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LATE-GLACIAL TO HOLOCENE BIOGENIC MOONMILK AND CALCAREOUS TUFA DEPOSITS FROM CAVES IN TRENTINO (NE-ITALY): ENVIRONMENT OF PRECIPITATION AND PALEOCLIMATIC SIGNIFICANCE

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RIASSUNTO - *Tufo calcareo e latte di monte biogenico nelle grotte del Trentino durante il Tardiglaciale e l'Olocene: ambiente di formazione e significato paleoclimatico* - Il Quaternario *Italian Journal of Quaternary Sciences*, 9(2), 1996, 473-480 - In molte cavità del Trentino si rinvengono veli e colate di latte di monte biogenico e di tufo calcareo associate a speleotemi di calcite macrocristallina. Il latte di monte biogenico è più frequente in grotte che si aprono a quote tra i 1400 e i 1900-2000 m, cioé tra il limite superiore della foresta decidua e il limite superiore della vegetazione arborea, mentre il tufo calcareo è tipico delle cavità di quote medio-basse, tra i fondovalle e i 1400 m. La maggior parte delle colate è attualmente fossile e spesso mostra evidenze di erosione. Datazioni ^{14}C effettuate su tufo calcareo e latte di monte, e datazioni U/Th effettuate su speleotemi di calcite macrocristallina associati, hanno permesso di riconoscere le seguenti tre fasi deposizionali che si possono correlare a eventi climatici ed ambientali verificatisi in superficie: (1) - Tra 12.000 e 9.000 anni B.P. speleotemi macrocristallini e tufo calcareo iniziano a formarsi nelle cavità alle quote più basse. (2) - Tra 9.000 e 5.000 anni B.P. si ha il periodo di massima precipitazione di latte di monte e, probabilmente, di tufo calcareo. Questo intervallo temporale corrisponde all' *Optimum* climatico dell'Olocene, durante il quale l'aumento di temperatura e di precipitazioni favorì un'intensa pedogenesi nei suoli al di sopra delle cavità. (3) - A circa 5.000 anni B.P. si arresta la deposizione di latte di monte biogenico nelle cavità di alta quota. Questo evento, che corrisponde alla drastica riduzione nella formazione di tufo calcareo nelle cavità a quote meno elevate, è connesso ad un importante deterioramento climatico responsabile dell'erosione dei suoli in superficie.

ABSTRACT - *Late-glacial to Holocene biogenic moonmilk and calcareous tufa deposits from caves in Trentino (NE Italy): Environment of precipitation and paleoclimatic significance* - Il Quaternario *Italian Journal of Quaternary Sciences*, 9(2), 1996, 473-480 - Flowstones and coatings consisting of biogenic moonmilk and calcareous tufa are commonly associated with macrocrystalline speleothems in several caves of the Trento Province. Biogenic moonmilk is most common in caves located at middle to high elevation, from 1400 m a.s.l.up to the timberline (1900-2000 m), whereas calcareous tufa flowstones occur in caves set at low and middle elevation, from the valley bottom up to the upper limit of the deciduous forest (1400-1500 m). Most of these flowstones are fossil and exhibit evidences of erosion. ^{14}C dating on both moonmilk and calcareous tufa, and U/Th dating on associated macrocrystalline stalagmites, allowed for the recognition of three depositional phases which can be correlated with the following environmental and climatic events at the surface: (1) - Between 12,000 and 9,000 year B.P., macrocrystalline and calcareous tufa speleothems started to form in caves at low elevation. (2) - Between 9,000 and 5,000 year B.P., the maximum deposition of moonmilk flowstones and, probably, of calcareous tufa flowstones, occurred. This time span corresponds to the Holocene climatic optimum, i.e. to an increase in both temperature and precipitation that promoted intense pedogenesis and the consequent increase in carbonate dissolution above the cave and speleothem precipitation within the caves. (3) - At about 5,000 B.P. moonmilk deposition stopped in caves located at high-altitude. This event corresponds to a dramatic drop in calcareous tufa deposition in low-altitude caves and is probably related to an abrupt climatic deterioration and strong soil erosion at the surface.

Key words: Late-glacial, Holocene, speleothems, calcareous tufa, moonmilk, paleoclimate, Trentino, Northern Italy
Parole chiave: Tardiglaciale, Olocene, speleotemi, tufo calcareo, latte di monte, paleoclima, Trentino, Italia settentrionale.

1. INTRODUCTION

In several natural caves of the Trento Province (NE Italy) macrocrystalline speleothems, such as stalactites, stalagmites and flowstones composed of coarse crystalline, columnar calcite (Kendall & Broughton, 1978) are commonly associated with flowstones and veils consisting of calcareous tufa or biogenic moonmilk. Calcareous tufa and biogenic moonmilk are relatively abundant if compared to Holocene macrocrystalline speleothems, and their occurrence allows for the recognition and precise dating of the most important warm and humid events of the last 15,000 years. In this study, the distribution and environmental setting of these deposits in 9 caves which open at different altitudes from the valley bottom up to the timberline is discussed.

2. ENVIRONMENTAL SETTING AND CAVE DESCRIPTION

2.1 Cave distribution and morphology

The studied caves are set in two distinct karstic areas of Trentino, the Brenta Dolomites-Paganella morpho-unit and Valsugana (Fig. 1; Table 1), and are characterized by wide, subhorizontal and downdipping passages. A first group of caves, located within the 900 to 2400 m elevation belt ("Grotta del Torrione di Vallesinella", "Bus del Toni", "Grotta Cesare Battisti", "Grotta di Costalta", "Caverna Staloti", "Grotta di Ernesto", "Grotta della Lovara"), exhibits predominant phreatic morphologies related to a pre-Pliocene karst cycle (Bini *et al.*, 1991), which were subsequently modified in the

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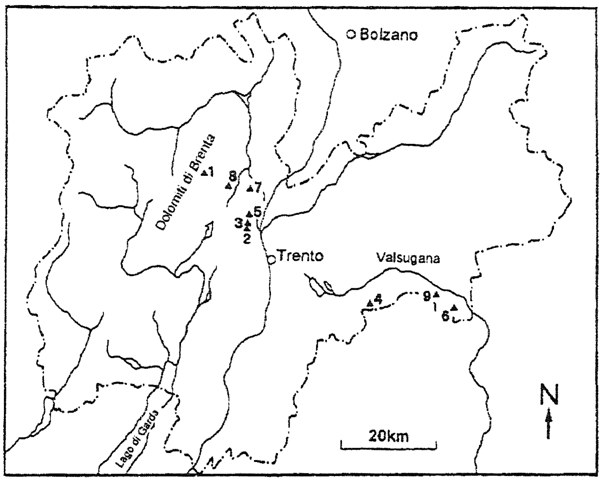

Fig. 1 - Location map of the studied caves. Numbers refers to Table 1.
Ubicazione delle cavità in studio: i numeri si riferiscono alla Tabella 1.

vadose environment during the Quaternary. This group of caves is almost fossil. Caves that open at lower elevations and at valley bottoms, in the 400 to 900 m elevation belt, are still partially active ("Grotta del Calgeron", "Bus de la Spia") and exhibit strong modifications related to Pleistocene climatic fluctuations (Conci & Galvagni, 1956; Borsato, 1995).

2.2 Host rock composition

Most of the studied caves are cut in the pure ($CaCO_3$ > 98.5%), well bedded inner carbonate platform limestones of the early Liassic *Calcari Grigi* formation (Bosellini & Broglio Loriga, 1971). Impurity content is commonly concentrated in clay layers up to 5 cm thick. However, the larger caves (Grotta del Torrione di Vallesinella, Grotta di Costalta and Grotta del Calgeron) develop in the late Carnian and Norian *Dolomia Principale* formation. This consists of well bedded, peritidal dolomites characterized by thick stromatolitic intervals and massive subtidal dolomites arranged in cycles up to 5 m thick (Bosellini & Hardie, 1988). Both peritidal and subtidal facies consist of calcic (54-56 mole % Ca) to stoichiometric, polymodal (diameters from 4 µm to >1 mm), planar to nonplanar dolomites which are characterized by heterogeneity of microstructure and geochemical parameters within single crystals (Frisia, 1995). All these characteristic favour high dissolution and erosion rates that, in some cases, are similar at those of pure limestones (Borsato & Frisia, 1996).

2.3 Vegetational zones and seeping water chemistry

Although there are some differences related to local microclimates and slope orientation, the following four major vegetational zones can be distinguished in the Brenta Dolomites-Paganella morphounit:

1 – From the valley bottom up to 1400 m a.s.l. the vegetation consists of deciduous trees such as beech (*Fagus selvatica*), oak (*Quercus ilex*), hornbeam (*Carpinus betulus*), etc. Above 900 m a.s.l. some conifers, mostly fir trees and pines, are present.

2 – At elevations higher than 1400 m a.s.l., the deciduous woodland is replaced by a conifer forest consisting of fir trees (*Abies alba, Picea excelsa*), pines and larches (*Larix decidua*). This association persists up to 1900 m a.s.l., which commonly corresponds to the elevation of the timberline.

3 – From 1900 m to 2200 m a.s.l., dwarf pine (*Pinus mugo*), rhododendron, heather (*Erica* sp.), and some solitary larches are the major components of the vegetation cover.

4 – Above 2200 m, a.s.l. there is only a scarce, rock vegetation of grass (*Carex firma, Dryas octopetala*), and succulents (*Saxifraga* sp.).

These vegetational zones strongly influence the chemistry of the seeping waters. At present, hypogean waters percolating through deciduous forest soil is supersaturated with respect to calcite (SIcc[(1)] = 0.1 to 0.7), with Total Dissolved Salts (TDS) value of 200-300 mg/l, because of the high CO_2 production in the soil. On the other hand, waters percolating through conifer forest soil cover tend to be at saturation on slightly undersaturated with respect to calcium carbonate. Above the timberline, hypogean waters are always undersaturated, with a TDS value of 110 to 140 mg/l (cfr. Table 1), and there is no deposition of speleothems.

3. BIOGENIC MOONMILK

In literature, the term moonmilk is referred to whitish, porous, plastic to powdery masses that can be found in caves, regardless of their origin and mineralogy (Hill & Forti, 1986; Fischer, 1989, Reinbacher, 1994). Several minerals such as calcite, aragonite, monohydrocalcite, magnesite, hydromagnesite, vaterite, nesquehonite, huntite and gypsum have been recognized in moonmilk deposits (Hill & Forti, 1986; Onac & Ghergari, 1993). When calcite content exceeds 90% in the solid part of the mass, the deposit is called calcite moonmilk, or mondmilch (Bernasconi, 1975; Fischer, 1989), or biogenic moonmilk (Onac & Ghergari, 1993). Biogenic moonmilk is a two-component (solid/liquid) system with a high water content (>52% in weight: Onac & Ghergari, 1993) consisting of micro- and cripto-crystalline calcite arranged in filaments, acicular crystals and rods with a diameter smaller than 1 µm (Fischer, 1989; Verrecchia & Verrecchia, 1994). Commonly, cyanobacteria (Hoeg, 1946, Williams, 1959) and heterotrophic bacteria (Williams, 1959; Bertouille, 1972; Szulc, 1994) are responsible for calcite precipitation. Subsequent aggradation and secondary calcite precipitation in pores creates needle-fiber paired rods (diameter 0,5 µm) and complex polycrystalline, dendritic aggregates (1-4 µm in diameter) (Bertouille, 1972;

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(1) SIcc = Saturation index for calcite. SIcc = log Ω. For dilute solution the saturation state (Ω) with respect to calcite is conveniently approximated as the ratio of the ion activity product (IAP), and the concentration product to the stoichiometric solubility product (Ksp): Ω = (IAP/Ksp).

Table 1 - Environmental parameters and Holocene speleothems for the 9 studied caves.
Parametri ambientali e presenza di speleotemi olocenici nelle 9 cavità studiate.

N° (°)	Cave	Entrance elevation (m a.s.l.)	Temp. (+)	Vegetational cover	Host rock (#)	Water TDS (mg/l)	Holocene speleothems (§)		
							C-M	Tuf	Mm
1.	Gr. Torr. Vallesinella	2350	1.7	Rupestrial	DP	110-140	0	0	0
2.	Bus del Toni	2032	3.1	*Pinus mugo* ass.	CG		0	0	3
3.	Grotta C. Battisti	1880	3.5	*Pinus mugo* ass.	CG	175-220	1	1	4
4.	Grotta di Costalta	1710	4.4	Conifers > deciduous	DP	195-240	0	0	2
5.	Caverna Staloti	1535	5.3	Conifers > deciduous	CG		0	0	3
6.	Grotta di Ernesto	1167	6.4	Deciduous woodland	CG	210-275	4	1	0
7.	Grotta della Lovara	985	8.5	Deciduous woodland	CG		1	3	2
8.	Bus de la Spia	610	8.1	Deciduous woodland	CG	220-300	3	3	1
9.	Gr. del Calgeron	467	8.6	Deciduous woodland	DP	200-265	3	4	0

Footnotes: (°) = Numbers refer to the map in Fig. 1. (+) = Percolating water mean annual temperature in °C. (#) = DP: Norian *Dolomia Principale* (dolomite); CG: Liassic *Calcari Grigi* (limestrones); (§) = Relative frequency: 0) absent; 1) rare; 2) common; 3) abundant; 4) very abundant; C-M: macrocrystalline calcite; Tuf: cal-careous tufa; Mm: biogenic moonmilk.

Note: (°) = Numeri riferiti alla Fig.1. (+) = Temperatura annua media dell'acqua di percolazione in °C. (#) = Litologie: DP: Dolomia Principale (Norico); CG: Calcari Grigi (Lias). (§) = Frequenza relativa degli speleotemi: 0) assente; 1) raro; 2) comune; 3) abbondante; 4) molto abbondante. C-M: calcite macrocristallina; Tuf: tufo calcareo; Mm: latte di monte biogenico.

Verrecchia & Verrecchia, 1994; Borsato, 1995). Once dehydrated, biogenic moonmilk is whitish and powdery.

In most cases, the precipitation environment of biogenic moonmilk is that of low temperature caves (*i.e.* at high elevation), where macrocrystalline calcite precipitation does not occur (Bertouille, 1972; Fischer, 1989; Maire, 1990). In these conditions, calcite precipitation is possible only through bacterial uptaking of CO_2, which induce intra- and extra-cellular precipitation (Szulc, 1994).

3.1 Distribution

Biogenic moonmilk flowstones and veils are common in caves located above 1400 m a.s.l. The thickest deposits, up to 0.4 m thick, have been observed in the caves of Brenta Dolomites-Paganella massif which open between 1600 to 2100 m a.s.l. (Borsato, 1985; 1991; 1995). In this altitudinal belt, Holocene macrocrystalline speleothems are extremely rare or absent and water is at saturation, or undersaturated with respect to calcium carbonate. At lower altitudes (caves: Bus de la Spia, 610 m a.s.l., Grotta della Lovara, 985 m a.s.l.), biogenic moonmilk is uncommon and restricted to some peculiar morphological conditions, for example along fault planes. At present, all the thickest moonmilk flowstones are starved and coated by a 1 mm thick clay layer, despite the fact that a film of water still wets them. The presence of this film allows for the conservation of the original moisture in the mass, which has a water content higher that 75% in weight.

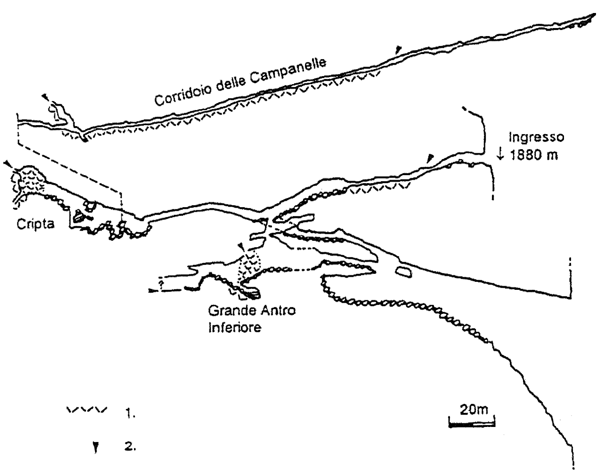

Fig. 2 - Partial and simplified cross section of Grotta Cesare Battisti (redrawn from Gruppo Grotte SAT Arco, 1989). 1) Biogenic moonmilk flowstones and draperies; 2) dripwater input.

Sezione longitudinale parziale semplificata della Grotta Cesare Battisti (dal rilievo del Gruppo Grotte SAT Arco, 1989). 1) Colate e festoni di latte di monte biogenico; 2) Venute d'acqua.

Biogenic moonmilk veils, coating fossil speleothems, bedrock and collapse blocks on the floor are common in most of the caves. Moonmilk coatings are few mm thick, but in certain cases they are thicker and form stalactites and draperies up to 5 cm long.

3.1.1 Biogenic moonmilk flowstones of Grotta Cesare Battisti

Grotta Cesare Battisti[2] developed at the top of Paganella mountain, and it is characterized by predominant subhorizontal passages (Fig. 2) cut in pre-Quaternary times (Bini *et al.*, 1991). At present, the cave is almost fossil. The few and short rivulets which are still present are characterized by discharge fluctuations between 0 and 0.5 l/min. At each water input (Entrance passageway, Corridoio delle Campanelle, Cripta and Grande Antro Inferiore), biogenic moonmilk flowstones developed. All the moonmilk flowstones are inactive and coated by a thin veil consisting of red-brownish clay. Only in some secluded pockets, moonmilk preserves the original

(2) Geographical coordinates: 46°08'45" N; 11°02'56" E; Spatial development 2342 m.

Table 2 - ^{14}C analyses on moonmilk from Grotta Cesare Battisti. All ages are uncalibrated B.P. referred to $\delta^{13}C = -25‰$ (PDB).

Datazioni ^{14}C di latte di monte della Grotta Cesare Battisti. Età B.P. non calibrate riferite a $\delta^{13}C = -25‰$ (PDB).

Sample	Laboratory number	Fraction	Position (mm from the surface)	$\delta^{13}C$ (‰PDB)	Age (years B.P.)
BAT#4b	UtC-3598	organic	-100 to -130	-24.00	5740 (±90)
BAT#4c	UtC-3599	inorganic	-100 to -130	-6.53	6850 (±90)
BAT#7b	UtC-3600	organic	-250 to -300	-17.80	6860 (±100)
BAT#7c	UtC-3601	inorganic	-250 to -300	-7.03	9850 (±100)

white colour. In the Cripta chamber, the entire S wall is covered by an up to 0.5 m thick vertical flowstone, which creates huge draperies, cone-pine-shaped stalactites and small pools. In this flowstone, a 310 mm long core was drilled manually. The deposit consists entirely of submillimetric biogenic moonmilk laminae and embedded small, angular limestone clasts.

Four AMS ^{14}C age determinations, which were car-

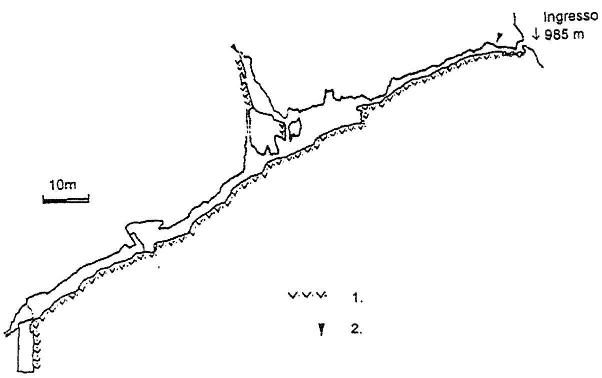

Fig. 3 - Schematic cross section of Grotta della Lovara (redrawn from Gruppo Grotte SAT Arco, 1975). 1) Calcareous tufa flowstones; 2) dripwater input.

Sezione longitudinale semplificata della Grotta della Lovara (dal rilievo del Gruppo Grotte SAT Arco, 1989). 1) Colate di tufo calcareo; 2) Venute d'acqua.

ried out by Dr. Klaas van der Borg at Faculteit der Natuur-en-Sterrenkunde, Van de Graaff Laboratorium, Utrecht University (Table 2), indicate that most of the deposition took place during the Holocene Climatic Optimum, at a mean growth rate of about 0.143 mm/year.

3.2 Mineralogy, water content and textures

Some samples taken from the core in Grotta Cesare Battisti, from Caverna Staloti and from Grotta di Costalta have been analysed (Table 3). The water content is always >75% in weight, and it is higher in flowstones that are still wet (87-93%), than in slow dripping morphologies such as stalactites and veils. X-ray analysis indicate that moonmilk consists entirely of calcite. Scanning Electron Microscope (SEM) observations of biogenic moonmilk from caves of both Brenta Dolomites-Paganella morphounit and Valsugana reveal the followings:

– Grotta Cesare Battisti samples consist entirely of

Table 3 - $CaCO_3$ content, water content and X-ray mineralogy of some biogenic moonmilk samples.

Contenuto in $CaCO_3$, in acqua e mineralogia (raggi X) di alcuni campioni di latte di monte biogenico.

Cave	Sample	Morphology	% H_2O	%$CaCO_3$	Mineralogy
Battisti	CB18a	dirty flowstone	92.7	87.3	calcite
Battisti	Cb18b	flowstone	89.3	93.8	calcite
Battisti	CB19a	flowstone	88.5	92.2	calcite
Battisti	CB19b	flowstone	87.6	94.1	calcite
Staloti	ST4a	stalactite	84.1	99.5	---
Staloti	ST4b	stalactite	81.6	99.6	---
Staloti	ST2	veil on limestone	76.8	97.1	---
Costalta	CS10	veil on drapery	93.5	---	calcite
Costalta	CS11	veil on dolomite	82.5	94.4	calcite
	Mean		**86.3**	**94.7**	

biogenic mats (Fig. 4A, B) and each single filament is about 0.02 to 0.1 µm in diameter;

– Grotta di Costalta moonmilk is composed of complex aggregates of single biogenic filaments, needle-fiber crystals, polycrystalline chains and nape aggregates (Fig. 4C, D). These morphologies are indicative of progressive aggradation, possibly triggered by weak evaporation.

4. CALCAREOUS TUFA DEPOSITS

Calcareous tufa is characteristic of areas near the entrance of many caves (Gascoyne, 1992) and forms microstratified sequences, up to 2-3 m thick in mamillary structures and rimstone dams which create pools and terraces.

Hypogean calcareous tufa consists of mm-thick laminae of porous and soft calcite exhibiting typical flow-related structures such as ripples and convolutions, which intercalate with fine detrital and/or biogenic-rich layers. The internal texture consists of white, soft, porous laminae rich in biogenic filaments and fibrous crystals alternating with brown, hardened laminae within which single crystals tend to aggrade and form polycrystalline chains and/or larger individuals (Chafetz *et al.*, 1991; Buczynski & Chafetz, 1991; Jones & Kahle, 1993; Verrecchia & Verrecchia; 1994; Borsato, 1995). Biogenic-rich laminae are usually brown-opaque under transmitted light microscope, and contain several compounds, such as humic acids (Lauritzen *et al.*, 1986) and allophane (Dziadzio *et al.*, 1993). Each couple of laminae reflects climatic cycles from annual to decennial scale (Dziadzio *et al.*, 1993; Borsato, 1995).

4.1 Distribution

Calcareous tufa deposits in Trentino are common in caves which developed below the upper limit of the deciduous forest (*i.e.* about 1400-1500 m). In most cases, calcareous tufa flowstones commenced to form from drips with discharges higher than 0.01 l/s, but characterised by strong discharge fluctuations (Borsato, 1995). For this reason, the drippings can be completely dry during some summer periods. In general, water flows from large and huge cone stalactites, up to 2 meters long and 0.5 m wide consisting of soft and porous calcite (Bus de la Spia, Grotta della Lovara, Grotta C.Battisti, Grotta di Ernesto). Less common are cylindrical-shaped stalactites with diameters ranging from 0.3 to 0.15 m (Grotta del Calgeron). The following 2 different settings have been observed:

1) *near-entrance flowstones,* which developed a few meters from the entrance and expanded inwards for tens or hundreds of meters. These are common in descending caves (Grotta della Lovara, Bus de la Spia, Grotta di Ernesto, Grotta C. Battisti) and are almost inactive.

2) *inner flowstones,* which developed from a single dripping, or spring and expanded either inwards or outwards according to the direction of dipping of the slope of the gallery. These are more common in caves located at low elevation (Grotta del Calgeron, Bus de la Spia e Grotta della Lovara) and some of them are still active.

It is possible to infer when calcareous tufa deposition at Grotta del Calgeron commenced by considering two alpha-spectrometric U/Th dates which were carried out on a 70 mm-long macrocrystalline stalagmite that grew inside a calcareous tufa pool (Borsato, 1995). The bottom of the stalagmite has a radiometric age of 13.0±3.2 ka(3), indicating that the deposition of macrocrystalline stalagmite and, probably, also of the tufa rimstone dam, started to form in this period. The top of the stalagmite has an age of 11.1±3.7 ka(3), and stopped because of the progressive rising of the tufa dam, which caused the submersion of the stalagmite. At present, the stalagmite lies 40 mm below the level of the water pool.

4.1.1 Calcareous tufa flowstone of Grotta della Lovara

Grotta della Lovara(4) developed at the top of a steep limestone cliff formed by the Calcari Grigi formation, and is characterized by the presence of a large tufa flowstone which covers the whole floor (Fig. 3). This flowstone originated from two pine-cone-shaped stalactites located 5 m inwards from the entrance. In the inner part of the cave, the flowstone is fed by several huge, porous stalactites set along the main gallery and, in the upper chamber, by a long drapery (Fig. 3). In some passages, the flowstone is eroded and it is possible to observe the following stratigraphic sequence (from the bottom to the top):

1) 100 mm – Angular and subangular autocthonous clasts (*Calcari Grigi*) and a little sandy matrix;

2) 50 mm – lithology as (1), but the space between the clasts is filled by irregularly laminated biogenic moonmilk;

3) 30 mm – Stratified, ivory-coloured biogenic moonmilk;

4) 100 mm – Stratified, whitish calcareous tufa intercalated with several mm-thick biogenic moonmilk. In the upper part of this level one sample yielded an AMS ^{14}C age (uncalibrated) of 1690±80 years for the organic fraction and of 2990±70 years for the inorganic carbonate.

5) 10 mm – Hardened, yellowish calcareous tufa.

In other sectors, the tufa flowstone lies directly on the limestone bedrock or on gravels and sands of glacial origin.

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(3) Ages corrected for the presence of detrital thorium (cfr. Schwarcz, 1980).
(4) Geographical coordinates: 46°13'07" N; 11°03'50" E; Spatial development 320 m.

4.2 Composition and textures

Calcareous tufa flowstones from Grotta del Calgeron, Grotta della Lovara and Bus de la Spia show a similar internal fabric consisting of light, soft laminae alternating with brown and harder laminae. Light, soft laminae are composed of aggregates of biogenic filaments, similar to those of biogenic moonmilk, and few microscopic rod-like crystals (Fig. 4E). In the harder laminae, bacterial filaments are almost absent, and the presence of polycrystalline needle-fiber chains and pseudo-hexagonal crystals (Fig 4F) is indicative of progressive aggradational crystallization.

Some specimens taken from the near-entrance, inactive flowstone at Bus de la Spia and from a rimstone dam at Grotta del Calgeron were analysed to determine mineralogy and water content (Table 4). The calcite content is the same as in biogenic moonmilk, whereas water content is much lower, between 20 and 30%.

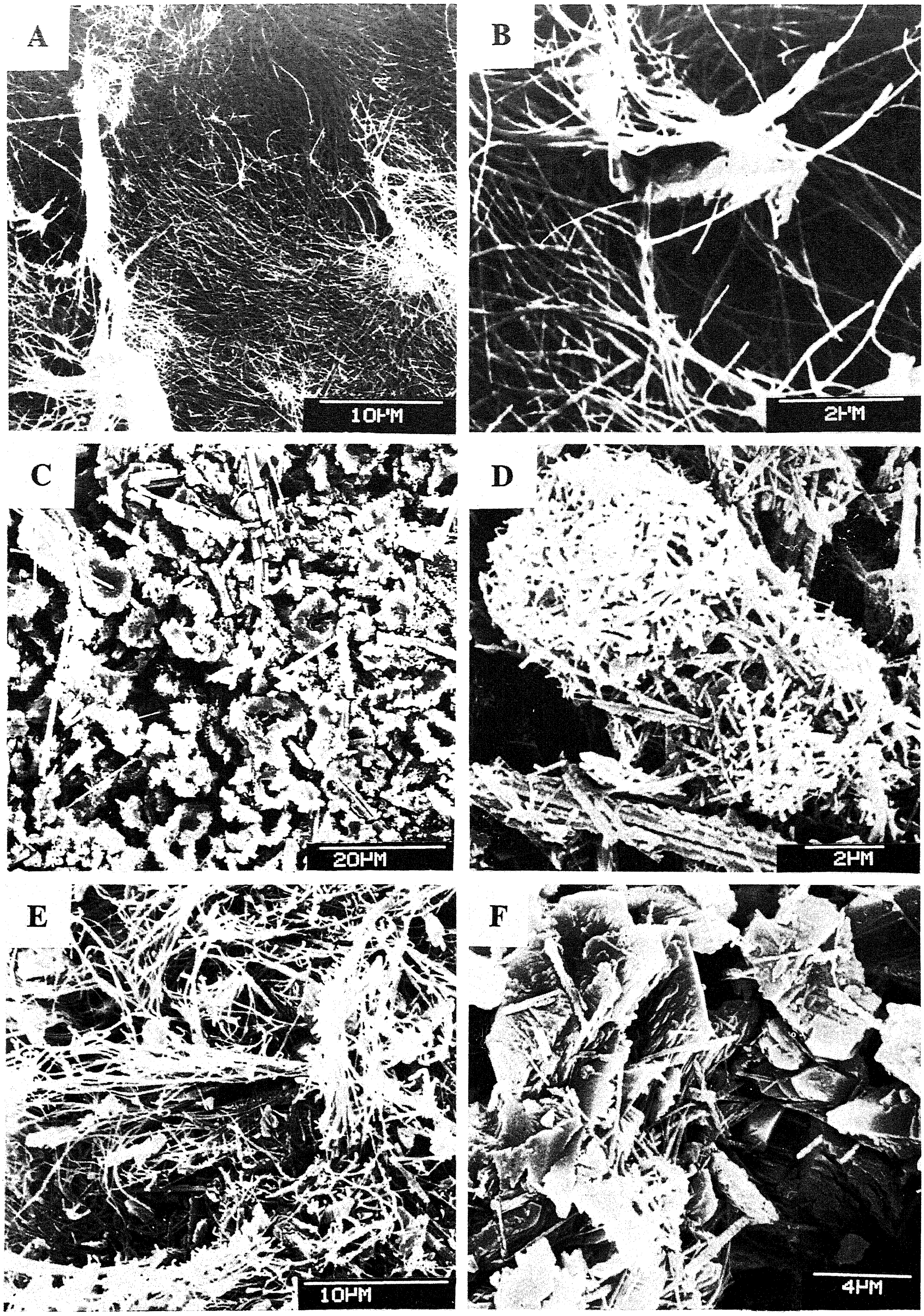
Table 4 - Porosity, $CaCO_3$ content, water content and X-ray mineralogy of some calcareous tufa samples.
Porosità, contenuto in $CaCO_3$, in acqua e mineralogia (raggi X) di alcuni campioni di tufo calcareo.

Cave	Sample	H_2O %	Porosity %	$CaCO_3$ %	Mineralogy
Calgeron	CN32a	23.6	45.5	94.6	calcite
Calgeron	CN32b	27.0	52.6	96.1	calcite
Spia	BS9nr	24.3	56.0	88.4	calcite + 5% dolomite
Spia	BS9bn	29.1	61.2	95.4	calcite
	Mean	**26.0**	**53.8**	**93.6**	

5. DISCUSSION: THE ENVIRONMENT OF PRECIPITATION AND PALEOCLIMATIC IMPLICATIONS

SEM photomicrographs indicate that moonmilk from caves in the Trento province is of biogenic origin. Moonmilk deposits mostly developed in caves located at middle and high altitudes, where the precipitation of macrocrystalline speleothems does not occur. However, small moonmilk layers and coatings can be found also in low altitude caves, although restricted to some peculiar settings, such as on fault planes, or interbedded within calcareous tufa deposits. Actually, several deposits have intermediate characteristics between pure biogenic moonmilk and pure "inorganic" tufa. This means that, in low elevation caves, biogenic moonmilk layers are diluted or interspersed within calcareous tufa or macrocrystalline speleothems. Nevertheless, it is possible to pinpoint the altitude at which biogenic moonmilk deposits are predominant over calcareous tufa flowstones. This compositional and textural boundary is set above the upper limit of the deciduous forest, between 1300 and 1500 m a.s.l. (Fig. 5). Consequently, it can be inferred that the precipitation of biogenic moonmilk took place from flows and drips of low mineralized waters (cfr. Table 1).

The environment of precipitation of calcareous tufa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10µM
4µM

is the same as that of macrocrystalline calcite, however, the formation of one fabric instead of the other is ruled by the rate of discharge. Calcareous tufa forms from higher discharge drippings and higher water supersaturation. Several deposits exhibit a variable degree of admixture between biogenic moonmilk and calcareous tufa that indicate the possibility of a gradual passage from one fabric to the other.

By taking into account the U/Th dates of Grotta del Calgeron, and the ^{14}C dates on calcareous tufa and moonmilk it is possible to reconstruct the following simple chronology of speleothems deposition:

– Between 12,000 to 9,000 B.P., macrocrystalline and calcareous tufa speleothems started to form in caves located at low elevation (Grotta del Calgeron and, possibly, Bus de la Spia). This time span corresponds to the initial dissolution and erosion of carbonate-bearing tills that covered the surface of most of the caves located below 1800 m a.s.l. (Trevisan, 1939a; 1939b; Borsato, 1995).

– Between 9,000 to 5,000 B.P. the maximum deposition of moonmilk flowstones and, probably, of calcareous tufa flowstones, occurred. In fact, if we hypothesize a constant growth rate for Grotta Cesare Battisti flowstone we can infer that moonmilk precipitation began at about 8,300±200 years B.P, and stopped at 4,940±100 years B.P (both uncalibrated ages). This period corresponds to the Holocene climatic optimum, *i.e.* to an increase in both temperature and precipitation (Crowley & North, 1991). These climatic conditions were responsible of intense pedogenesis above the caves which increased CO_2 production in the soil. As a consequence, dissolution in the soil zone increased, seeping waters were more supersaturated with respect to calcium carbonate and calcite precipitation was favoured in the caves below. The intensification of pedogenetic phenomena in this time-span is further supported by ^{14}C dates on the inorganic fractions in Grotta Cesare Battisti core, which yielded ages that are systematically older than their organic counterparts (cfr. Table 2). The age difference is 2700 years for the older samples and 1110 years for the younger samples, indicative of a progressive decrease in dead carbon contribution, *i.e.* an enhancement in soil pedogenesis that diminished the amount of fine detrital imput in the feeding water.

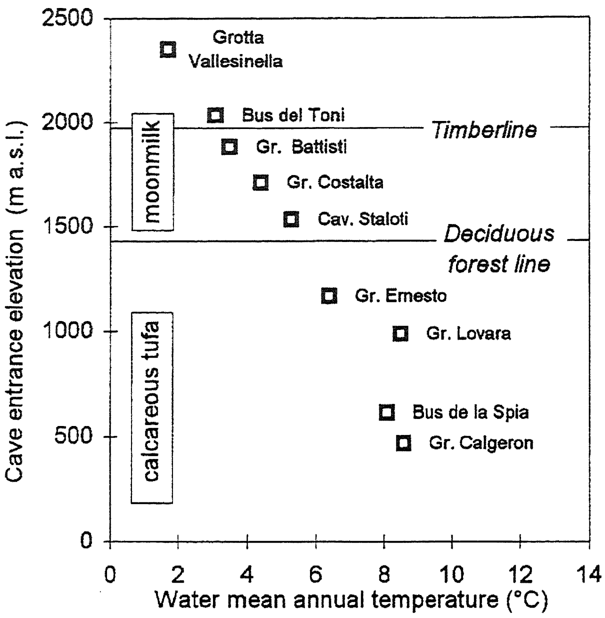

Fig. 5 - Moonmilk and calcareous tufa distribution with respect to altitude and temperature (cfr. Tab. 1).

Distribuzione di latte di monte biogenico e tufo calcareo in funzione di altitudine e temperatura (vedi Tab. 1).

– The end of moonmilk deposition at about 5,000 B.P. in caves located at high-altitude corresponds to a clear drop in calcareous tufa deposition in caves set at low altitude. This abrupt event is recorded by the clay veils coating many moonmilk and tufa flowstones, which are indicative of strong soil erosion phenomena related to a dramatic climate deterioration. The colder temperature and the clay coats destroyed the biological activity in moonmilk and strongly inhibited precipitation in the following 5,000 years.

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Fig. 4 - SEM micrographs. A) Grotta Cesare Battisti , "La Cripta" - sample CB19: moonmilk flowstone composed of a mat of biogenic filaments; B) Detail of (A): the diameter of each single filament is about 20÷100 nm. Note the polycrystalline needle-fiber individual at the centre. C) Grotta di Costalta - sample CS11: biogenic moonmilk veil on dolomitic substratum composed of single filaments, needle-fiber crystals (coupled acicular rods and polycrystalline chains) and nape aggregates. D) Grotta di Costalta - sample CS10, biogenic moonmilk veil on macrocrystalline calcite substratum: complex aggregates of needle-fiber calcite crystals and polycrystalline chains. E) Bus de la Spia - sample BS9bn, calcareous tufa flowstone, light lamina: biogenic moonmilk mat embedding polycrystalline needle-fiber crystals. F) Bus de la Spia - sample BS9nr, calcareous tufa flowstone, brown lamina: polycrystalline needle-fiber chains and pseudo-hexagonal crystals tied by few biogenic filaments.

Immagini SEM. A) Grotta Cesare Battisti presso "La Cripta" - campione CB19: colata di latte di monte biogenico composto da un feltro di filamenti di origine batterica. B) Particolare di (A): il diametro di ciascun filamento è circa 20÷100 nm. Al centro si nota un individuo aciculare-fibroso policristallino. C) Grotta di Costalta - campione CS11: latte di monte biogenico su substrato dolomitico composto da singoli filamenti, cristalli aciculari-fibrosi (bastoncini aciculari accoppiati e catene policristalline), e aggregati a coppella. D) Grotta di Costalta - campione CS10, velo di latte di monte biogenico su substrato di calcite macrocristallina: complessi aggregati di calcite aciculare-fibrosa e catene policristalline. E) Bus de la Spia - campione BS9bn, colata di tufo calcareo, lamina chiara: feltro di latte di monte biogenico che ingloba cristalli aciculari-fibrosi. F) Bus de la Spia - campione BS9nr, colata di tufo calcareo, lamina scura: catene policristalline aciculari-fibrose e cristalli pseudo-esagonali legati da rari e sottili filamenti biogenici.

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