Geogr. Fis. Dinam. Quat.
36 (2013), 259-266, 5 figg.

DOI 10.4461/GFDQ.2013.36.21

GIANDOMENICO FUBELLI (*), FRANCESCO DRAMIS (*), GILBERTO CALDERONI (**),
GIUSEPPE CILLA (***), MARCO MATERAZZI (****), ILARIA MAZZINI (*)
& MICHELE SOLIGO (*)

HOLOCENE AGGRADATION/EROSION OF A TUFA DAM AT TRIPONZO (CENTRAL ITALY)

ABSTRACT: FUBELLI G., DRAMIS F., CALDERONI G., CILLA G., MATERAZZI M., MAZZINI I. & SOLIGO M., *Holocene aggradation/erosion of a tufa at Triponzo (Central Italy)*. (IT ISSN 0391-9838, 2013).

The ^{14}C dating of organic-rich layers from the backfill sequences of the Triponzo village tufa dam (Tiber River basin) allows us to outline the Holocene aggradation/erosion stages of fluvial tufa in Central Italy. Here, the deposition of tufa first occurred prior to 8240 ± 75 ^{14}C yr BP (7480-7070 cal bC) and continued, even if with different rates, giving rise to a lacustrine/swampy basin upstream. Since 3760 ± 60 ^{14}C yr BP (2350-2010 cal bC) a sequence of alternating periods of dam erosion and aggradation occurred. After 2825 ± 60 ^{14}C yr BP (1160-830 cal bC) fluvial incision eventually cut the dam down to the present valley bottom, being only interrupted by a short-lived phase of dam aggradation which caused the formation of a strath terraces covered with gravels and tufa sands. A comparable evolution pattern is shown by other tufa dams in Central Italy. This paper deals with the control factors of tufa deposition/erosion during the Holocene with a particular reference to the role of climate changes.

KEY WORDS: Tufa, Holocene, Palaeoclimate, Central Italy.

RIASSUNTO: FUBELLI G., DRAMIS F., CALDERONI G., CILLA G., MATERAZZI M., MAZZINI I. & SOLIGO M., *Erosione e deposizione di travertino fluviale nel corso dell'Olocene: la diga di Triponzo (Italia Centrale)*. (IT ISSN 0391-9838, 2013).

La datazione ^{14}C di livelli organici contenuti nella sequenza sedimentaria depositatasi a monte della diga di travertino di Triponzo (bacino del Fiume Tevere) consente di definire le fasi oloceniche di aggradazione/erosione del travertino fluviale in Italia Centrale. La deposizione di travertino è qui iniziata prima di 8240 ± 75 ^{14}C yr BP (7480-7070 cal bC) ed è proseguita, anche se con tassi differenti, dando origine, verso monte, a un bacino lacustre/palustre. A partire da circa 3760 ± 60 ^{14}C yr BP (2350-2010 cal bC) ha fatto seguito una serie di alterne fasi di erosione e aggradazione della diga. Dopo 2825 ± 60 ^{14}C yr BP (1160-830 cal bC), il fiume ha finalmente inciso la diga fino al fondovalle attuale con l'interruzione di due brevi fasi di aggradazione che hanno causato la formazione di due terrazzi di erosione laterale, il più alto dei quali ricoperto di ghiaie calcaree e sabbia di travertino. Una storia evolutiva comparabile è mostrata da altre dighe di travertino dell'Italia Centrale. Questo lavoro prende in considerazione i fattori che hanno controllato i processi di erosione e deposizione del travertino nel corso dell'Olocene con particolare riferimento al ruolo dei cambiamenti climatici.

TERMINI CHIAVE: Travertino, Olocene, Palaeoclima, Italia Centrale.

INTRODUCTION

The term «tufa» (or freshwater travertine) is used in scientific literature to describe carbonate deposits precipitated from fresh waters around springs and along watercourses in correspondence with breaks of river profiles where they build up dams, or in swamps and lakes (Julia, 1983). A common element for tufa deposits is the presence of a «skeleton» made up of remnants of vegetal organisms such as mosses and algae (blue-green algae and bryophitae) which, through respiration and photosynthetic processes, contribute to induce $CaCO_3$ precipitation (Hynes, 1978). From a sedimentological point of view, tufa deposits are made up of alternances of massive phytohermal facies (directly resulting from in situ precipitation of $CaCO_3$) and layered phytoclastic facies (mostly made up of tufa sands and gravels which derive from the dismantling of phytohermal bodies) and form onward and upward prograding systems (Pedley, 1990).

The most frequent location of tufa is in their mountain sector of the river catchments, not too far from the springs. Thick bodies of phytohermal facies are often formed in correspondence with stream waterfalls and knickpoints, damming the valley and giving rise to swamps

---

(*) *Dipartimento di Scienze, Roma Tre University*, fubelli@uniroma3.it; dramis@uniroma3.it; soligo@uniroma3.it; ilaria.mazzini@igag.cnr.it

(**) *Dipartimento di Scienze della Terra, University of Rome «La Sapienza»*, gilberto.calderoni@uniroma1.it

(***) *Consultant geologist*, cillagiu@libero.it

(****) *Scuola di Scienze, University of Camerino*, marco.materazzi@unicam.it

or small lakes upstream, where clayey sediments and tufa sands with alternating peaty layers are deposited (Pentecost, 2005).

Investigation carried throughout Europe and the circum-Mediterranean area indicates that widespread deposition of tufa started in the early Holocene and declined or ceased at all in the late Holocene (Goudie & *alii*, 1993). Phases of tufa aggradation/erosion also characterized earlier Quaternary times (Preece & *alii*, 1986; Frank & *alii*, 2000; Soligo & *alii*, 2002; Dramis & *alii*, 2008).

Concerning the tufa deposition/erosion controls, there is general agreement in referring the aggradation of dams to climatic causes: in particular, warm and wet climates are believed to trigger and enhance tufa deposition due to the rise of biogenic CO_2 levels in top soils (Atkinson, 1977; Brook & *alii*, 1983) which, in turn, boosts the rates of limestone dissolution. By reverse, cold climates would be responsible for reducing tufa deposition rates, thus inducing erosion of dams (Vaudour, 1986; Pentecost, 2005).

More controversial is the interpretation of the decline of tufa deposition during the late Holocene (Goudie & *alii*, 1993). Two main explanatory models have been proposed: a «climatic» model, emphasizing the influence of climatic induced stream incision and related lowering of water tables (Preece & *alii*, 1986), and a «human impact» model (Nicod, 1986; Goudie & *alii*, 1993), stressing the effects of man-made forest clearance and related drop of CO_2 levels in soils and ground water, changes in stream hydrology and increase of water turbidity.

An additional explanatory model for tufa aggradation/erosion making reference to the influence of climate changes (Dramis & *alii*, 1999) is based on the reverse thermal gradients between the ground surface and the deep limestone aquifers induced by surface temperature changes and the poor thermal conductivity of bedrock (Vasseur & *alii*, 1983). In the occasion of major climatic changes to warmer conditions, such as that occurred at the Pleistocene-Holocene transition (Dansgaard & *alii*, 1989), ground water percolating through progressively colder layers would become more and more enriched in dissolved $CaCO_3$ (Schoeller, 1962; Thrailkill, 1968). At the emergence of spring waters, higher air temperatures would induce $CaCO_3$ oversaturation, tufa precipitation and damming at stream waterfalls or knickpoints. The aggradation of tufa dams could last over a long time, until the thermal disturbance in the ground is exhausted. Opposite effects, that is $CaCO_3$ deposition in the upper bedrock layers and the emergence of undersaturated spring waters should be expected at the onset of a major climatic change towards cold conditions.

To verify the effects of the Holocene climate changes on the deposition/erosion stages of tufa, a detailed geomorphological-stratigraphical analysis of a tufa dam and backfill deposits built up across the Nera River (Tiber River basin, Central Italy) at the village of Triponzo has been carried out (fig. 1). This paper illustrates the resulting investigation data, comparing them with those available for other tufa sites of Central Italy.

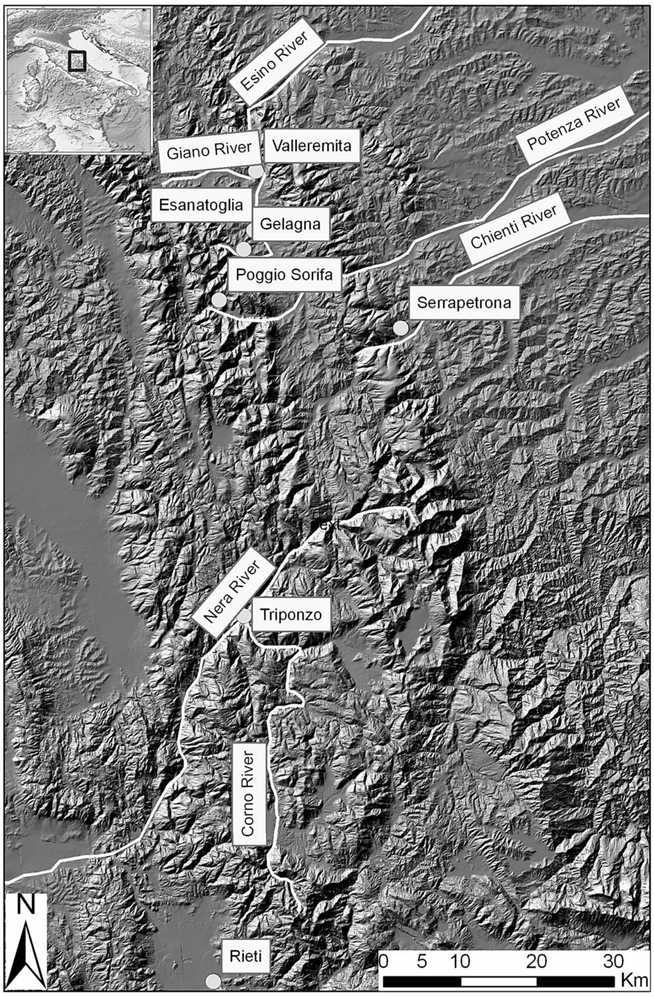

FIG. 1 - Location map of the study area showing the localities cited in the text.

THE TRIPONZO VILLAGE TUFA DAM

The Triponzo village tufa dam (figs. 2 and 3) has grown up by ca. 53 m (from 367 to 420 m a.s.l.) across the Nera River, immediately downstream of the confluence with the Corno River, over a knickpoint caused by a lithology change from limestone to marls.

Due to the river damming, a vast swampy-lacustrine basin formed, branching into the Corno and Nera valleys over a distance of some kilometers upstream. The tufa dam is presently incised by the Nera River down to the underlying bedrock. The Corno River is fed by high discharge springs a few kilometers upstream from the dam.

The Nera River catchment includes a mountain area (Sibillini Mts.) with altitudes exceeding 2000 m a.s.l. (2478 m a.s.l at Mt. Vettore), mostly carved in limestone (Umbria-Marche succession; Bigi & *alii*, 1992). The climate is temperate with mean annual air temperatures ranging between 14 and 5 °C, and annual rainfall from 800 to 1500 mm (Touring Club Italiano, 1986).

FIG. 2 - The Triponzo tufa dam deeply incised by the Nera River.

A first description and ^{14}C dating of the Triponzo dam and backfill sequence was provided by Vinken (1968) who showed that tufa aggradation occurred at least between 8240 ± 75 ^{14}C yr BP (7480-7070 cal bC) and 3085 ± 75 ^{14}C yr BP (1510-1120 cal bC). According to the same author, a phase of dam erosion occurred around 4120 ± 85 ^{14}C yr BP (2890-2480 cal bC), followed by further phase of tufa aggradation («*younger travertine*»).

FIG. 3 - Phyto-hermal tufa on the right side of the Nera River valley at Triponzo.

A more recent geo-archaeological research, carried out by Taliana & *alii* (1996) on a small karstic cave, with the entrance floor located at 410 m a.s.l. on the right slope of the Nera River valley, showed that the cave was inhabited at 5730 ± 75 ^{14}C yr BP (4730-4440 cal bC) thus implying that the lake level was something lower than the cave entrance. Subsequently, around 4000 ± 60 ^{14}C yr BP (2750-2300 cal bC), the water level rose up sealing the cave with 7 m thick silty-clayey sediments.

INVESTIGATION METHODS

The Triponzo tufa complex has been investigated by detailed geomorphological survey and stratigraphic observations carried out both on the dam and backfill deposits. Paleontological analyses have been performed on the fossil fauna (mollusca and ostracoda) contained in the backfill sedimentary sequence.

In order to provide chronostratigraphic constraints, four samples of vegetal remnants and organic-rich levels included in the backfill sequence were dated at the Radiocarbon Laboratory of the Department of Earth Sciences, «Sapienza» University (Rome) at 6190 ± 70, 5390 ± 70, 3760 ± 60 and 2825 ± 60 yr BP (Rome-1882, –1881, –1878 and –1879, respectively).

All these dates are conventional radiocarbon ages, reported with ± 1s of uncertainty and were calculated following ^{14}C activity normalization to the d^{13}C value of –25% (Stuiver & Polach, 1977). Calibrated ages (2s confidence level) were calculated from these dates, as well as from those obtained by the previous authors, following the Stuiver & Reimer (1993) program.

GEOMORPHOLOGICAL AND STRATIGRAPHICAL DATA

The geomorphological map of the study area (fig. 4) shows that the investigated dam is entrenched in a more

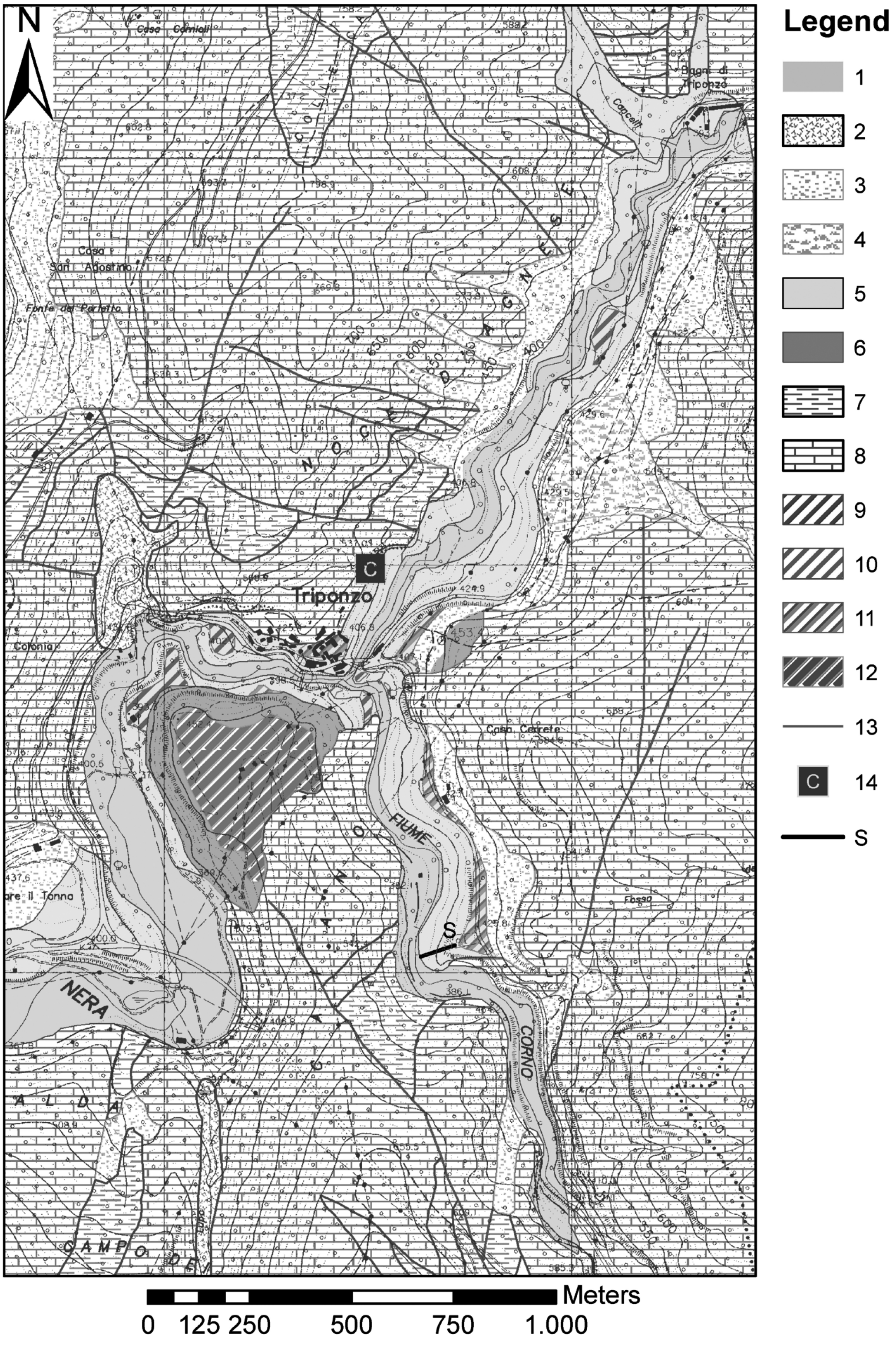

FIG. 4 - Geomorphological map of the Nera River valley at the confluence with the Corno River. Legend: 1. alluvial plains of the Nera and Corno rivers; 2. slope debris; 3. colluvium; 4. alluvial fan; 5. Holocene tufa and backfill deposits; 6. Pleistocene tufa; 7. marly bedrock; 8. limestone bedrock; 9. low terrace; 10. middle terrace; 11. top terrace; 12. ancient tufa terrace; 13. fault; 14. cave; S. investigated section.

ancient tufa deposit that formed a wide terrace at ca. 80 m above the present valley floor. The U/Th dating at Roma Tre University of a tufa sample located 7 meters below to the top of the terrace gave an age of 46,000 ± 5000 yr BP, a late Pleistocene time roughly corresponding to a mild climatic interval characterized by several Dansgaard-Oeschger events with abrupt increases of air temperature up to several degrees (Bond & *alii*, 1999; Martrat & *alii*, 2004).

The stratigraphical analysis of the Holocene tufa dam backfill, supported by ^{14}C dating of organic-rich remains, allowed to obtain a detailed outline of the environmental changes occurred in the area during the Holocene. The investigated section (fig. 5) is located on the right slope of the Corno River valley, between 387 and 420 m a.s.l., ca. 600 m upstream from the Vinken (1968) sampled slope that is today completely covered with dense vegetation. The upstream location of the investigated slope and the bad exposure of its basal part prevented us from reaching the lowermost backfill levels (374 to 387 m a.s.l.) decribed by Vinken (1968), including that dated at 8240 ± 75 ^{14}C yr BP (7480-7070 cal bC). The data provided by this author were used to complete the missing part of the backfill sequence.

The lower part of the section (387 to 391 m a.s.l.) consisted of a silty-clayey lacustrine sediments with scattered peat lenses, wooden fragments and leaves. The fossil content included a rich assemblage of oligo-thermophilous ostracoda (e.g., *Cytherissa lacustris*, *Potamocypris zschokkei* and *Candona neglecta*) indicating a relatively deep water environment supplied by cold spring water (Danielopol & *alii*, 1988, Meisch, 2000). Cold water ostracoda (e.g. *Candona neglecta*) were reported also by Vinken (1968) from the basal part of the backfill sequence, not reached by the investigated section.

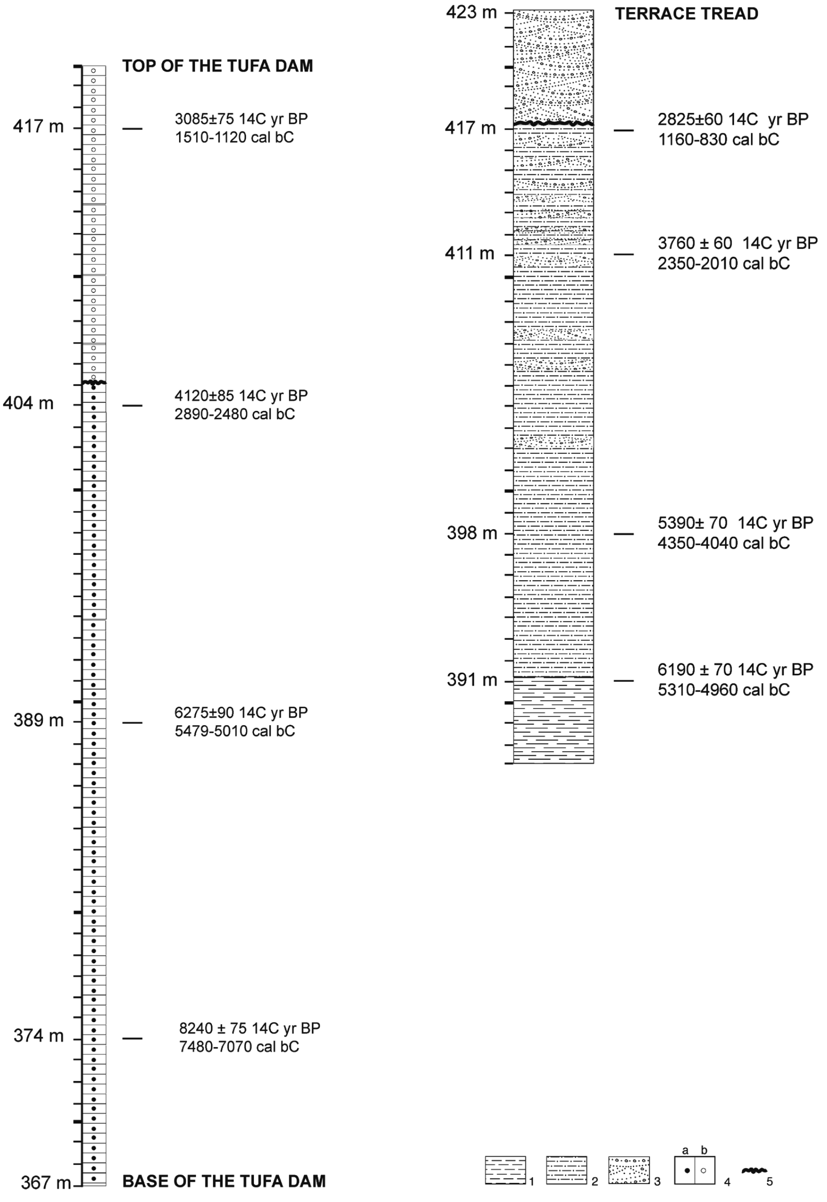

FIG. 5 - Stratigraphic scheme of the investigated backfill section. On the left side the vertical development of the tufa dam and the dates by Vinken (1968) are reported. Legend: 1. lacustrine deposits; 2. swampy deposits; 3. alluvial levels; 4. a) tufa - first depositional phase; b) tufa - se-cond depositional phase (*«younger travertine»* - Vinken, 1968); 5. main unconformity.

Between 391 and 411 m a.s.l., the section followed with a sequence of thin laminated levels of silty-clay and phytoclastic tufa sands indicating a long-lasting occurrence of shallow-water, swampy basins upstream from the dam. Some minor fluvial episodes are present in the upper part of this interval. The transition from lacustrine to swampy environment may be chronologically located around 6190 ± 70 ^{14}C yr BP (5310-4960 cal bC), a date obtained from an organic-rich silty-clayey level.

The upper part of the section (between 411 and 417 m a.s.l.) consisted of swampy levels interrupted by short-lived alluvial episodes, mostly calcareous silt, tufa sands and gravels, locally filling buried channels.

The last 7 meters of the investigated slope (417 to 424 m a.s.l.) consisted of alluvial gravels (supplied by the Mesozoic limestone bedrock) forming a wide terrace whose remnants are recognizable in different parts of the Corno and Nera valleys upstream of the dam («*top terrace*» in fig. 4).

After 2825 ± 60 ^{14}C yr BP (1160-830 cal bC), the age of a wooden fragment included in the uppermost backfill layers (417 m a.s.l.), the deposition rates of tufa dramatically dropped and the Nera and Corno rivers incised both the dam and the backfill down to the present valley bottom. During this period, the incision rates were not constant as testified by the formation of two strath terraces across the dam, hanging at ca. 18 m («*middle terrace*» in fig. 4) and 9 m («*low terrace*» in fig. 4) respectively above the river bed. The first strath terrace is topped by tufa sands overlying a few meters thick layer of limestone gravels.

The Nera and Corno River channels are presently incised in a relatively wide alluvial plain, mostly made of limestone gravels, with a scarp more than 2 m high, immediately upstream from the dam front wall.

OTHER TUFA DAMS FROM CENTRAL ITALY

Other tufa dams from Central Italy (fig. 1) display a comparable evolution trend (Calderoni & *alii*, 1994; Calderoni & *alii*, 1996; Gliozzi, 2000; Ricci Lucchi & *alii*, 2000).

According to Calderoni & *alii* (1996), the aggradation of tufa dams started in the Marchean valleys prior than 8260 ± 80 yr BP (7490-7070 cal bC) at Gelagna (Chienti River basin) and continued at least up to 4840 ± 65 ^{14}C yr BP (3770-3510 cal bC) at Esanatoglia (Esino River basin), 4535 ± 60 ^{14}C yr BP (3380-3020 cal bC) at Valleremita (Giano River basin), 4780 ± 60 ^{14}C yr BP (3660-3370 cal bC) at Poggio Sorifa (Potenza River basin), 4750 ± 60 ^{14}C yr BP (3650-3370 cal bC) at Serrapetrona (Chienti River basin). Then, the rates of tufa deposition gradually declined.

In the northern sector of the Rieti basin (Latium), lacustrine sediments with mollusc assemblages, oligo-thermophylous ostracoda and arboreal leaves mark the onset of a tufa dam before 10,000 yr cal (Calderoni & *alii*, 1994, 1996; Gliozzi, 2000; Ricci Lucchi & *alii*, 2000). The transition from lacustrine to alternating fluvial and swampy environments, marked by buried channels filled with gravels, was recorded from core drillings after 4610 ± 100 ^{14}C yr BP (3650-3000 cal bC) at Ripasottile and before 3680 ± 70 ^{14}C yr BP (2290-1880 cal bC) at Lago Lungo. In the latter site, a minor tufa aggradation phase, giving rise to an ephemeral lacustrine basin upstream, was dated at 1070 ± 100 ^{14}C yr BP (760-1180 AD).

DISCUSSION

Basing on the investigated section (fig. 4), the evolutionary trend of the Triponzo dam is marked by significant changes in the deposition rates of tufa (fig. 5). Between 5310-4960 and 4350-4040 cal bC, the average rate of tufa deposition was quite high, ca. 0.85 (0.55-1.15) cm/yr, corresponding to a 7 m tufa growth (371 to 378 m a.s.l.) in 1270-610 years. The high rate of tufa deposition allowed the formation of a relatively deep lacustrine basin upstream, as testified by the sedimentary facies and the ostracoda content of the backfill sequence. A lacustrine facies was also reported by Vinken (1968) from the lowermost part of the backfill, (not reached by the investigated section).

Between 4350-4040 and 2350-2010 cal bC, the average rate declined to ca. 0.61 (0.51-0.71) cm/yr: 12 m (398 to 411 m a.s.l.) in 2340-1690 years. In this interval the upstream basin was characterized by shallow water, swampy environment with scattered fluvial episodes. Subsequently, from 2350-2010 to 1160-830 cal bC, the average rate further declined to ca. 0.55 (0.39-0.71) cm/yr, for a growth of 6 m between 411 and 417 m a.s.l. in 1520-850 years, with a series of alternating phases of dam aggradation and erosion. In this stage, the rising water invaded the small karstic cave.

After 2825 ± 60 ^{14}C yr BP (1160-830 cal bC) the deposition rates of tufa dramatically dropped to very low values, not sufficient to counter the erosive action of the Nera River that cut down the dam to the present valley bottom with a total incision rate of ca. 1.8 cm/yr.

Even if with some uncertainties due to the overlapping of the extreme minimum/maximum values, the above data indicate a progressive decline of tufa deposition rates from the lower stages of the dam construction to its ultimate incision. A comparable behaviour of tufa deposition rates from the early to the late Holocene has been reported from Belgium by Geurts (1976).

The above described long term evolution of the Triponzo tufa dam seems to assign a significant role to climate as a controlling agent. In particular, the progressive decline of tufa deposition rates from the first stages of dam aggradation could be correlated the general aridification trend that affected the Mediterranean area from the early to the late Holocene (Zanchetta & *alii*, 2007; Roberts & *alii*, 2008).

The above described evolutionary trend seems also compatible with the surface-ground thermal disequilibrium model proposed by Dramis & *alii* (1999) as a concurrent factor for the aggradation/erosion of tufa. Some support to this hypothesis might be provided by the occurrence a cold water fauna in the upstream lacustrine basin confirming the presence of cold spring waters in a warmer fluvial environment. It is noteworthy in this respect that cold water ostracoda were also reported from the lower backfill deposits of different Holocene tufa dams (Davies

& Griffiths, 2005; Pentecost, 2005; Limondin-Lozouet & *alii*, 2006; Sohar & Meidla, 2010).

Consideration should be also given to the incidence of short term climate changes. The cycles of tufa dam erosion/aggradation recorded since around 2350-2010 cal bC (4300-3960 cal BP) could be related to the occurrence of high frequency dry/wet climate fluctuations. A high variability of climate, with at least some episodes, synchronous with North Atlantic IRD (*Ice Rafted Detritus*) events, is recorded in central Italy after the so-called «4.2 ka event» (Bond & *alii*, 1997), characterized by cool-dry conditions following a short cool period (Drysdale & *alii*, 2006; Magny & *alii*, 2009; Giraudi & *alii*, 2011; Zanchetta & *alii*, 2012). The phase of dam incision preceding the Vinken (1968) *younger travertine* might be related to this event.

The two strath terraces cut across the tufa dam during its late incision stage after 1160-830 cal bC could have formed by the incidence of wetter climate intervals during which increased deposition rates of $CaCO_3$ caused interruption of dam cutting or a new short lived dam aggradation. Actually, wetter conditions are reported from Lake Accesa (Central Italy) by high stand levels at 850-650 cal bC, 550-750 AD and 1450-1650 AD, contemporaneous with glacial advances in the Alpine and Apennine glaciers (Magny & *alii*, 2007; Giraudi & *alii*, 2011). Even in the absence of chronological references, the upper strath terrace, located ca. 35 m below the backfill top terrace, might be tentatively dated around 550-750 AD, a time interval not too far from the short-lived period (780-1160 AD) of tufa dam aggradation recorded in the Rieti basin. Accordingly, the lower strath terrace (9 m a.s.l.) might be referred to the 1450-1650 AD interval.

The reference to climate changes as the main factors of dam aggradation/erosion does not exclude the role of human activities. In more recent times, man-made deforestation certainly provided a relevant contribution in lowering $CaCO_3$ deposition rates, especially during the periods of climate deterioration (Berakhi & *alii*, 1998; Ramrath & *alii*, 2000). This could be the case of the fluvial incision/deposition phase that closes the tufa dam backfill sequence, chro-nologically related to the starting of intensive man-made deforestation in Central Italy (Calderoni & *alii*, 2007) as well as to the incidence of dry climate conditions (Giraudi & *alii*, 2011).

The aggradation of the late Nera River alluvial plain was likely induced by the widespread clearance of forests for agriculture and pasture that occurred in the drainage basin, as in other parts of Italy and Europe, during the last centuries. The subsequent incision of the alluvial plain may be related to spontaneous regrowth of forest covers after the abandonment of farmlands and pastoral areas as well as to the reforestation programs and anti-erosion measures implemented in Italy since the second half of the 20th Century (Piussi & Pettenella, 2000).

CONCLUSIONS

The geomorphological/stratigraphical analysis of the Triponzo tufa dam and backfill deposits, coupled with radiocarbon dating, proved to be a valuable tool for outlining the role of Holocene climate changes in controlling the rates of tufa deposition in Central Italy.

Over a long-term timescale, the general decline of tufa deposition rates from the lower to the late Holocene seems to respond to the progressive aridification of climate. A possible concurrent role might be assigned to the occurrence of reverse thermal gradients induced in the ground by the early Holocene climate warming.

Over short-term timescales, the short-lived dry/wet fluctuations that have affected central Italy in the late Holocene may provide an explanation for the repeated increase/decrease phases of tufa deposition rates which match the phases of dam aggradation/erosion.

REFERENCES

Ariztegui D., Chrondrogianni C., Lami A., Guilizzoni P. & Lafargue E. (2001) - *Lacustrine organic matter and the Holocene paleoenvironmental record of Lake Albano (central Italy).* Journal of Paleolimnology, 26, 283-92.

Atkinson T.C. (1977) - *Carbon dioxide in the atmosphere of the unsaturated zone: an important control of hardness in limestones.* Journal of Hydrology, 35, 111-123.

Berakhi O., Brancaccio L., Calderoni G., Coltorti M., Dramis F. & Umer M. (1998) - *The Mai Maikden sedimentary sequence: a reference point for the environmental evolution of the Highlands of Northern Ethiopia.* Geomorphology, 23 (2-4), 127-138.

Bigi G., Cosentino D., Parotto M., Sartori R. & Scandone P. (1992) - *Structural model of Italy 1:500,000 and gravity map.* SELCA, Florence, Italy.

Bond G., Showers W., Cheseby M., Lotti R., Almasi P., de Menocal P., Priore P., Cullen H., Hajdas I. & Bonani G. (1997) - *A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates.* Science, 278 (5341), 1257-1266.

Bond G.C., Showers W., Elliot M., Evans M., Lotti R., Hajdas I., Bonani G. & Johnson S. (1999) - *The North Atlantic's 1-2 kyr climate rhythm: relation to Heinrich events, Dansgaard/Oeschger cycles and the Little Ice Age.* In: Clark P.U., Webb R.S. & Keigwin L.D. (Eds.), «Mechanisms of global change at millennial time scales», Geophysical Monograph 112, American Geophysical Union, Washington DC, 59-76.

Brook G.A., Folkoff M.E. & Box E.O. (1983) - *A world model of soil carbon dioxide.* Earh Sorface Processes Landforms, 8, 79-88.

Calderoni G., Carrara G., Ferreli L., Follieri M., Gliozzi E., Magri D., Narcisi B., Parotto M., Sadori L. & Serva L. (1994) - *Palaeoenvironmental, palaeoclimatic and chronological interpretations of a late Quaternary sediment core from Piana di Rieti (central Apennines, Italy).* Giornale di Geologia, serie 3a, 56 (2), 43-72.

Calderoni G., Cilla G., Dramis F., Esu D., Magnatti M. & Materazzi M. (1996) - *La deposizione di travertino nelle aree prossimali dei fiumi Esino, Potenza e Chienti durante l'Olocene antico (Appennino Centrale Marchigiano).* Il Quaternario, 9 (2), 481-492.

Calderoni G., Cilla G., Dramis F. & Gobbi C. (2007) - *Environmental changes and human settlement in the Central Marches (Italy) during the Early-Middle Holocene.* Physio-Géo - Géographie Physique et Environment, 1, 21-32.

Danielopol D.L., Geiger W., Toelderer-Farmer M., Orellana C.P. & Terrat M.N. (1988) - *In search of* Cypris *and* Cythere - *A report of the Evolutionary Ecological Project on Limnic Ostracoda from the Mondsee (Austria).* In: Hanai T., Ikeya N. & Ishizaki K. (Eds.), «Evolutionary biology of ostracoda: its fundamentals and applications», Developments in Paleontology and Stratigraphy, 11, Elsevier, Amsterdam, 1356 pp.

Dansgaard W., White J.W.C. & Johnsen S.J. (1989) - *The abrupt termination of the Younger Dryas climatic event*. Nature, 339, 532-533.

Davies P. & Griffiths H.I. (2005) - *Molluscan and ostracod biostratigraphy of Holocene tufa in the Test valley at Bossington, Hampshire, UK*. The Holocene, 15 (1), 97-101.

Dramis F., Materazzi M. & Cilla G. (1999) - *Influence of climatic changes on freshwater travertine deposition: a new hypothesis*. Physics and Chemistry of the Earth, Part-A, Solid Earth and Geodesy, 24 (10), 893-897.

Dramis F., Soligo M., Graciotti E., D'Orefice M. & Graciotti R. (2008) - *U/Th dating of a tufa deposit from the Carsoli intramontane basin (Abruzzo, Italy)*. Geografia Fisica e Dinamica Quaternaria, 31 (2), 255-258.

Drysdale R.N., Zanchetta G., Hellstrom J., Maas R., Fallick A., Pickett M., Cartwright I. & Piccini L. (2006) - *Geology Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone*. Geology, 34 (2), 101-104.

Frank N., Braum M., Hambach U., Mangini A. & Wagner G. (2000) - *Warm period growth of travertine during the last interglaciation in Southern Germany*. Quaternary Research, 54, 38-48.

Geurts M.A. (1976) - *Genèse et stratigraphie des travertins de fond vallée en Belgique*. Acta Geographica Lovaniensa, vol. 16, 66 p.

Giraudi C, Magny M, Zanchetta G & Drysdale R.N. (2011) - *The Holocene climatic evolution of Mediterranean Italy: A review of the continental geo- logic data*. The Holocene, 21 (1), 105-115.

Gliozzi E. (2000) - *Tardiglacial-Holocene freshwater ostracod assemblages from Ripasottile well (Rieti basin, Latium, central Italy)*. Giornale di Geologia, s. 3a, 62, 159-171.

Goudie A.S., Viles H.A. & Pentecost A. (1993) - *The late-Holocene tufa decline in Europe*. The Holocene, 3 (2), 181-186.

Hynes H.B.N. (1978) - *The ecology of running waters*. University Press, Liverpool, 378 pp.

Julia R. (1983) - *Travertines*. In: Scholle P.A., Bebout D.G. & Moore C.H. (Eds.), «Carbonate depositional environments», AAPG, Tulsa, Oklahoma, 64-72.

Kotthoff U., Pross J., Müller U.C., Peyron O., Schmiedl G., Schulz H. & Bordon A. (2008) - *Climate dynamics in the borderlands of the Aegean Sea during formation of sapropel S1 deduced from a marine pollen record*. Quaternary Science Reviews, 27, 832-845.

Limondin-Lozouet N., Antoine P., Auguste P., Bahain J.J., Carbonel P., Chaussé C., Connet N., Duperon J., Duperon M., Falgueres C., Freytet P., Ghaleb B., Jolly-Saad M.C., Lhomme V., Lozouet P., Mercier N., Pastre J.F. & Voinchet P. (2006) - *Le tuf calcaire de la celle-sur-Seine (Seine et Marne): nouvelles donneés sur un site clé du stade 11 dans le nord de la France*. Quaternaire, 17, 51-67.

Magny M., de Beaulieu J.-L., Drescher-Schneider R., Vannière B., Walter-Simonnet A.-V., Miras Y., Millet L., Bossuet G., Peyron O., Brugiapaglia E. & Leroux A. (2007) - *Holocene climate changes in the central Mediterranean as recorded by lake-level fluctuations at Lake Accesa (Tuscany, Italy)*. Quaternary Science Reviews, 26, 1736-1758.

Magny M., Vannière B., Zanchetta G., Fouache E., Touchais G. & Arnoud F. (2009) - *Possible complexity of the climatic event around 4200-4000 cal. BP in the central and western Mediterranean*. The Holocene, 19, 823-834.

Martrat M., Grimalt J.O., Lopez-Martinez C., Cacho I., Sierro F.J., Flores J.A., Zahn R., Canals M., Curtis J.H. & Hodell D.A. (2004) - *Abrupt temperature changes in the western Mediterranean during the last and penultimate glacial and interglacial periods*. Science, 306, 1762-1765.

Meisch C. (2000) - *Freshwater ostracoda of Western and Central Europe*. In: Schwoerbel J. & Zwick P. (Eds.), Süßwasserfauna von Mitteleuropa 8/3, Spektrum Akademischer Verlag, Heidelberg-Berlin, 522.

Nicod J. (1986) - *Facteurs physico-chimiques de l'accumulation des formations travertineuses*. Mediterranée, 57 (1-2), 161-164.

Pedley H.M. (1990) - *Classification and environmental models of cool fresh-water tufas*. Sedimentary Geology, 68, 143-154.

Pentecost A. (2005) - *Travertine*. Springer-Verlag, Berlin, 445 pp.

Piussi P. & Pettenella D. (2000) - *Spontaneous afforestation of fallows in Italy*. In: Weber N. (Ed.), «New forests for Europe» Proceedings of the NEWFOR Scientific Symposium, February 16-17, Freiburg, Germany, ETI Proceedings, 35, 151-163.

Preece R.C., Thorpe P.M. & Robinson J.E. (1986) - *Confirmation of an interglacial age for the Condat Tufa (Dordogne, France) from biostratigraphic and isotopic data*. Journal of Quaternary Science, 1, 57-65.

Ramrath A., Sadori L. & Negendank J.F.W. (2000) - *Sediments from Lago di Mezzano, central Italy: a record of Lateglacial/Holocene climatic variations and anthropogenic impact*. The Holocene, 10 (1), 87-95.

Ricci Lucchi M., Calderoni G., Carrara C., Cipriani N., Esu D., Ferreli L., Girotti O., Gliozzi M., Lombardo M., Longinelli A., Magri D., Nebbiai M., Ricci Lucchi F. & Vigliotti L. (2000) - *Late Quaternary record of the Rieti basin, central Italy:* paleoenvironmental and paleoclimatic evolution. Giornale di Geologia, s. 3a, 62, 105-136.

Roberts N., Jones M.D., Benkaddour A., Eastwood W.J., Filippi M.L., Frogley M.R., Lamb H.F., Leng M.J., Reed J.M., Stein M., Stevens L., Valero-Garcés B. & Zanchetta G. (2008) - *Stable isotope records of Late Quaternary climate and hydrology from Mediterranean lakes: the ISOMED synthesis*. Quaternary Science Reviews, 27 (25-26), 2426-2441.

Schoeller H. (1962) - *Les eaux souterraines*. Masson et Cie, Paris, 642 pp.

Sohar K. & Meidla T. (2010) - *Changes in the Early Holocene lacustrine environment inferred from the subfossil ostracod record in the Varangu section, northern Estonia*. Estonian Journal of Earth Sciences, 59 (3), 195-206.

Soligo M., Tuccimei P., Barberi R., Delitala M.C., Miccadei E. & Taddeucci A. (2002) - *U/Th dating of freshwater travertine from Middle Velino Valley (Central Italy): paleoclimatic and geological implications*. Palaeogeography, Palaeoclimatology, Palaeoecology, 184, 147-161.

Stuiver M. & Polach H.A. (1977) - *Discussion: reporting of* ^{14}*C data*. Radiocarbon, 19, 355-363.

Stuiver M. & Reimer P.J. (1993) - *Extended* ^{14}*C data base and revised Calib. 4.1.2.* Radiocarbon, 35 (1), 215-230.

Taliana D., Alessio M., Allegri L., Capasso Barbato L., De Angelis C., Esu D., Girotti O., Gliozzi E., Improta S., Mazzini I. & Sardella R. (1996) - *Preliminary results on the «Grotta del Lago» Holocene deposits (Triponzo, Nera River Valley, Umbria, Central Italy)*. Il Quaternario, 9 (2), 745-752.

Thrailkill J. (1968) - *Chemical and hydrologic factors in the excavation of limestone caves*. Geological Society of America Bulletin, 79, 19-46.

Touring Club Italiano (1986) - *Atlante enciclopedico, vol. I*, Milano.

Vasseur G., Bernard P.H., Van de Meulebrouck J., Kast Y. & Jolivet J. (1983) - *Holocene paleotemperatures deduced from borehole temperature data*. Palaeogeography, Palaeoclimatology, Palaeoecology, 43, 237-259.

Vaudour J. (1986) - *Travertins holocènes et pression anthropique*. Méditerranée, 57 (1-2), 168-173.

Vinken R. (1968) - *Zur entstehung und altersstellung der travertine, limnichen sedimente und fluviatilen terrassen im gebiet der mittleren Nera und des Corno (Umbrien, Mittelitalien)*. Eiszeitalter und Gegenwart, 19 (5-30), 17-30.

Zanchetta G., Borghini A., Fallick A.E., Bonadonna F.P. & Leone G. (2007) - *Late Quaternary palaeohydrology of Lake Pergusa (Sicily, southern Italy) as inferred by stable isotopes of lacustrine carbonates*. Journal of Paleolimnology, 38, 227-239.

Zanchetta G., Giraudi C., Sulpizio R., Magny M., Drysdale R.N. & Sadori L. (2012) - *Constraining the onset of the Holocene «Neoglacial» over the central Italy using tephra layers***.** Quaternary Research, 78 (2), 236-247.

(Ms. received 1 September 2012; accepted 1 May 2013)