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AN EIGHTEENTH CENTURY TUNNEL AS POSSIBLE ARCHIVE FOR PALAEOCLIMATE STUDIES

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ABSTRACT: Pascucci V. *et al.*, *An eighteenth century tunnel as possible archive for palaeoclimate studies.* (IT ISSN 0394-3356, 2010)
The former Silva Lake (present "Pian del Lago", Siena, Italy) developed during late Quaternary and formed as a poljie on the Triassic limestones. The depression, nowadays completely drained, is N-S oriented, 4.5 km wide and 12 km long. The lake never exceeded 6 m in depth, and it was mainly a grassy swamp during the dry season. The lake depression is filled with 20 to 30 m of a reddish silty-clayey succession. Starting from the Middle Age till late 18th century, the shallow waters of the lake and the humid area around acted as a swampy area infested by malaria.

In 1766 a Sienese nobleman, Francesco Bindi Sergardi drained the lake excavating a drainage 2124m-long tunnel in Triassic limestones to connect the Silva Lake with the closeby Rigo Creek. However, quite often the tunnel was filled with debris and the lake swamped up again. In 1780 Pietro Leopoldo Grand Duke of Tuscany definitively reclaimed the Silva Lake and completed the construction of the drainage tunnel by paving and extending it for an additional 197 m. Since then, the tunnel is called the "Canale del Gran Duca". The entrance altitude of the canal is at 252 m a.s.l., and the exit is at 247 m a.s.l. The altitude difference is therefore of 5 m, and the canal floor has a slope of 0.2 %.

The canal is for the most part paved but, in places, solid walls of Triassic limestone are still visible. Diffuse karst features are forming locally. Stalactites have lengths varying from 5 to 10 cm, and flowstones occur along the tunnel walls. The presence of these speleothems has allowed geochemical investigations to establish climatic variations of the last two centuries. The tunnel was probably cleaned and well maintained for sometime after its construction (1780), and it is likely that all the remaining speleothems have developed in the last two centuries with an estimated growth of a 0.5/6 mm per year. A petrographic investigation of a well laminated flowstone with a parasitic stalagmite has been undertaken to determine the growth mechanisms. Oxygen and carbon isotope data ($\delta^{18}O$ and $\delta^{13}C$ values) were used as indirect proxies for palaeoenvironmental reconstructions. Preliminary, data show significant variations along the axis of the flowstone possibly related to environmental and climatic variations within and above the "canale".

RIASSUNTO: Pascucci V. et. al., Una galleria artificiale del XVIII secolo come possibile archivio per studi paleoclimatici. *(IT ISSN 0394-3356, 2010)*
L'attuale Pian del Lago, ubicato circa 5 km a nord di Siena, si è sviluppato durante il Quaternario nei calcari triassici della Serie Toscana non metamorfica (noti anche come Calcare Cavernoso), come un lago di natura carsica (polje). Il lago (Lacus Silva), oggi completamente prosciugato, orientato N-S, largo 4.5 km a lungo 12 aveva una profondità massima di circa 6m ed era utilizzato dalla vicina città di Siena come riserva di pesca/caccia e di legno. La modesta profondità del lago faceva sì che nella stagione secca questo si prosciugasse quasi completamente diventando un acquitrino maleodorante infestato dalla malaria. Le cronache senesi del XVIII secolo parlano dei miasmi che raggiungevano la città, soprattutto durante l'estate. Nel 1776 un nobil uomo Senese, Francesco Bindi Sergardi, pressato dai continui appelli dei cittadini, decise di prosciugare il Lago Silva, bonificandone così l'area circostante. Il progetto prevedeva la costruzione di una galleria lunga 2124 m da scavare nei calcari triassici, che collegasse il lago con il Torrente Rigo. Il progetto funzionò solo parzialmente: il canale spesso si riempiva di detriti e il lago si impaludava di nuovo. Solo con l'intervento del Gran Duca Pietro Leopoldo di Toscana, nel 1780, che pavimentò e allungò il canale, il Lago Silva fu definitivamente prosciugato. Da allora il canale viene chiamato Canale del Gran Duca. Il canale parte da una quota di 252 m slm e la sua uscita si trova a 247 m. La differenza di altitudine è di 5 m con una pendenza dello 0.2%. Il canale è per la maggior parte rivestito di mattoni; solo in alcuni tratti è visibile il calcare. Molto diffusi sono i fenomeni carsici in formazione sia sulla volta (stalattiti di lunghezza compresa tra i 5 ed i 10 cm, vele), sia sulle pareti (depositi di scorrimento di acqua - flowstones) che sul fondo (piccole vasche). La presenza di queste concrezioni (speleotemi) ha permesso di condurre alcune analisi geochimiche sugli isotopi del C e dell'O e di capire se le concrezioni presenti nel canale potessero essere usate come sistema di riferimento per lo studio delle variazioni climatiche degli ultimi due secoli. Il Canale del Gran Duca fu pulito e ben mantenuto negli anni successivi alla sua costruzione. Pertanto, tutte le concrezioni presenti nel suo interno non sono più vecchie di circa 200 anni. Il tasso di crescita massimo stimato è di 0.5/0.6 mm per anno. È stata condotta un'analisi di dettaglio su di un singola concrezione di flusso con associata una stalagmite parassita. L'analisi petrografica ha mostrato che la crescita della concrezione è stata costante nel tempo e che quindi avrebbe potuto registrare tutte le variazioni climatiche succedutesi negli ultimi due secoli. Le lamine dello speleotema sono state campionate ogni mm e la polvere di calcite raccolta analizzata con uno spettrometro di massa per ricavare i valori di $\delta^{18}O$ and $\delta^{13}C$. Le analisi preliminari condotte hanno indicato sia una buona corrispondenza tra i valori dei due isotopi che una buona correlazione tra questi e i valori di piovosità registrati nell'area senese dal 1836. Questi dati dimostrano che le concrezioni presenti nel Canale del Gran Duca hanno registrato le variazioni ambientali e climatiche succedutesi negli ultimi 200 anni e che quindi possano essere utilizzate come sistema di riferimento.

Keywords: palaeoclimate, stable isotopes, speleothems, lake, Canale del Gran Duca, Siena.

Parole chiave: paleoclima, isotopi stabili, Pian del lago, Canale del Gran Duca, Siena.

1. INTRODUCTION

The chronic lack of water that vexed Siena during the medieval period explains the town's preoccupation with gathering and using any available fresh water and retain as a valuable potential resource. The theme of water assumed a central importance in the history of the city of Siena and forced the local authorities to construct in the 13th–15th centuries, a subterraneous network of galleries created to collect and send to the city fountains the water retrievable near Siena, the so called "*bottini*" (Costantini & Martini, 2004; Kucher, 2005; Martini *et al*. 2010).

The countryside farther from Siena, instead, was locally richer in water, especially where, due to the geomorphology and karst features, vast ponds to shallow lakes were formed. Lakes allowed the establishment of several communities and, in the middle ages, they represented important economic sources. Villages and abbeys such as Monteriggioni and S. Leonardo al Lago (Figs. 1, 2) developed thanks to the presence of these lakes. Special rules where established for the exploitation of the waters. In time, however, some of these lakes became the breeding grounds of malaria-carrying mosquitoes and several attempts were made to drain them. During the 18th century the lake near San Leonardo (Silva Lake, present Pian del Lago) was drained with a construction of a large canal (*Canale del Duca*) cut through calcareous bedrock (Fig. 2). Water seeping into the canal further led to the development of several carbonate concretions (flowstones, thin stalactites and stalagmites). Although in an artificial environment, these concretions have formed as part of the hydrological cycle, and have the potential to record information on the climate of the last two centuries.

Fig. 1 - Schematic map of Tuscany with location of the Lacus Silva (size of the lake not to scale), Siena and Monteriggioni.

Mappa schematica della Toscana con l'ubicazione del Lacus Silva (la dimensione del lago non è in scala), Siena e Monteriggioni.

This paper reports on how the need for draining the infected ponds north of Siena led to the construction of the *Canale del Duca* during the 18th century, and how this canal can be used nowadays to reconstruct a record of climatic changes for the last centuries.

2. GEOLOGICAL SETTING

The studied area is located in the western inner part of the Northern Apennines complex chain (Vai & Martini, 2001) and occupies the northernmost part of the Siena Graben (SI). This depression is bounded to the west by the Middle Tuscany Ridge (MTR) (Pascucci *et al*., 1999; Sagri *et al*., 2004) (Fig. 3).

This ridge is composed of low grade Jurassic-Cretaceous metamorphic rocks that are tectonically overlain by mid-late Triassic limestones and anhydrites. The ridge has played an important structural palaeogeographic role through time. (a) During late Miocene it prevented the marine ingression into basins located to its east and provided much of the material of the large alluvial fans developed on its southeastern flank. Most of these fans are made of Triassic limestones and today they contain the main freshwater resource for the city of Siena (Capacci *et al*., 2008). (b) During the Pliocene, a widespread marine transgression inundated the whole area and parts of the ridge formed a series of islands along a NW-SE lineament. (c) During the Quaternary MTR was 700 to 800 m high and separated areas with different climatic conditions: dry to the west and relatively humid to the east. These humid conditions likely led to the development of karst, lakes and river systems (Mancini, 1962; Ghinassi & Magi, 2004).

Most of the karst features occurring in the studied area developed into the Triassic *Calcare Cavernoso* limestone. They form a complicate underground system made of various-size caves and connecting tunnels with several sinkholes (some time connected to form a *polje*) at the surface (Pascucci & Dallai, 2004).

3. HISTORY OF USAGE OF WATER RESOURCES

Since Roman times, a careful management of water resources deriving from the presence of ponds

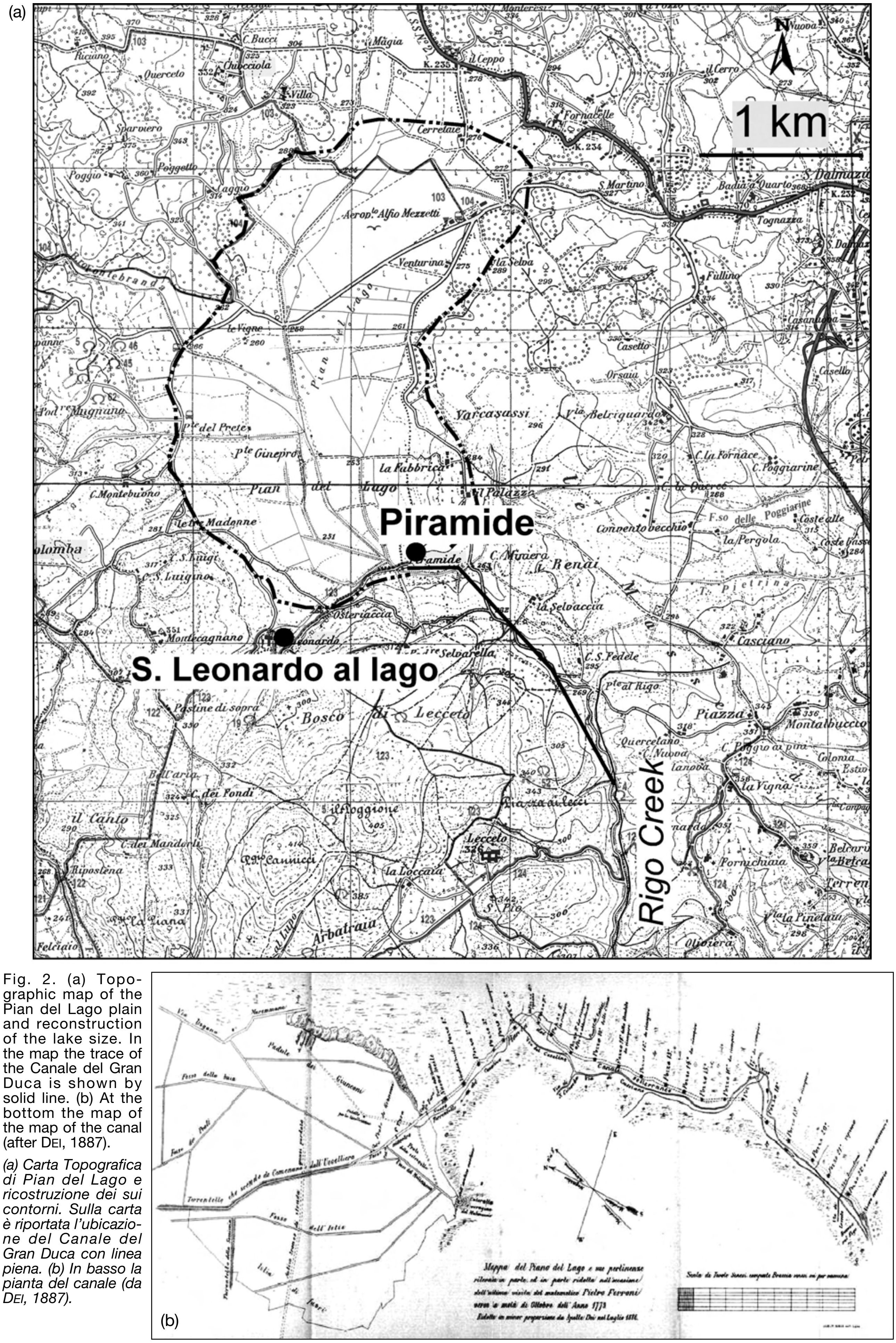

Fig. 2. (a) Topographic map of the Pian del Lago plain and reconstruction of the lake size. In the map the trace of the Canale del Gran Duca is shown by solid line. (b) At the bottom the map of the map of the canal (after DEI, 1887).

(a) Carta Topografica di Pian del Lago e ricostruzione dei sui contorni. Sulla carta è riportata l'ubicazione del Canale del Gran Duca con linea piena. (b) In basso la pianta del canale (da DEI, 1887).

was typical both of the coastal and inland areas. Coastal lagoons and inland lakes and ponds have strongly influenced the economy of numerous communities such as those of the medieval cities of Pisa and Lucca (Wickham, 2001; Sarti *et al.*, this volume). In medieval Tuscany, lagoons and ponds were intensely used exploiting, for example, vegetation in agriculture (the ditch reeds were used as a light support for vineyards, shrubs for bedding or as a building material for huts; Cammarosano, 1983), and obtaining food by fishing and hunting. These environments were very valuable and they were managed but not drained for a considerable long time, until the 17th and 18th centuries.

In the 13th century Siena established an area for fish and wood provision close to the city, strictly protected by written rules for its maintenance. This area called "*Silva Lacus*", the (Silva Lake – lake of wood), corresponds to the current Pian del Lago plain (Figs. 1, 2). The "*Silva Lacus*" laws established a strict limit of fishing activities, and the punishments were listed in a specific chapter of the *Sienese* Constitution, dating back to 1262, entitled:"*De pena piscantium in lacu Silve*" (about the punishments for fishing in Silva Lake):*"…Et in lacu de Silva piscari non permittam in toto meo termino; et si quis contra fecerit, totiens XL sol. sibi auferam, quotiens contra fecerit et ibi piscatus fuerit …"* The application of this law was entrusted to a special guard corps, called forestarii; *"…teneatur dicti forestarii rumpere et frangere tramallium et guadam et rete et omne argumentum, cum quo aliquis piscatur, ita minutatim quod ab inde in antea non possit cumeo piscari;et potestati renunctiare postea teneatur, qualiter et quomodo fecerint …"* (Zdekauer, 1974; Pascucci & Dallai, 2004). The rude attitude of the forestarii, so clearly described in the Sienese laws is similar to that of the "*silvani*" or "*custodes*" which were engaged by the canonicals of the cathedral of Santa Maria in Pisa, in order to dissuade the abbot of the monastery of San Rossore from the use of the *Silva Tumulus*, the a lagoon located north of the Arno River mouth (Pisa, Fig. 3), the ownership of which was disputed between the two ecclesiastic entities (these documents refer to the years 1155–1156) (Wickham, 2001).

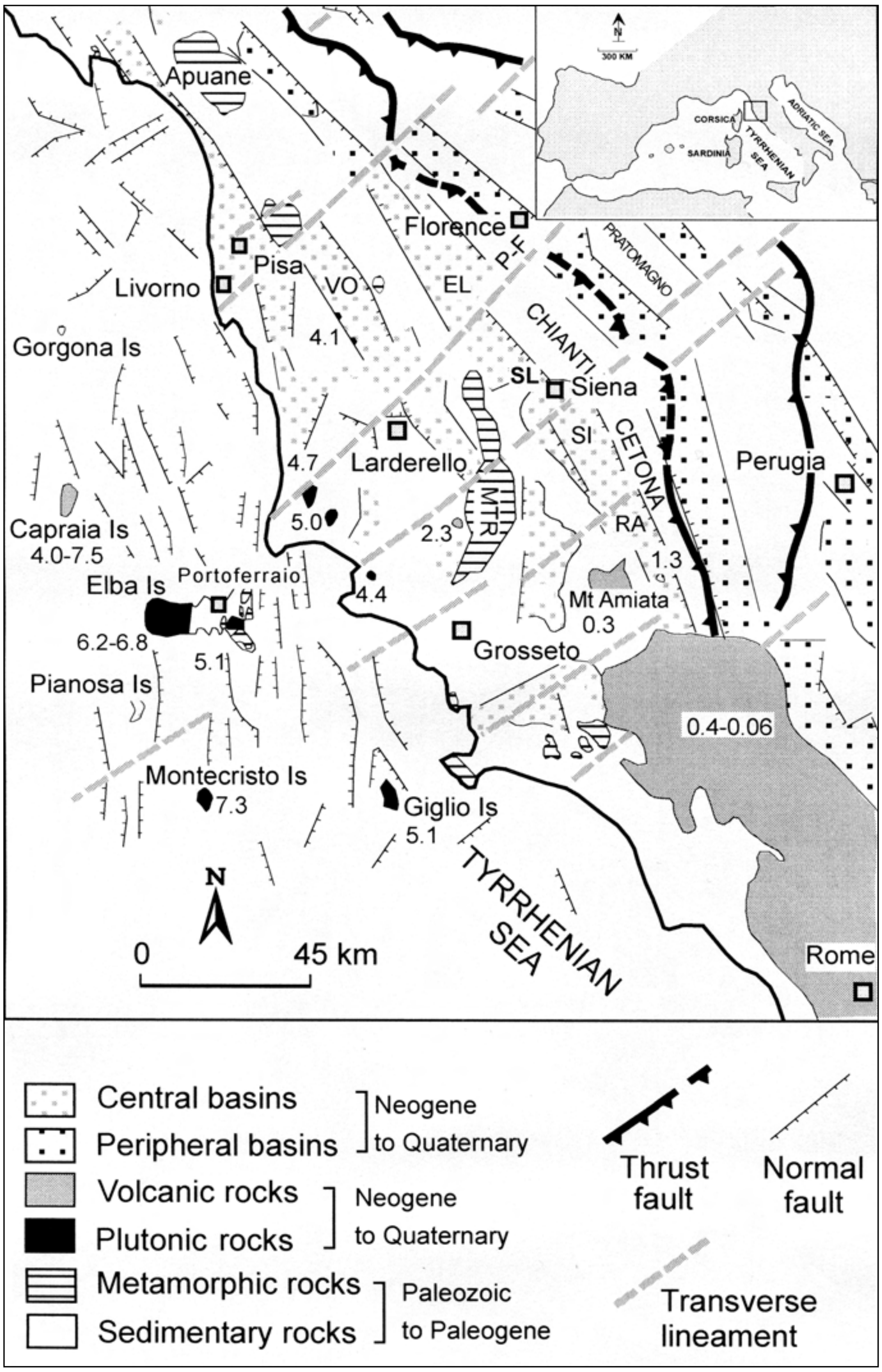

Fig. 3 - Schematic geological map of Tuscany (Italy) to show major Tertiary basins and magmatic centres, with ages of igneous activity in millions of years before present. SL= location of the Silva Lake. EL = Elsa Basin, MTR = Middle Tuscany Ridge, RA = Radicofani Basin, SI = Siena Basin, P-F = Piombino-Faenza line (major transverse lineament), VO = Volterra Basin. Pratomagno corresponds to the Apennine crest. Inset shows study area within western Europe. (Modified after Pascucci *et al.* , 2007).

Carta geologica schematica della Toscana (Italia) dove sono indicate i principali bacini Terziari ed i centri magmatici con le età di attività espresse in milioni di anni. SL= ubicazione del Lago Silva. EL = Bacino dell'Elsa, MTR = Dorsale Medio Toscana, RA = Bacino di Radicofani, SI = Bacino di Siena, P-F = Linea Piombino-Faenza (uno dei principali lineamenti trasversali), VO = Bacino di Volterra. Pratomagno corrisponde al crinale appenninico. Nell'inserto è riportata l'Europa occidentale. (da Pascucci et al. *, 2007).*

The Silva Lake developed during late Quaternary and formed as a polje on the Calcare Cavernoso limestone. The depression is N-S oriented, 4.5 km long and

12 km wide. The lake never exceeded 6 m in depth, and it was mainly a marshy plain during the dry season.

The shallow marshy lakes became a breeding ground for malaria-carrying mosquitoes. This combined with the strong bad odour caused by rotting vegetation, which during the dry period reached the city of Siena, induced a nobleman (belonging to the *Contrada della Selva*), Francesco Bindi Sergardi, to reclaim the lake in 1764. The project presented by Bindi Sergardi was anomalous for those times because it required the construction of a 2 km long tunnel through the bounding Calcare Cavernoso hills to drain the water from the lake to the Rigo Creek (Fig. 2a). The 2173 m long tunnel was excavated (Fig. 2b) from 1764 to 1777 with a total expense of 36,000 "*scudi*" that eventually led Bindi Sergardi to bankruptcy.

The lake was temporarily drained, but quite often the tunnel became clogged with debris and the area swamped up again. In 1777 Pietro Leopoldo Grand Duke of Tuscany, under strong pressure of Bindi Sergardi and with other 3000 *scudi*, paved and extended the tunnel for 197 m. In 1780 the Silva Lake was definitively drained leaving a flat land now called "Pian del Lago" (Figs. 2, 4a).The original depression is filled

Fig. 4 - (a) Flat lacustrine terrain of Pian del Lago as it is today, surrounded by hills. (b) Sign marking the entrance to the *Canale del Gran Duca* and its length; (c) Pyramid near the entrance of the canal (location – *Piramide* – is on Fig. 2a). (d) The exit of the canal along the Rigo Creek.

(a) Il territorio pianeggiante di Pian del Lago delimitato da rilievi collinari come si presenta oggi. (b) Targa indicante l'inizio del Canale del Gran Duca e la sua lunghezza. (c) la piramide che segna l'ingresso del canale (ubicazione in Fig. 2a). (d) l'uscita del canale nel Torrente Rigo.

with 20 to 30 m of a reddish silty-clayey lacustrine succession lying on Triassic limestone (Calcare Cavernoso) and/or Miocene conglomerate/breccia mainly made of Triassic limestone.

The drainage tunnel is called the *Canale del Gran Duca* (Grand Duke Canal) in honour of the Duke (Dei, 1887) (Fig. 4b). The entrance altitude of the canal is at 252 m a.s.l., and the exit is at 247 m a.s.l. The altitude difference is therefore 5 m, and the floor of the canal has a constant slope of 0.2 %. The canal starts at the SE margin of Pian del Lago plain, a pyramid (Masonic symbol to which the Grand Duke belonged) marks the entrance (Cioli *et al*., 2000) (Figs. 2, 4c) and ends in the Rigo Creek (Figs. 2, 4d).

The canal was tunnelled following the easier route rather than the straightest, and bends were made (the first after 620 m from the entrance) (Fig. 2b) to bypass thick, hard limestone layers. The maximum depth of the tunnel from the surface is 22 meters and 22 wells were used for aeration and to carry out the excavated material (only 10 of them are still visible) (Fig. 5a). The canal has a barrel vault, generally 2.85 m high and 2.25 m wide; it is for the most part paved and the walls are covered by bricks (Figs. 5b, c).

However, in places, solid walls of Triassic limestone are still visible. Because it has been excavated in limestone, diffuse karst features were formed (Figs. 6a, b). Speleothems are mostly developed in the central part of the *Canale del Gran Duca*. They consist of draperies, soda-straw stalactites and flowstones. The first two formed on the vault by water seepage between bricks (Fig. 6a). The second formed where drainage holes were purposively left on the brick walls (Fig. 6b). Some incipient stalagmites may form as well but their growth is limited by the water flowing through the canal (Figs. 5c, 6).The tunnel was probably cleaned and well maintained during and after its construction (1780), and it is reasonable to assume that all the still existing speleothems have developed in the last two centuries.

4. CLIMATIC PROXY RECORDS FOR THE LAST TWO CENTURIES

4.1 Samples and Analytical Methods

A compact well laminated flowstone collected in the central part of the canal has been investigated petrographically and geochemically to determine its growing conditions (Fig. 6b). Different from most of the flowstones sampled along the canal, it is active and shows poor contamination from detrital material, and moderate to low porosity. Petrographic investigations indicate that this flowstone grew continuously through time. It is composed of several aggrading "fan" body-like laminas with a maximum linear thickness of 141 mm (Fig. 7).

Assuming a continuous growth of the speleothem for the 200 years from the time routine cleaning of the canal ceased soon after its final construction and the time of ur sampling (2006), the estimated rate of growth is about 0.5-0.6 mm/yr.

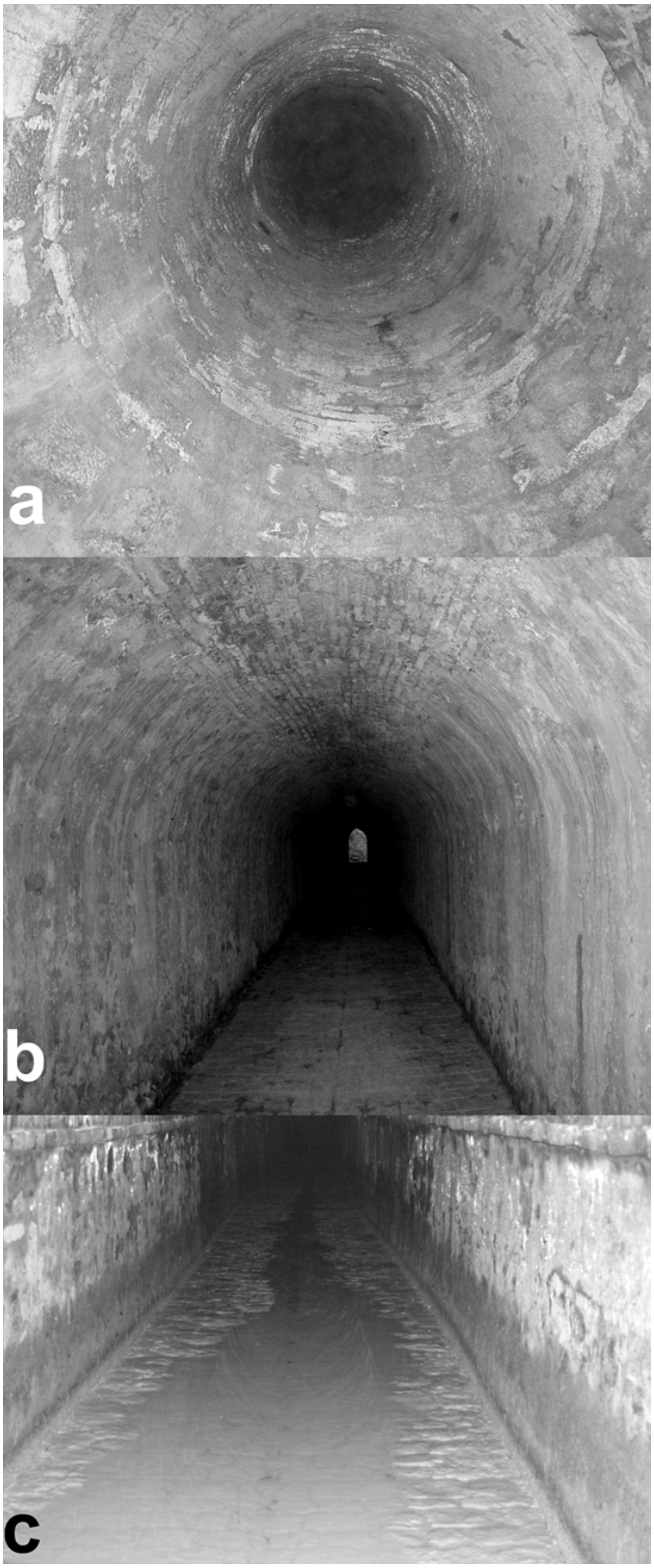

Fig. 5 - (a) One of the wells drilled to remove the excavated material and for aeration. (b) The pavement and vault of the canal close the entrance. (c) Water still flowing inside the canal (middle part).

(a) Uno dei pozzi che servivano per il trasporto in superficie del materiale scavato e per areazione. (b) Pavimento e la volta del canale nei pressi dell'ingresso. (c) Acqua che scorre sul fondo nella parte intermedia del canale.

Fig. 6 - (a) Stalactites and draperies on the vault of the canal. (b) Flowstones on the walls of the canal (bricks are 30x20 cm).

(a) Stalattiti e vele nella volta del canale. (b) Depositi di scorrimento di acqua sui muri del canale (i mattoni sono 30x20 cm).

The internal stratigraphy of the flowstone has been reconstructed using different sections and the best developed surfaces were sampled every 1 mm with a drill of 0.7 mm diameter (Fig. 8) for isotopic analyses. This should give an average record resolution of ca. 2.5 yr (Figs. 7, 8).

Powdered samples were first H_3PO_4-digested, and the produced gas was cryogenically purified and then measured for $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios with a ThermoFisher Delta XP Isotope Ratio Mass Spectrometer at the CNR-IGG of Pisa. Isotopic results are reported using the conventional δ notation in *per mille* (‰), and normalized to the Vienna Standard Mean Oceanic Water (V-SMOW) and Vienna Pee Dee Belemnite scale (V-PDB) using internal working standards of Carrara Marble. These latter standards were cross-checked against the international standards NBS18 and NBS19. Mean analytical precision for both $\delta^{18}O$ and $\delta^{13}C$ is usually better than 0.1‰. Replicate measurements were made where adjacent sample results differed by ≥0.4‰.

To test calcite precipitation and parameters influencing calcite deposition preliminary sampling of calcite-rich dripping waters was carried out during the several visits to the canal. Waters were collected from drips form soda-straw stalagmites and from micro-pools formed at the base of brick walls.

5. RESULTS AND DISCUSSION

Chemical and physical parameters of speleothems, such as lamina thickness, crystal morphology and stable isotopic composition record potential information on palaeoclimate (Fairchild *et al.*, 2006). The flowstone isotopic record shows significant variability both in the carbon and oxygen isotopic composition indicating decadal scale environmental variability. Noticeably, the carbon and oxygen isotopic trends are substantially matching (Fig. 9). This covariance may result from kinetic fractionation during calcite precipitation, but in most cases it is a genuine environmental and climatic signal (Mickler *et al.*, 2006).

The $\delta^{13}C$ values are in good agreement with data from temperate regions, usually between -4‰ and -12 ‰, where a significant soil cover occurs, and the $^{13}C/^{12}$ ratios of speleothemic carbonate are influenced by the isotopically light soil CO_2 produced by plant respiration (Lauritzen & Lundberg, 1999; McDermott, 2004). Changes in $\delta^{13}C$ values could be tentatively related to changes of CO_2 production in the soil present above the canal. Increases in rainfall and

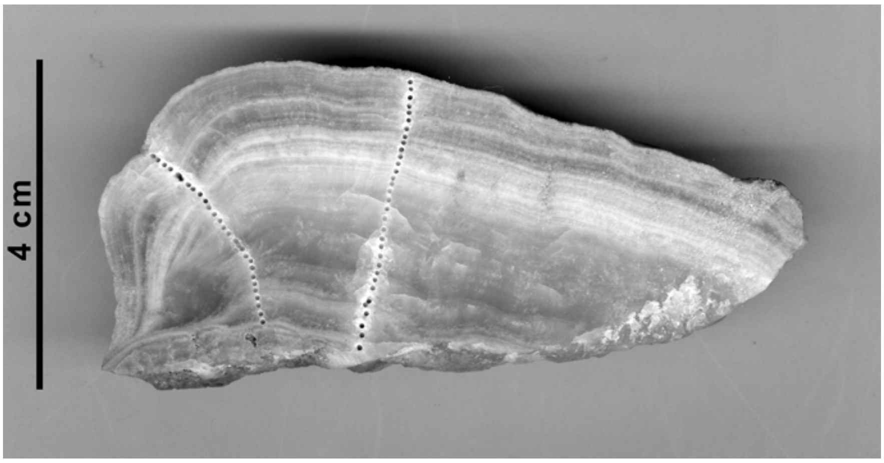

Fig. 7 - Cross section of the study flowstone showing the internal fan body-like (laminar) feature at the top. Holes indicate the drilled sampling points.

Parte superiore del deposito di scorrimento mostrante la sua struttura laminare. I buchi indicano i punti dove è stata eseguita la campionatura con il micro-trapano.

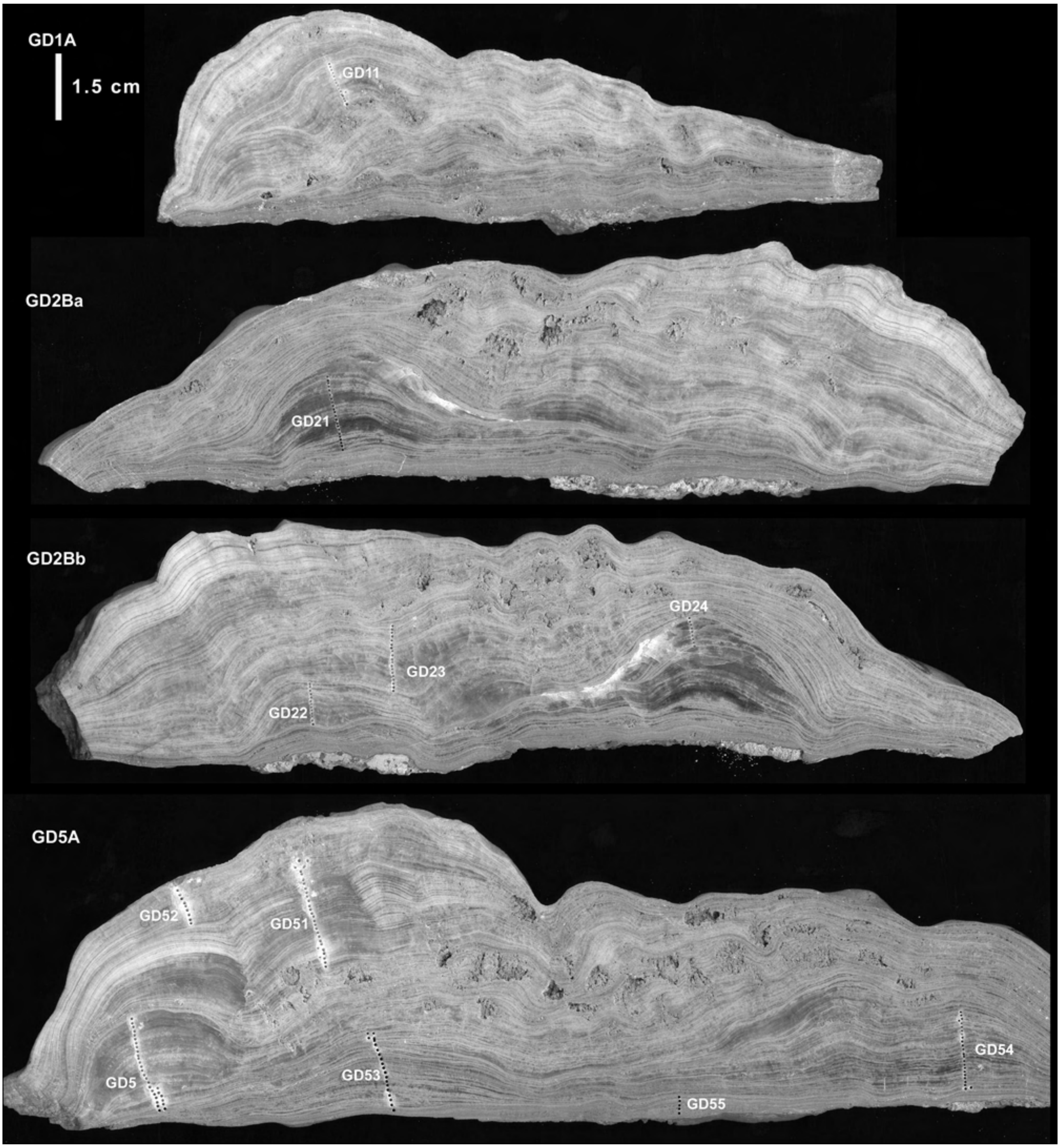

Fig. 8 - Internal stratigraphy of the analyzed flowstone shown on different sections and the best developed surfaces. Holes are made with drill of 0.7 mm diameter to collect calcite powder for isotopic analyses.

Stratigrafia interna del deposito di scorrimento analizzato ricostruita attraverso l'uso di diverse sezioni tagliate lungo le superfici meglio sviluppate. I buchi hanno un diametro di 0.7 mm e sono stati fatti per raccogliere polvere di calcite per le analisi isotopiche.

temperature may improve soil CO_2 productivity (Raich & Schlesinger, 1992) and reduce speleothem $\delta^{13}C$ values (Genty *et al.*, 2003). Abundant rainfall can also limit the opportunity of prior calcite precipitation during seepage (Fairchild *et al.*, 2000), a process that may enrich $\delta^{13}C$ along the percolation pathway due to progressive degassing of CO_2.

Variations of $\delta^{18}O$ values in speleothems can be caused by changes in cave temperature (a proxy for mean annual temperature), O-isotope composition of the source drip waters, and different in-cave physico-chemical processes (evaporation due to air currents; McDermott, 2004). In temperate regions, the $\delta^{18}O$ values of cave drip-water reflect those of local rainfall, which in turn may vary according to changes in rainfall amount, air-mass history, condensation temperatures and global ice volumes (McDermott, 2004). The isotopic composition of speleothem calcite within a

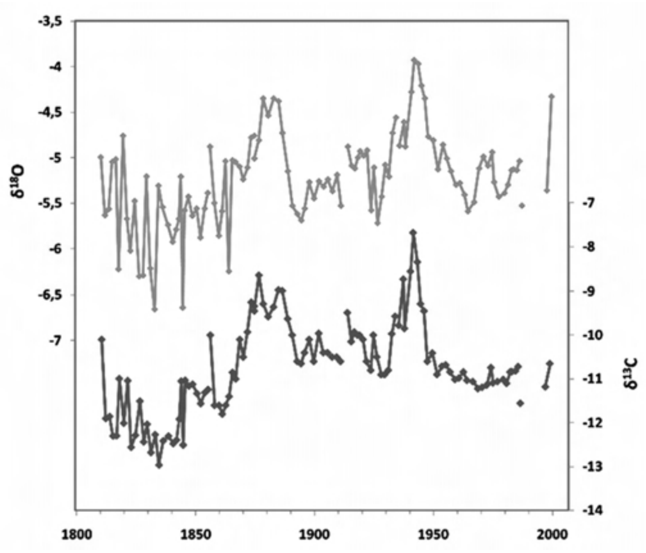

Fig. 9 - Stable isotope compositions ($\delta^{18}O$ and $\delta^{13}C$) data from the sampled flowstone. On the X axis the estimated ages are reported.

Composizione degli isotopi stabili ($\delta^{18}O$ and $\delta^{13}C$) derivati dall'analisi del deposito di scorrimento. Sull'asse delle X sono riportate le età stimate.

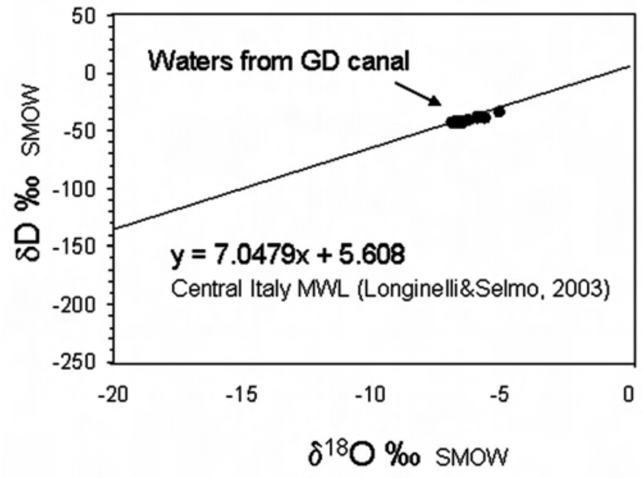

Fig. 10 - Relationship between $\delta^{18}O$ and $\delta^{13}C$ of mean monthly water samples collected in Central Italy (Longinelli & Selmo, 2003). Grey circles: samples of drip waters collected in the Canale del Gran Duca; black dot: average meteoric waters from the city of Siena.

Relazione tra le medie mensili degli isotopi $\delta^{18}O$ and $\delta^{13}C$ come ricavate dall'analisi delle acque dell'Italia centrale (Longinelli & Selmo, 2003). I cerchi in grigio sono i campioni di acqua di percolazione raccolti nel Canale del Gran Duca. Il cerchio nero è relativo ai valori misurati nelle acque meteoriche raccolte a Siena.

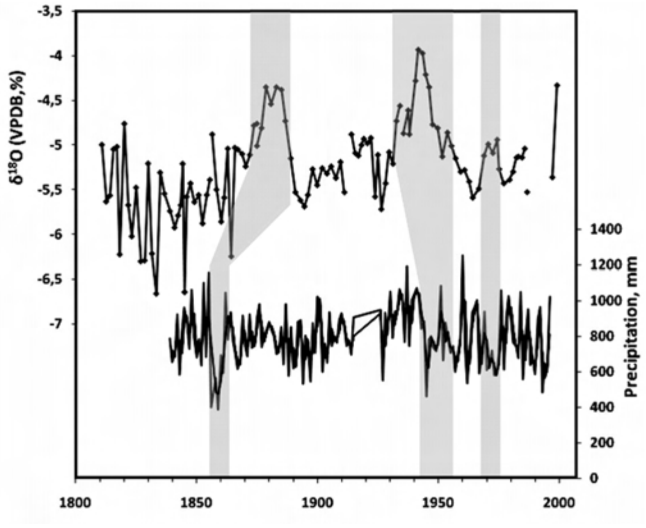

Fig. 11 - $\delta^{18}O$ values and annual average rainfall as measured in the Siena area from 1839 to date.

Correlazione tra i valori isotopici $\delta^{18}O$ e le precipitazioni dell'area di Siena misurate dal 1839.

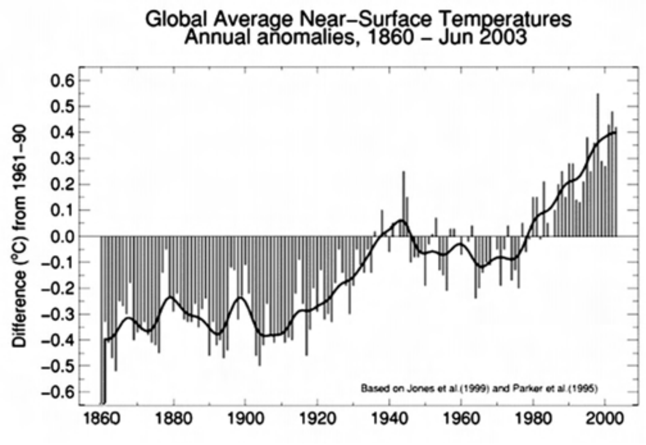

Fig. 12 - Global average near-surface temperature annual anomalies, 1860–2003 (after Jones *et al*., 2010). (5y = five-years running average).

Anomalie delle temperature annuali prossime alla superficie dal 1860 al 2003 (da Jones et al., *2010).*

Mediterranean environment is principally related to the isotopic composition of precipitation (which is in turn strongly related to the amount of the precipitation) rather than average temperature (Bar-Matthews *et al*., 1997, 2000; Bard *et al*., 2002; Drysdale *et al*., 2004; Zanchetta *et al*., 2007). However, this relatively simple observation is complicated by several factors like the provenance of precipitation (Celle-Jeanton *et al*., 2001).

Figure 10 shows that the isotopic composition of the canal waters is substantially aligned along the local meteoric water line defined by Longinelli & Selmo (2003). This figure indicates that evaporation is not a significant process affecting soil and seepage waters. Although some variability may also indicate that seepage water of the Grand Duke Canal system has different routes and residence time within the soil/epikarst zone and that it is recharged by different meteoric events. However, the average isotopic composition ($\delta^{18}O$: -6.0±0.5‰; δD:-39.8 ±2.9) is close to that reported for the city of Siena ($\delta^{18}O$: -6.5 ‰; δD: -39.6, Longinelli & Selmo, 2003). This suggests that seepage waters are relatively well mixed and, as first approximation, the measured $\delta^{18}O$ values represent the average local meteoric precipitation waters. Accordingly, higher

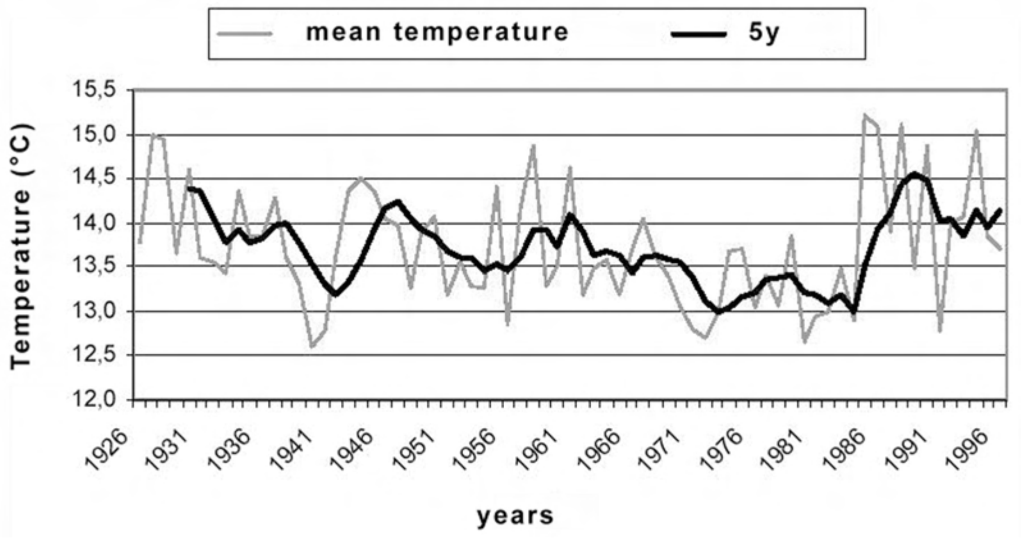

Fig. 13 - Temperature data of the area of Siena from 1926. (bold line= 5 yr: five-years running average) (data from ANNALI IDROLOGICI TOSCANI).

Temperature misurate a Siena dal 1926 (la linea in grassetto indica la media calcolata ogni 5 anni) (dati derivati da ANNALI IDROLOGICI TOSCANI*).*

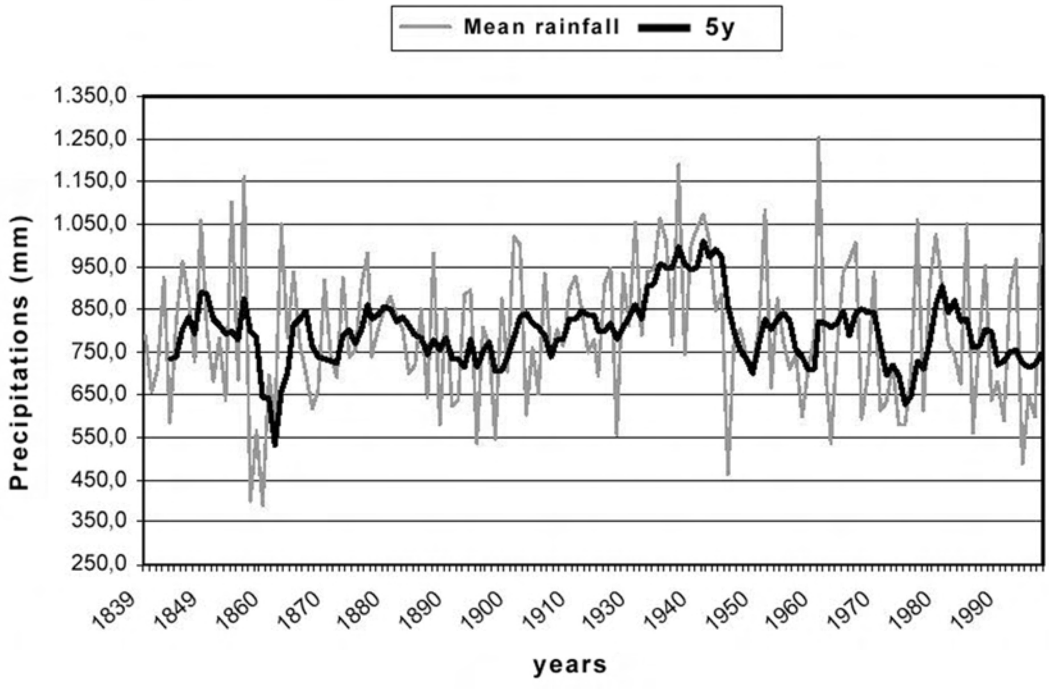

Fig. 14 - Rainfall data of the area of Siena from 1839. (bold line=5 yr: five-years running average) (data from ANNALI IDROLOGICI TOSCANI).

Precipitazioni misurate a Siena dal 1839 (la linea in grassetto indica la media calcolata ogni 5 anni) (dati derivati da ANNALI IDROLOGICI TOSCANI*).*

‰18O values in calcite are interpreted in terms of decreasing amounts of rainfall (and viceversa; ZANCHETTA *et al.* , 2007).

Although our age model is only a preliminary approximation, two main phases of prominent reduction of rainfall (and soil CO_2 productivity) at ca. AD 1870–1890 and AD 1930–1950 can be envisaged, whereas a very wet phase seems to have persisted between ca AD 1810 and 1830 (Fig. 11). It is interesting to note that the sharp rise in isotopic values at ca AD 1860 corresponds to the “classic” end of the Little Ice Age (BRADLEY & JONES, 1993). This may be interpreted as an overall reduction in meteoric precipitation.

A direct comparison between palaeoclimatic proxies and direct measurements can be performed using the long meteorological record available for Siena (ANNALI IDROLOGICI TOSCANI, www.idropisa.it). Temperature data derived from the Siena archives can be compared with those of global average near-surface temperature annual anomalies, 1860–2003 (JONES *et al.*, 1999, 2010; PARKER *et al.*, 1995) (Fig. 12). The warmest global years are recorded around 1940, whereas the same period is considered the coldest around Siena area (Fig. 13).

Global temperature remained stable until 1980, from where they started to increase continuously until 2003. Data relative to Siena, however, indicate that temperature increased between 1986 to 1990, to drop down (still remaining 1°C higher than before) from 1991 to 2003 (Fig. 14). No significant correlation can be sustained between isotopes and temperature data (even if our age model and the short period of comparison can hide any correlation) (Figs. 9, 13). However, using precipitation data (Figs. 11, 14) the correlation is clearer (although some relatively few adjustments are needed). Periods of low rainfall recorded between 1870–1890 in the flowstone may correspond to the low rainfall period centred at about 1860 in the meteorological record. A better correlation exists in the recent part of the record where the very low period of rainfall inferred from isotopes between ca. 1930 and 1950 is correlated with the period centred at about 1950 in the meteorological records. It is obvious that an improved age model is essential to provide more accurate conclusions. Nevertheless, our isotopic interpretation is robust (as tested in many other cases in central Mediterranean even if not for so fine scale resolution; DRYSDALE *et al*., 2004, 2006, ZANCHETTA *et al*., 2007), and an improving of our preliminary age model will allow for a transfer function to longer study records.

It is also quite clear that the observed isotopic variability cannot only result from changes of average annual climate conditions. This likely reflects a seasonal component, which can have impact on tunnel air flow and temperature, and influence the kinetics of calcite precipitation. For such reasons future research must be addressed to obtain a better constrained age model (coupled with increasing record resolution) and to improve the temperature, precipitation and humidity monitoring of the canal.

6. CONCLUSIONS

Between 1760 and 1780 an about 2 km long canal (Grand Duke Canal) was tunnelled to drain Lake Silva. Part of the vault and walls of the canal are now covered by speleothems, mainly stalactites and flowstones, which record past climatic conditions. The tunnel was cleaned and well maintained after the first years of its construction. We have assumed that the speleothems have developed in the last two centuries. One flowstone was selected for study in the central part of the canal for its good quality and absence of significant growth hiatuses. Data obtained from this flowstone show interesting covarying isotope trends and large variability in the environmental condition within and above the canal, of potential climatic significance. Using consolidate "paradigm" on the interpretation of isotopic composition (oxygen and carbon isotope compositions) in cave carbonates from the central Mediterranean, our data show an important isotopic change at about 1860, likely reflecting progressively drier conditions related to the end of the Little Ice Age, with two prominent dry phases at 1870–1890 and 1930–1950. A better numerical geochronology is needed to constrain the correlation of the stable isotope record with the historical instrumental data.

The methods here used can be tied back to ancient Siena and/or similar cities, to reconstruct past palaeoclimatic conditions through man-made tunnels such as the "*bottini*" in Siena. Calibrating the results with whatever historical information are available, one could try to understand particular events that occurred in the old cities or territories possibly related to climatic changes (such as infestation of ponds, famines, floods, sicknesses). Generally historical climate archives of the last 200-300 years, although not always easy to understand and to correlate to real climatic events, are relatively precise and quite often available. Such as an example, we may argue that 1860 and close years were relatively dry. Probably it is not only a case that at the same time around Siena, Baron Ricasoli established the institution of the Sant Isodoro fest as good hope for rain (ADDABBO & RASMUSSEN, 1994).

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