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CHRONOLOGICAL ASSESSMENT AND PALAEOENVIRONMENTAL IMPLICATIONS OF THE SPELEOTHEMS FROM THE CAVES AT THE EDGE OF FUCINO PLAIN (ABRUZZO, CENTRAL ITALY)

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ABSTRACT - Radiometric and archaeologic data suggest that the speleothems in the natural caves along the carbonate rim of Fucino plain belong to four distinct depositional episodes. The oldest group of features were those from Continenza cave, yielding the U/Th age of 10.5±0.8 Kyr statistically indistinguishable from the ^{14}C reading, measured on charcoal, of 9.7±0.10 Kyr BP (calendar age: 10.9÷10.6 Kyr BP). In the same cave, within a cultural deposit of Neolithic Age, a further group of speleothems was recognized. The age of these latter, besides the archaeological evidence, has been placed from 6.9 to 6.2 Kyr BP (overall calendar time span: 7.8÷6.9 Kyr BP) by several ^{14}C datings run on strictly associated charcoal, thus in fair agreement with the mean age of 8.3±1.0 Kyr provided by U/Th dating of two speleothems. The subsequent phase of speleothems generation, recorded at Ciccio Felice cave, was mainly referred to the Iron Age on the basis of archaeologic data. Finally, a critical evaluation of historical, palaeohydrological and field data strongly support that the speleothems from Cunicoli di Claudio deposited later than the 4th-6th century.
By considering the fluctuations of the water level of the former Fucino lake it results that three out of four episodes of speleothems formation took place during significant highstands of the water level.
The flowstone dated at some 9.7±0.1 Kyr BP formed during a time span of almost steady lowstand of Fucino lake level. This flowstone could have formed during a humid climatic pulse that did not affect the Fucino lake level because of a coinciding enhanced evaporation due to some rising of the temperature.

RIASSUNTO - Gli speleotemi rinvenuti nelle grotte presenti alla base dei versanti carbonatici che circondano la Piana del Fucino si sono formati in quattro fasi. I più antichi sono stati rinvenuti nella grotta Continenza di Trasacco e hanno fornito un'età U/Th di10.5±0.8 Ka statisticamente indistinguibile dalle data ^{14}C, relativa a carboni, di 9.7÷0.10 Ka BP (età calendario 10.9 ÷ 10.6 Ka BP). Nella stessa grotta, all'interno di un livello archeologico di età neolitica, sono presenti altri speleotemi. L'età di questi é compresa tra 6.9 ÷ 6.2 Ka BP (età calendario 7.8÷6.9 Ka BP) in base ad alcune date ^{14}C su carbone, in accordo con l'età media di 8.3±1 Ka BP fornita dalla datazione U/Th di due stalattiti.
La seguente fase di deposizione di speleotemi, rinvenuta nella grotta di Ciccio Felice, é stata datata all'Età del Ferro in base a dati archeologici.
Gli speleotemi presenti nei Cunicoli di Claudio si sono deposti dopo il IV - VI secolo d.C.
Correlando le fasi di formazione degli speleotemi con le oscillazioni di livello del lago del Fucino (ora bonificato) si osserva che in tre casi su quattro gli speleotemi si sono formati quando il livello del lago era alto, quindi in condizioni climatiche umide.
Gli speleotemi datati 9.7±0.1 Ka BP si sono formati invece durante un periodo nel corso del quale il livello del Fucino era prevalentemente basso. In tale periodo deve essersi verificato un episodio di clima caldo umido che non ha prodotto un aumento di livello del lago Fucino a causa della forte evaporazione.

Key words: speleothemes, caves, paleoclimate, Fucino Plain, Central Italy.
Parole chiave: speleotemi, grotte, paleoclima, Piana del Fucino, Italia Centrale.

STRATIGRAPHICAL AND CHRONOLOGICAL DISTRIBUTION OF THE SPELEOTHEMS

A preliminary literature review and an overall survey throughout the study area were carried out to recognize and select the speleothems deposits better complying with the aims of this work. As a result, the occurrences considered were those from three natural caves previously excavated for archaeological research, say, Tronci, Ciccio Felice and Continenza, located nearby Venere dei Marsi, Avezzano and Trasacco, respectively. The recognized speleothems are limited in size and thickness, the most extended and of greater concern being those from Continenza cave. Further, because of their peculiar significance, also the speleothems grown in the Roman reclamation tunnels (hereafter referred to as Cunicoli di Claudio) were judged of interest.

TRONCI CAVE

At Tronci cave (Fig. 1) the speleothems are represented by a restricted flowstone overlying the debris fill containing artefacts assigned to the upper Paleolithic Bertonian culture by Radmilli (1981). The debris overlies lacustrine gravels laid down in the course of the dramatic highstand of the Fucino lake during the last glacial maximum. Radiometric dating, archaeological and field evidence and tephrochronological data provided a ca. 14 Kry BP *post-quem terminus* for the deposition of the flowstone. Radmilli (1981) first claimed that the age of the cultural debris can be bracketed between the *post-* and *ante-quem termini* of some 20 and 14 Kry BP, re-

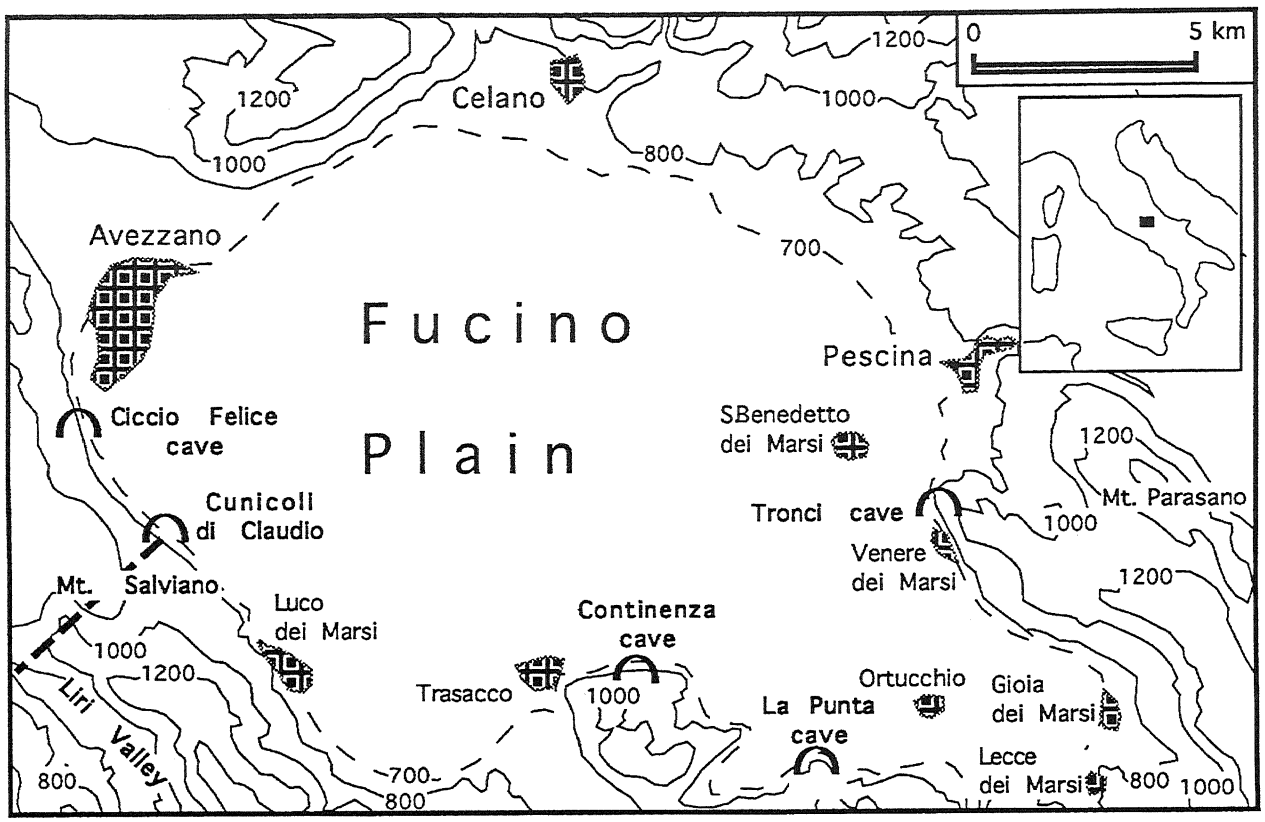

Fig. 1 - Sketch map showing the location of the natural caves and the Roman drainage tunnels discussed in the text.
Ubicazione delle grotte considerate e dei Cunicoli di Claudio.

spectively. This could imply that the infilling of the cave was over prior to the fall of a widespread level of tephra that in the nearby La Punta cave overlies a hearth ^{14}C dated at 14.6±0.8 Kry BP. Such a tephra has been referred by Narcisi (1993) to the Biancavilla Montalto explosive event of Mt. Etna dated at 14.7±0.3 Kyr BP (weighted mean of the ^{14}C readings after Delibrias *et al.*, 1972; Cortesi *et al.*, 1988). The above chronostratigraphical assessment received further support in that Giraudi (1995) recognized the tephra level at the base of the debris that seals the cave.

CONTINENZA CAVE

The stratigraphy of the sediments deposited into the Continenza cave (Fig. 1) has been previously reported in several accounts (Grifoni Cremonesi, 1985; Barra Incardona & Grifoni Cremonesi, 1989; Bevilacqua, 1994; Giraudi & Frezzotti, in press). Blocks of variable size, originated from both inside the cave and the surrounding slopes, make up most of the fill sequence.

In a reach of the cave the archaeological excavations uncovered a 5-6 cm thick flowstone, interbedded within the debris and overlying an occupation level assigned to the upper Paleolithic Bertonian culture. Further, in a small reach of the cave were also found stalactites and stalagmites representing the younger members of a suite of speleothems interbedded in an archaeologic layer of Neolithic age. Such latter features, dry and coated by a yellowish patina, are by far the most frequent speleothems. They are up to ca. 1 m in length, from 5 to 40 cm in diameter and, apart from the outer layers, show a quite compact structure. According to Grifoni Cremonesi (personal communication, 1995) their development was over in Neolithic times, say some 6.2-6.1 conventional ^{14}C Kyr BP (7.2÷6.9 calendar Kyr BP) and then were sealed by debris. Both speleothems varieties from Continenza cave were submitted to radiometric dating, as the stratigraphical and archaeological data and the overall characteristics strongly suggest that they originated during two distinct, rather limited in time, episodes. In particular the U/Th method yielded the age of 10.5±0.8 Kyr (Giraudi & Frezzotti, in press) for the flowstone resting on the Bertonian culture layer, while ^{14}C dating of charred vegetal matter from a correlated archaeological layer (Bevilacqua, 1994; Grifoni Cremonesi, personal communication, 1999) provided the age of 9.7±0.1 Kyr BP (10.9÷10.5 calendar Kyr BP). In turn, the inner part of two stalactites from the Neolithic layer was U/Th dated at 8.1±1.0 and 8.4±1.0 Kyr. Further, the charcoal found at the base of one of these latter features provided the ^{14}C conventional reading of ca. 6.9±0.1 Kyr BP (calibrated age: 7.8÷7.5 Kyr BP). It is noted that the radiometric datings are consistent with the typology of the archaeologic findings uncovered in the cultural layers that sealed the speleothems (Bevilacqua, 1994) and further, the three ages are indistinguishable at the ±1 sigma level. Finally, it is worthy of mention that in the same reach of the cave were the dated speleothems were collected are also exposed small, bright white colored stalactites and stalagmites, up to 1 and 10÷15 cm

in diameter and length, respectively, that seem very recent and still developing.

CICCIO FELICE CAVE

Radmilli (1956) first reported on two stratigraphically distinct occurrences of speleothems in a limited area of Ciccio Felice cave (Fig. 1) and, based on archaeological evidence, constrained the timing of their deposition. In particular the deepest feature, a ca. 50 cm thick flowstone, likely formed mainly during the Iron Age as it rests on debris rich of Sub-Apennine (a cultural phase of Late Bronze Age here flourished from the 13th to the 11th century BC) potsherds and is separated from the upper speleothemes by a level of soil and debris with pottery of Roman Republican age (4th÷1st century BC).

CUNICOLI DI CLAUDIO

The term Cunicoli di Claudio (Fig. 1) refers to a tunnel system implemented by the Romans during the first two centuries AD for the reclamation of the area of the ancient Fucino lake. The workings, here of great concern because of the speleothems grown onto their walls, stretch through Mt. Salviano towards the village of Capistrello in the Liri valley.

They include the main, larger in section tunnel planned for the outflowing of the lake water as well as a network of narrower analogs dug at higher elevations. Since long ago researchers of different scientific fields investigated such impressive hydraulic workings. The most up to date papers are those after Cairoli *et al.* (1994), dealing with style and age of the artefacts, Burri (1994) and Burri & Castellani (1994), reporting on topography and structure of the tunnels network, respectively, and Forti (1994), focusing on distribution and macroscopic features of the speleothems encrusting the walls of the tunnels. Obviously all speleothems from Cunicoli di Claudio originated later than the 2nd century AD. Their detailed survey revealed that besides those of larger size, also small, tubular-shaped, still developing stalactites occur, thus suggesting that following a pause, the speleothems formation was re-triggered in recent times. Forti (1994), based on the location of the flowstones into Cunicolo Maggiore (a subordinate tunnel above that used for draining the lake water) and the data from the reclamation project of the lake after Brisse & De Retrou (1883), argued that their formation required a flooding of ca. two\third of the tunnel section, this in turn implying that the water level in the tunnel could have attained some 656 m a.s.l. However, it is reasonable to infer that for the water level to rise so much, the underneath drainage tunnel must has been inactive, this resulting in an dramatic highstand of the lake water level. It is conceivable that the water flooding Cunicolo Maggiore was in part supplied by the karst hydrology through the slopes of Mt. Salviano and in part by water permeation through the western limestone rim of the lake. From the above it derives that the water level in Cunicolo Maggiore depended upon that of the lake and/or the piezometric surface of the karst water table associated to the lake. There is general consensus that the effectiveness of the Roman drainage workings declined in a few centuries for causes still under debate. Although there is not full agreement on the timing of their collapse, by coupling the evaluations after Letta (1994) and D'Amato (1980) the failure can be dated at the 4th-6th century AD. Since the Roman drainage system and the water table flow towards the Liri valley, less elevated than the bottom of Fucino lake, it derives that the water level of the ancient lake could have exceeded 656 m a.s.l., thus surpassing the maximum elevation inferred for the water level in Cunicolo Maggiore.

RELATIONSHIPS BETWEEN THE AGE OF THE SPELEOTHEMS AND THE LEVEL OF THE FORMER FUCINO LAKE

Radiometric and archaeologic data suggest that the speleothems in the natural caves along the carbonate rim of Fucino plain belong to four distinct depositional episodes. The oldest group of features were those from Continenza cave, yielding the U/Th age of 10.5±0.8 Kyr statistically indistinguishable from the ^{14}C reading, measured on charcoal, of 9.7±0.10 Kyr BP (calendar age: 10.9÷10.6 Kyr BP). In the same cave, within a cultural deposit of Neolithic Age, a further group of speleothems was recognized. The age of these latter, besides the archaeological evidence, has been placed from 6.9 to 6.2 Kyr BP (overall calendar time span: 7.8÷6.9 Kyr BP) by several ^{14}C datings run on strictly associated charcoal, thus in fair agreement with the mean age of 8.3±1.0 Kyr provided by U/Th dating of two speleothems. The subsequent phase of speleothems generation, recorded at Ciccio Felice cave, was mainly referred to the Iron Age on the basis of archaeologic data. Finally, a critical evaluation of historical, palaeohydrological and field data strongly support that the speleothems from Cunicoli di Claudio deposited later than the 4th-6th century. It is recalled that concerning the origin of the speleothems from Tronci cave only the *post-quem terminus* of ca. 14 Kyr BP is available, this precluding to ascertain whether or not they belong to one of the four depositional events above depicted..

As a whole the presented chronological data suggest that in the study area most of the speleothems from natural cavities formed during the postglacial Hypsithermal interval (Deevey & Flint, 1957), this finding being in fair agreement with the overall framework after Ford (1968) for the global speleothems distribution. The plot in Fig. 2 depicts the relationships between the origin of the speleothems and the fluctuation pattern of the level of the ancient Fucino lake (Giraudi 1998 and references therein). It appears that the deposition of the speleothems in Cunicoli di Claudio, estimated younger than 4th÷6th century AD, can reasonably match phases of lake level highstand. Some constraints on the age of their formation are provided by an up to date account (Giraudi, 1998) claiming that following the decline of the Roman drainage workings, Fucino plain was re-flooded. In fact, according to the ^{14}C readings after Galadini *et al.* (1997) and Brunamonte *et al.* (1991) the water level raised significantly at 1.45±0.1 Kyr BP (calendar age: 540-660 AD) and at 0.93±0.1 Kyr BP (calendar age: 1000÷1150 AD), respectively, as well as during the Little Ice Age (LIA). In particular both in the 17th century AD and from 1780 to the time of the final reclamation the level of Fucino lake likely exceeded that of all previous Holocene highstands. However, as the overall macroscopic features of the speleothems from Cunicoli di

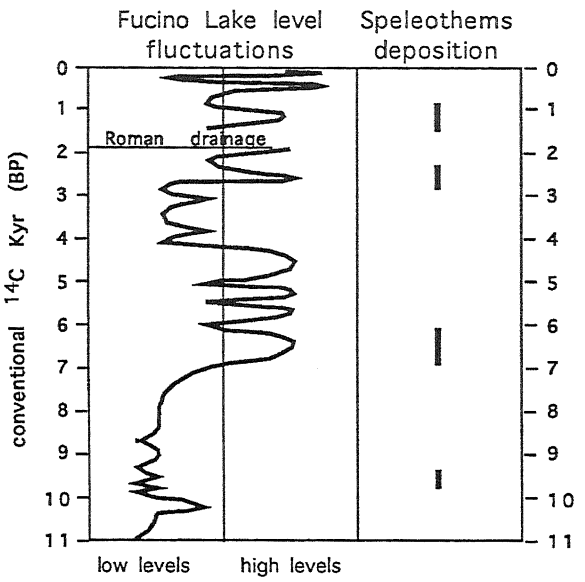

Fig. 2 - Correlation between the fluctuation pattern of the water level of Fucino lake and the timing of speleothems deposition.

Correlazione temporale tra le variazioni di livello dell'antico lago del Fucino e gli episodi di formazione degli speleotemi.

Claudio conflict with an origin so recent to match the LIA cool phases, it is inferred that their deposition paralleled one (or both) the dated level highstands above mentioned. During the Iron Age, thus while a further group of speleothems was forming, a notable highstand of Fucino lake is recorded by the evidence of flooding shown by some nearshore settlements of late Bronze Age (Radmilli, 1981).

Alike, field and radiometric data point out that the growth of the speleothems from the archaeologic deposits of Neolithic age at Continenza cave paralleled the phase of raised lake level peaking at ca. 6.5 Kyr BP. By contrast it is noted that the oldest recognized feature, viz., the flowstone overlying the upper Paleolithic layer at Continenza cave (dated at 10.5±0.8 and 9.7±0.1 Kyr with U/Th and ^{14}C methods, respectively) formed during a prolonged phase of marked lake level lowstand just interrupted by a few, feeble fluctuations. However, to establish whether or not the flowstone is coeval to one of the weak signals of increased lake level recorded through this time span is far behind the reach of the detail of the lake level variation curve.

FINAL REMARKS

At first glance the discussed chronological data point out that the speleothems deposition during the Holocene occurred discontinuously and enhanced in the Hypsithermal interval. Further, their formation shows an overall good correlation with the timing of some among the main highstands recorded for the ancient Fucino lake, viz., at 6.2÷6.9, 3.3÷2.1 Kyr BP and later on, following the IVth÷VIth century AD. Let's note that such a finding is consistent with the known forcing mechanisms for the formation of the speleothems, in that humid climatic phases are the environmental prerequisite for the lake level rising as well as speleothems deposition. In fact, the faster pedogenesis under warm and humid conditions enhances the production rate of the CO_2 available for the dissolution into the water permeating through topsoils.

In the course of their hydrologic cycle the resulting groundwater, acidic in character and rich in inorganic carbon compounds, react with the carbonate rocks of the aquifer and then deposit $CaCO_3$ while dripping into natural cavities. However, the plot in Fig. 2 also shows that some lake level highstands are not paralleled by the occurrence of coeval speleothems. By assuming a representative recognition and sampling of the speleothems throughout the study area, the apparent lackings could be accounted for by some local and transient change of the annual rain and/or temperature patterns, effective in clearing or reducing the vegetation cover. As a result, the topsoil could have been easily washed away from the slopes, this dramatically dropping the input of pedogenic CO_2 to the groundwater and therefore preventing the speleothems formation. If such an inference holds true, the speleothems could also be used as sensitive markers of the seasonality of the climatologic factors. The flowstone from Continenza cave that has been correlated to the archaeological layer dated at some 9.7±0.1 Kyr BP is particularly worth of arguing. In fact, contrasting with the origin of all the other considered features, it formed during a time span of almost steady lowstand of Fucino lake level (Fig. 2), that is under conditions apparently conflicting with the humid climatic regime accounting for the speleothems deposition. However, as a tentative explanation, it is recalled that the pattern of the water level for a lake mostly mirrors the balance between input and losses of water resulting from the amount of precipitation and the mean annual temperature, respectively. On such grounds it is conceivable that the ca. 9.7 Kyr old flowstone could have formed during a pluvial climatic pulse that did not affect the Fucino lake level because of a coinciding enhanced evaporation due to some rising of the temperature. In our knowledge data for supporting the above hypothesis are meagre, as only one account (Rossignol-Strick *et al.*, 1982) claims about a warm and humid climatic pulse following the Younger Dryas (less than some 11 Kyr BP) locally recorded until ca. 10 Kyr BP by the Mediterranean sapropel muds.

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