di Tenerano *	510	+ 210	3100
2 - Abisso dello Smilodonte	1365	– 655	2000
3 - Buca di Foce Luccica	985	– 440	2000
4 - Abisso Olivifer	1565	– 1215	7500
5 - Abisso Pannè-MC5 *	1620	– 580	3500
6 - Grotta Topolinia	350	– 50, + 190	3500
7 - Abisso P. Saragato *	1465	– 1080	7000
8 - Abisso P. Roversi	1710	– 1250	4000
9 - Abisso dell'Aria Ghiaccia *	1100	– 610, + 190	7000
10 - Complesso del M. Tambura	1400	– 964	5100
11 - Abisso O. Coltelli *	1210	– 730, + 40	2500
12 - Complesso Simi-Pelagalli-Mamma G.	1180	– 690	3500
13 - Abisso dello Gnomo *	1400	– 925	5500
14 - Abisso dei Draghi Volanti	1425	– 880	1800
15 - Complesso di Monte Pelato	1260	– 655	5900
16 - Abisso dei Fulmini + A.G. Ribaldone	1330	– 760	3000
17 - Abisso F. Milazzo *	1250	– 700	8000
18 - Complesso di M. Corchia *	1640	– 1190	52000
19 - Buca del Vento di Trimpello	635	– 45, +100	4200

EVOLUTION OF KARST

Cave levels

To find a relationship between cave morphology and landscape, we examined the vertical distribution of epi-phreatic passages in all the caves of the Alpi Apuane. It is widely accepted that phreatic passages develop below piezometric surface and that they evolve to large tubes along the water table. If the base level remains stable for a long time, cave systems form a complex and hierarchized network of epi-phreatic tubes in correspondence with the piezometric surface, just above the altitude of the spring level (Palmer, 1987, cum bibl.).

During a tectonic standstill or a low uplift-rate stage, landscape and karst systems evolve to a low-gradient setting which is emphasized by a low relief topography on the surface, and by horizontal epi-phreatic levels in the cave systems. This allows us to find a relationship between cave levels and residual low gradient surfaces.

The hypsometric analysis of Apuane reveals the existence of topographic anomalies that can be referred to the presence of peripheral summit-plains, valley-side benches and horizontal ridges. Since the complex structure of the Apuane doesn't allow a statistically significant structural control of slope profiles, we can assume that these hypsometric anomalies record some stages with low uplift-rate or tectonic standstill.

The vertical distribution of the epi-phreatic passages in all the major caves of the Alpi Apuane displays three main different generations of caves (Piccini, 1994-a) (fig. 5).

The first generation is preserved as relict caves found at an altitude of 1,600 to 1,700 m on the central part of Apuane and in the upper part of the Corchia Complex, from 1,100 to 1,450 m a.s.l. (fig 5-a). Most of them seem to be related to a general underground flow from NW to SE. From 1,100 to 1,250 m the phreatic passages in the Corchia Complex form a wide anastomosing network. Only

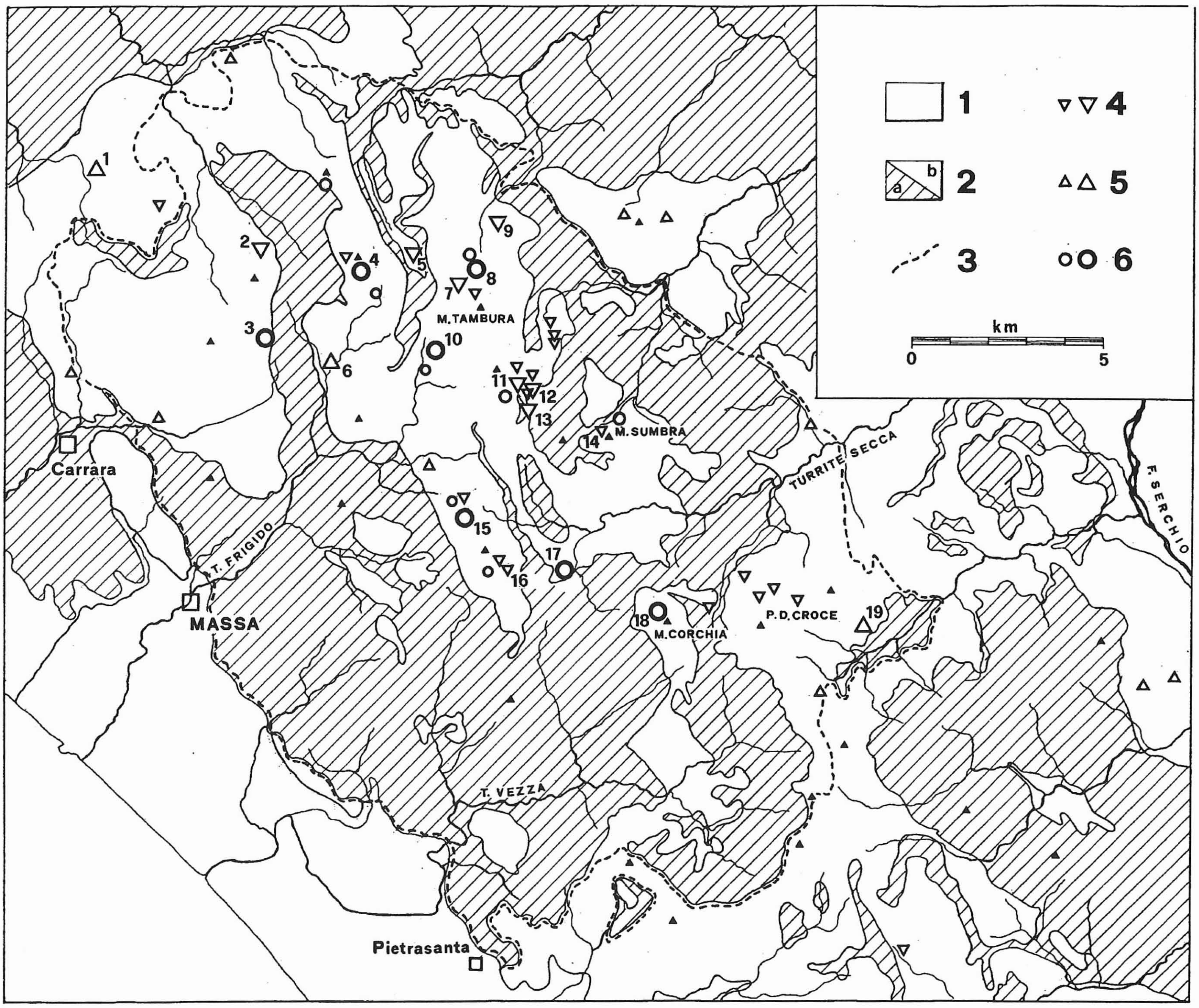

FIG. 4 - Location of the main caves of the Alpi Apuane. The numbers are those of the list in table 1. 1) Carbonate rock; 2) Non-carbonate outcrops: a - rock, b - alluvial deposits; 3) Boundaries of the metamorphic outcrop; 4) «Simple caves» with vertical pattern: length < 2,000 m, length > 2,000 m; 5) «Simple caves» with horizontal pattern: symbols as in 4; 6) «Complex caves»: symbols as in 4.

below 1,000 m we find notable phreatic caves in the other parts of the Apuane.

The second generation is the more developed and is located between 750 m to 950 m. Most of these caves are located in the seaward side of the Apuane and have phreatic passages with a direction of drainage towards SW. This generation of epi-phreatic caves signifies a stage of standstill of the base level and can be related to the low gradient surfaces and valley-side benches located between 900 and 1,050 m a.s.l.

The third generation is located at an altitude of 500 to 650 m. Phreatic tubes are largely developed at the bottom of the most important vertical caves and in correspondence with the karst springs along the border of the karst massif. This generation is still active in the N-E side of Apuane where the karst base level is at around 500 m. In the seaward side, this generation of phreatic caves is being abandoned because of the downcutting of the base level, and a new generation of epi-phreatic caves is presently developing at an elevation of 250-350 m a.s.l.. (Piccini, 1994-b).

The Corchia Complex

The Corchia Complex represents the key-area for the comprehension of the evolution of endokarst in the Alpi Apuane, for this reason this large cave-system has been accurately studied.

A morphological analysis of the whole underground complex shows the existence of four different epi-phreatic

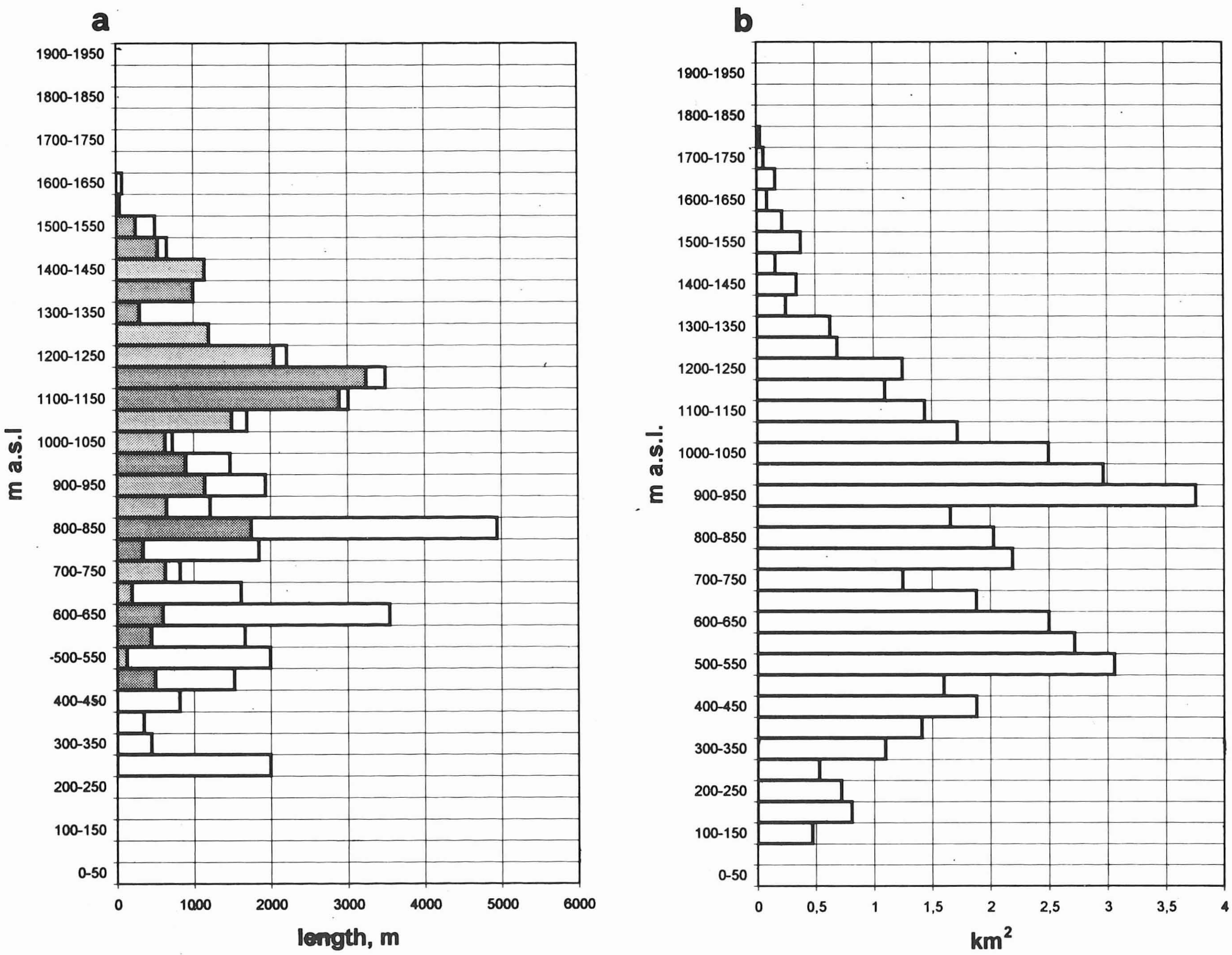

FIG. 5 - a) Vertical distribution of phreatic tubes: in dashed lines the phreatic level in the Corchia Complex; b) Vertical distribution of low-gradient surfaces (acclivity < 30%).

levels, now connected by juvenile vadose caves. These four levels are found in the followings current elevation ranges: 1,350-1,450, 1,100-1,250, 800-950, 550-650 m a.s.l. (fig. 6).

The morphological features of the higher level indicate a development under phreatic conditions with a high water discharge. Using morphometric analysis of scallops (Curl, 1974, Lauritzen, 1989) we can estimate a mean water discharge of about 1 m^3/s. The feed area should be allogenic because of the presence of alluvial filling with well-rounded pebbles of non-metamorphic carbonate sandstone. The pebbles are probably made of turbiditic formations from Ligurian Units (the bad condition of conservation of the pebbles doesn't allow accurate identification of the mother rock). This conglomerate suggests that, when these galleries were forming, an ancient river basin, placed at a present elevation of more than 1,500 m, existed and fed the palaeo-Corchia cave (Piccini, 1991).

The largest phreatic tubes of Corchia, which in some cases reach a diameter of 5-6 m, are located in the second level, at an altitude ranging from 1,000 to 1,250 m. Many of them experienced a vadose downcutting that formed deep canyons with a height of more than 50 m. The mean palaeo-discharge during the phreatic stage should have been about 2-3 m^3/s, and the feed area should have had an extension of more than 20-30 km^2

During this stage the Apuane landscape was probably similar to the present-day one in the central Apennines, where wide enclosed basins (for instance, on Sibillini M.s) are drained by underground systems. The increase of discharge from the first to the second level suggests that the enclosed basin, probably located NW of the M. Corchia, was widening in the first stages of development. This enclosed drainage pattern remained for a long time, during a period of low depression-rate of the base-level (probably due to a low uplift-rate stage or standstill), which allowed the formation and the long vadose re-arrangement of the canyons placed around 1,100 m a.s.l.

According to this evolutionary scheme, the first and the second levels can be considered as a single complex generation of caves formed under allogenic recharge.

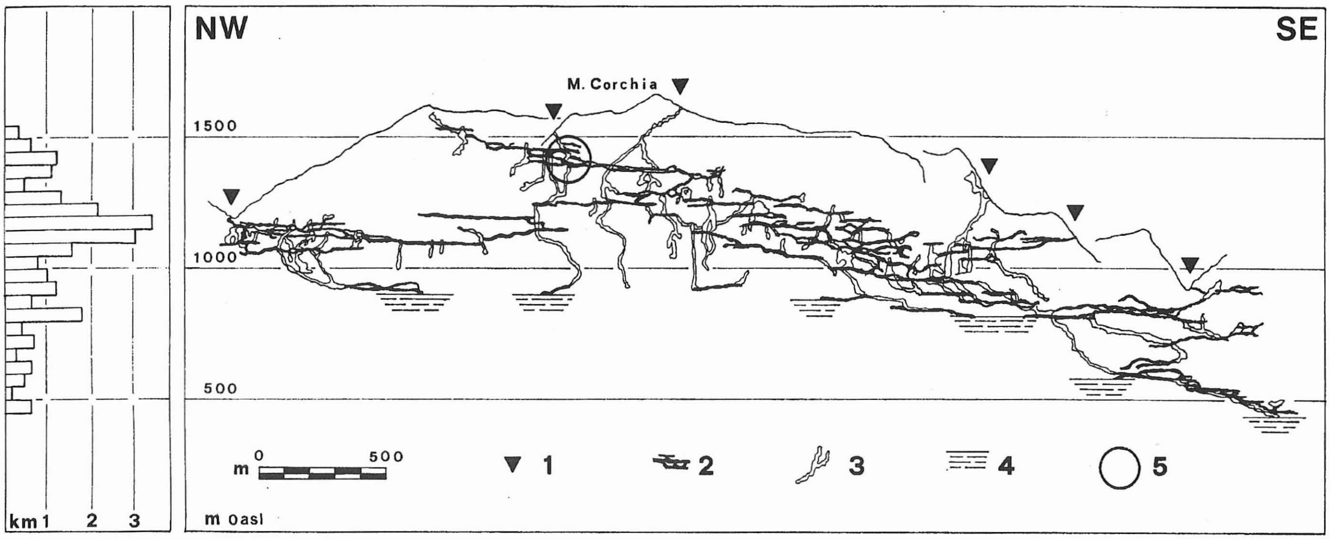

FIG. 6a - Schematic profile of Corchia Complex 1) Main entrances; 2) Phreatic or epiphreatic passages; 3) Vadose passages (shafts and high-gradient meanders); 4) Present piezometric level; 5) Location of «exotic» pebbles. Graph on the left: vertical distribution of phreatic conduits.

FIG. 6b - Evolutionary sketch table of Corchia Complex showing the possible relationships between karst level and geomorphic events.

CAVE LEVELS (m a. present s.l.)	TYPICAL SECTIONS OF PHREATIC PASSAGES	GEOMORPHIC EVENTS	RELATIVE MOVEMENT OF BASE LEVEL
I = 1350 - 1450		formation of the closed feed basin	slow lowering
II = 1100 - 1250 (phreatic tubes) = 1100 - 1150 (vadose canyons)		widening of the closed feed basin capture of the feed area by headward erosion	standstill lowering
III = 800 - 950		downcutting of the seaside impermeable thresholds	standstill rapid lowering
IV = 550 - 650		formation of the seaside benches	standstill ?
500 - 450 (active epi-phreatic)	5 m	seaside-river entrenching	rapid lowering

The uplift that affected the Apuane massif in the Late Pliocene-Early Pleistocene, could be the main cause of the progressive capture of this basin, first by underground paths towards the Versilian basin, and then towards the Garfagnana basin by the headward capture of the Turrite Secca, a stream tributary of Serchio River. The effects of the latter capture are particularly visible in the vadose passages located at an altitude of 1,000 m, where an abrupt change in the size of the canyons reveals a rapid loss of discharge.

The third level of Corchia consists of large phreatic tubes, placed around 900 m a.s.l., not entrenched under vadose conditions. The morphological features of this level reveal conditions of high variability in the water discharge. This level is still partially active in the NW part of the complex, whereas the SE part is inactive because of a diversion of the underground stream towards the lower level.

The fourth level is at an altitude of 550-560 m a.s.l., and it seems to represent a brief stage of standstill in the lowering of the base level. Currently a further level exists next to the bottom of the cave, at an altitude of 450 m. Only the upper part of this level is open to the air, while most of the conduits, from the bottom of the cave to the spring, are probably water filled.

Age of karst

Currently we have no accurate data about the age of the different developmental stages of karst in the Alpi Apuane, but we can assume that the oldest relict caves and the upper level of Corchia developed during the first denudation phases of metamorphic carbonate rock.

About the core complex, Carmignani & Kligfield (1990) suggest a tectonic exhumation by low-angle normal faults acting from Late Miocene to Middle Pliocene.

Apatite fission tracks dating of metamorphic rocks give us an initial constraint for the time of exhumation. According to the data obtained by Abbate & *alii*, (1994), 5-6 Ma ago the top of the core complex was still covered by a thickness of 3-4 km of rock. We don't know the exhumation rate of the core complex but we can suppose that it was bare no earlier than 3.5-4 Ma ago, assuming that the exhumation processes were mainly tectonic.

A second chronological constraint comes from the age of the alluvial fans in the Serchio basin, which contain pebbles of marble and other metamorphic rocks. These fans cover a lacustrine deposit of Late Pliocene (2-2.5 Ma) (Calistri, 1974; D'Amato Avanzi & Puccinelli, 1988).

According to all these chronological data, we can take 3-3.5 Ma as a reasonable age of the first outcrop of metamorphic carbonate rocks and of the oldest karst.

A minimum age can be extrapolated from dating speleothems inside the Corchia Complex. Some samples of no longer active flowstones, collected in the phreatic level at an altitude of 800 m, were analysed with U/Th obtaining an age of more than 350,000 years (Piccini, 1992). If we consider that this level is currently 300 m above the water table we can calculate the mean depression rate of the piezometric surface as 0.9 mm/y. Extrapolating from this rate, the passages 600 m above this level must have been affected by the phreatic stage no later than 1 Ma ago. This value is undoubtedly underestimated, because the morphological differences between the lower and the upper part of the Corchia Complex suggest that the latter experienced a lower mean depression-rate of the base level.

A more detailed, but more speculative, chronological scheme of the development phases of caves can be obtained by relating karst level with the generation of low gradient surfaces in the area and with the morphotectonic evolution of the intermontane basins surrounding the Alpi Apuane.

A tentative scheme of the evolution of karst with respect to the evolution of landscape and neotectonics is summarized in fig. 7. According to this scheme, the development of the Corchia Complex occurred mainly in the Late Pliocene whereas the development of the other cave systems was mainly in the Middle and Late Pleistocene.

CONCLUSIONS

According to fission tracks dating and to the age of the alluvial fans with metamorphic pebbles in the border basins of Apuane, we can presume that the first outcrop of carbonate rocks of the metamorphic complex began about 3-3.5 Ma ago. Since karst quickly affects bare carbonate rock, the first karstic phase, preserved only as relict caves, must have occurred just minimally later.

During the end of the Pliocene, karst processes must have been very active, thanks to the low relief of the landscape and the favourable climatic conditions of high rainfall and warm temperatures. In this important phase of karst development, the phreatic level at 1,100-1,250 m. of the Corchia Complex was probably formed. The morphological features of this cave-level suggest that it developed during a stage of stand-still or moderate uplift-rate. On the

age	Ma	PHREATIC CAVE LEVELS (m a. present s.l.	LANDSCAPE EVOLUTION	NEOTECTONIC
HOLOC				
PLEISTOCENE		250-300 (only on seaward side)	lowering of the seaward base level	general uplift (including intermontane basins)
		500-650	formation of benches of 600-700 m	absent or slow uplift
	1			
		800-900	capture of feed basin of Corchia	uplift
			deposition of alluvial fans in Serchio basin	
PLIOCENE	2	1000-1250 (in the Corchia Complex))	widening of the enclosed feed basin of Corchia	absent or slow uplift
		1400 - 1450 (in the Corchia Complex)		uplift
	3	1550-1650 (relict caves)	first karst landforms and caves	tectonic exhumation of metamorphic carbonate rock

FIG. 7 - Chronological correlation table between development phase of karst, landscape evolution and neotectonics.

Alpi Apuane, remnants of a low relief landscape related with this stage of low tectonic activity, are doubtfully preserved as horizontal ridges and small residual surfaces at 1,150-1,250. The structural setting of Alpi Apuane suggests that during this stage, the carbonate aquifers were still dammed on the SW side by the reverse flank of impermeable basement. In this hydrogeological context the underground drainage would be prevalently towards SE. So it is possible that during this developmental phase the Corchia acted as the main underground drainage way for a wide area of the central part of the Alpi Apuane.

The intense uplift of the massif during Early Pleistocene caused the downcutting of the streams on the seaward basins, causing the rapid lowering of the impermeable structural threshold of the carbonate aquifers. This made possible the development of new karst systems with a flow towards SW and caused the loss of alimentation to the Corchia Complex.

A new standstill of the base level probably occurred at the beginning of the Middle Pleistocene. In this stage we can imagine a new development of karst levels that can be identified in the phreatic systems at around 600 m.

The last uplift stage occurred during the Late Pleistocene-Holocene (probably in the inter Riss-Wurm). This stage also affected the Serchio basin, and for this reason only the streams on the seaward side of the Alpi Apuane are affected by a further downcutting. Here the karst systems are still evolving towards a new equilibrium stage, as indicated by the fact that the seaward karst systems have a hydraulic gradient higher than the inner systems. In the latter, the piezometric surface is very near to the elevation of springs, while in the former it is more than 200 m from the piezometric surface to the springs. This difference in hydraulic gradient between the seaward and the inner systems is causing a general underground capture towards the seaward basins.

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