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Archaeology and Hydrogeology in Sicily: Solunt and Tindari¹

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Abstract: This contribution concerns the relationship between the hydrogeological and archaeological characteristics of Solunt and Tindari (North Sicily), within the framework of the Watertraces project. The two cities face the Tyrrhenian Sea, on the northern coast of Sicily, are characterised by a relatively recent urban history compared to other Greek or Phoenician cities, being founded in the 4th century BC. The Hellenistic-Roman city of Solunt was moved from the promontory of Solanto to Mount Catalfano after the devastation of the first in 397 BC. The new position of the habitat offered advantageous defensive conditions and allowed it to control a vast territory, from the Gulf of Palermo to the Gulf of Termini and the hinterland. The steep slopes of Mount Catalfano did not prevent the inhabitants realising a regular urban network. Considering the hydrogeological characteristics of the mountain, the rise of hydrothermal waters along fracturing planes led to the formation of small surges which were used by the inhabitants and whose waters were collected through tanks and basins. In this way, the city could benefit from a double supply of water: precipitation and natural rises.

Tindari is also located on a cliff overlooking the sea. The site was founded at the beginning of the 4th century BC. The city soon became an important commercial centre due to its advantageous geographical location. As for Solunt, the orographic features provided an important natural defence of the site, reinforced by powerful ramparts embracing the contour lines. The discovery of travertine formations close to a cistern underlines, as in Solunt, the importance of the hydrogeological context, here characterised by karst exes whose waters served the city and more probably the public area.

In Solunt and Tindari, the hydrothermal and karstic springs are now dry. This could be related to a seismic event described in the ancient sources. We know in fact that the city of Tindari was shaken by several earthquakes during its history. One of them is reported to us by Pliny and dates back to the 1st century BC. Another one would have caused several devastations in the city during the late period. Ongoing analyses at the archaeological, geomorphological, hydrogeological and palaeosimological levels, coupled with geochronology and isotopic water geochemistry, little by little, we discover the history of the water supply and management of these two key cities of the Hellenistic-Roman Sicilian world.

Keywords: hydrogeology, sources, cisterns, Solunt, Tindari

Introduction

Interdisciplinary studies have been widely developed for several years. Collaborations between archaeologists and geomorphologists promote increasingly detailed reconstructions of landscape dynamics.² In Sicily, conversely, the study of ancient cities has focused more widely on their archaeological aspects, above all urban planning and architecture, while the geological, geomorphological and environmental aspects have been integrated there for only a few decades. Today, with the rise of recent scientific projects, this type of integrated approach seems to be better invested in by the community of archaeologists.

In Sicily, the first analyses of this type concerned Termini Imerese, during the study of the Cornelio aqueduct by Oscar Belvedere.³ The author proposed an integrated reading of the landscape and geology of the territory of the Roman colony. His work also dealt with the topographical and structural aspects of the Himera landscape, adding paleoclimatic and geological data to clarify the causes of the wealth of the Chalcidian colony.⁴ Also worth mentioning are specific isolated studies, including geological analyses, on the indigenous sites of western Sicily during the 1990s. In Colle Madore, the study carried out by Stefano Vassallo on a shrine, probably linked to the cult of local sulphurous waters, saw the participation of a geologist who helped the team understand the context.⁵ For Monte Maranfusa, a monograph directed by Francesca

¹ The project leading to this publication has received funding from Excellence Initiative of Aix-Marseille University – A*Midex, a French 'Investissements d'Avenir' programme.

² <https://www.topoi.org/>.

³ Belvedere 1986.

⁴ Belvedere *et al.* 2002.

⁵ Vassallo 1999.

Spatafora incorporates a geological analysis, treated separately from the topographical and archaeological aspects of the site.⁶ Later, geomorphological studies at Tindari focused on the impacts of earthquakes on the ancient city⁷ and its harbour.⁸ Finally, the most recent research on Syracuse, conducted by Sophie Bouffier, has sought to determine the origin of the waters supplying the city through the Galerme aqueduct.⁹

In this contribution, our objective is to show how we have approached this recent orientation of classical archaeology, which integrates archaeology, human ecology and environmental sciences, on the study of two cities, Solunt and Tindari, founded in the 1st millennium BC on the northern coast of Sicily, and how we were able to understand part of the policy of the authorities of these cities to supply the population with drinking water. The natural element could indeed influence the choices of the inhabitants, for instance the location of the buildings or the urban organisation. According to Philippe Fraisse, the urban planning of Delos could be determined by the presence of numerous natural depressions, which could offer reserves of natural water and thus determine the location of neighbourhoods, by constituting open-air reservoirs.¹⁰

As part of the Watertraces programme, in October 2018 an interdisciplinary team carried out research at both sites. The aim was to understand the geomorphological and hydrogeological specificities and to detect possible impacts of the environmental context on the development of Solunt and Tindari,¹¹ as well as to verify through rock and water sampling the possible rise of the waters of the sub-soil within sites. This last aspect, discussed in the following chapters, is well known in the geological context of the Sicilian landscapes.¹² Sicily has rich reserves of hydrothermal or thermo-mineral water; these waters are in contact with magmatic fluxes that enriched it with minerals and the pressure caused by the heat of the subsoil allows the waters to rise and create thermal springs whose temperature is variable.¹³ For the first time we reported the traces of this phenomenon in Solunt and we were able to relate it to the archaeological remains, allowing a new and innovative reading of the water supply in apparently anhydrous sites.

Solunt and Tindari do not present today clear traces of a water supply other than rainwater systems (cisterns). However, while the Mediterranean climate has always been influenced by annual and interannual irregularity, with very dry periods, the question is raised as to how a city of some eight thousand inhabitants could have been founded, develop over almost eight centuries, between the 8th century BC – 3rd century AD, with a water autonomy of almost 10,000 m³: how were the periods of water deficit overcome? The issues of diversity and origin of water supply patterns were crucial. The field missions carried out under the Watertraces project allowed us to cross hydrogeological data and archaeological remains, and to show that the local populations were able to take advantage of resources, that have now disappeared, in order to provide abundant water to the cities, whatever its needs.

Solunt and Tindari: a similar geological and climatic framework, but with specific characteristics

Solunt and Tindari are located on the northern coast of Sicily among high mountains. Our previous research had shown that at these sites the rise in waters could be verified in geological time as well as in recent times.¹⁴ Our research was conducted from this point of view: it was always thought that for the hydraulic supply of a city that rainwater collected in cisterns was sufficient. In view of the rather dry nature of the Sicilian climate, of a thermo-Mediterranean type (up to three consecutive months of dry season over the year), it seems necessary to consider additional contributions only to waters resulting from precipitation.

Solunt, founded by the Carthaginians c. the 4th century BC, is located on Mt Catalfano, a limestone massif 235 m a.s.l., marked by its steep slopes (average of 32%) and cliffs (average of 75%) overlooking the Tyrrhenian Sea. From the lithological point of view (Figure 1), this region belongs to the deposits of the Bacino Imerese,¹⁵ where different types of formations are followed from top to bottom, including:

- Limestones of the Caltavuturo Formation (Eocene), the Crisanti Formation (Upper Middle Cretaceous Jurassic) and the Fanusi Formation (FUN), which corresponds mainly, in our sector, to a Mesozoic Brechic and Dolomitic limestone complex (at a 40° dip towards the south-west), whose series of the Lias (Lower Jurassic) approaches a thickness of 300 m.
- Dolomites and dolomite veins, with high fracture and karstification permeability, emerging along the coast, especially at Sant'Elia (Scillato-SCT Formation).

⁶ Spatafora 2003.

⁷ Bottari *et al.* 2008.

⁸ Bottari *et al.* 2012.

⁹ <https://hydromed.hypotheses.org/893>

¹⁰ Fraisse 2015–2016: 864–865. See also the example of the large open cistern of 'House B' south-east of the Theatre, which, according to the excavators, had a collective function, being used by the inhabitants of the neighbouring houses. Chamonard 1933: 146–147.

¹¹ Polizzi *et al.* 2017; Ollivier 2020.

¹² Bonica Santamaria 2001: 22–27.

¹³ Montanari *et al.* 2017.

¹⁴ Polizzi *et al.* 2017; Polizzi *et al.* 2020.

¹⁵ Catalano *et al.* 2013: 61.

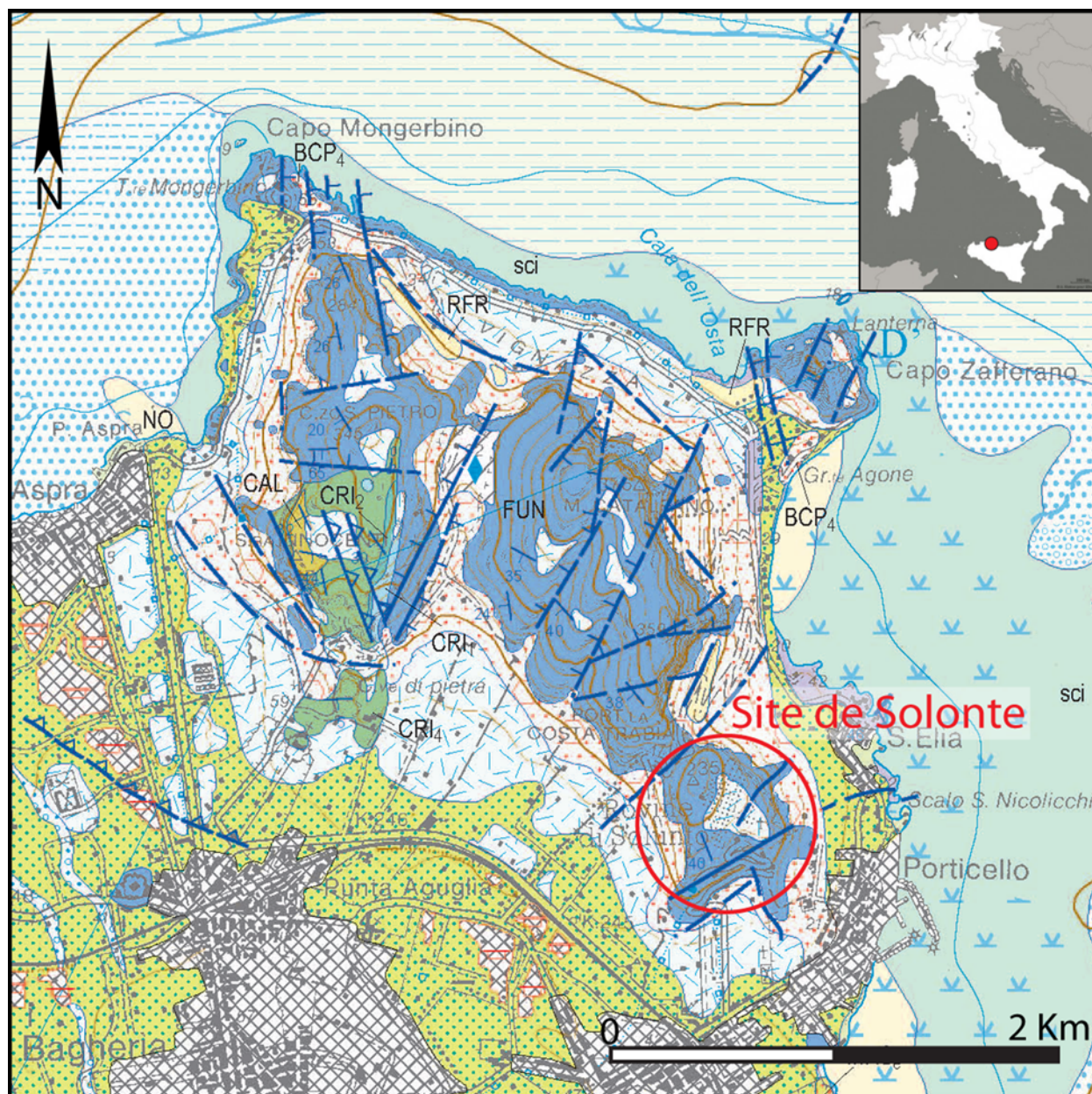


Figure 1: Geological map of Monte Catalfano (Catalano *et al.* 2013).

- Mufara Formation (MUF) clay limestone. The latter are impermeable and are not flush in this area.

This morphological unit, structurally belonging to the Palermo Mountains, is intensely fractured by relatively active tectonics. Along the main fractures widened by the karst there are caves of varying importance, the depths of which can reach -66 m, which contain important forms of concretions (speleothems).¹⁶

Some 160 km to the east, the town of Tindari was founded at the beginning of the 4th century BC on the

promontory of the same name,¹⁷ on the Tyrrhenian side of the Peloritain Mountains. This feature, elongated north–west/south–east, is characterised by a notable cliff on the north–east sector and by slopes more or less accentuated to the west. Tindari itself is located in the north–eastern sector of Sicily, and its lithology (Figure 2) is part of the northern range, which constitutes the structural unit of the Peloritain Mountains.¹⁸ The latter consists of superimposed levels, the main ones being:

- Aspromonte Unit (PMP, MLE a-c): metamorphic rocks composed mostly of highly fractured grey

¹⁶ Catalano *et al.* 2013: 31.

¹⁷ Diod., XIV, 78, 5–6.

¹⁸ Marbot 1961: 311.



Figure 2: Tindari geological map (Catalano *et al.* 2013).

marble¹⁹ (biotitic gneiss, muscovite-biotitic schist, micaschist, amphibolites and marbles).²⁰

- Capo d'Orlando Flysch (COD): poly-genetic conglomerates with arenites and thin clay levels.²¹
- Current alluvial and coastal deposits (g2): gravel and sand originating from erosion of metamorphic rocks.²²

From the morphostructural point of view, the sector is crossed by the Tindari Fault, oriented NNW²³ and crossing eastern Sicily from the Aeolian Islands to the northeast sector of Etna. This fault is characterised by straight-lateral and extensional movements dated from

the middle and upper Pleistocene.²⁴ These movements have caused several earthquakes over the centuries,²⁵ one of the most important, probably 6° on the Richter scale,²⁶ caused extensive damage in Tindari shortly before the abandonment of the site, in the 8th century AD.²⁷

Tectonic and seismic movements directly influence the rise of the fluids by artesian conditions by fracturing the various aquifers and reservoirs. The composition of the freshwater, hydrothermal, hypothermal or karstic, by rebalancing with atmospheric pressure, then generates carbonate precipitation and concretions that directly testify to the hydrogeological origin of the waters.

¹⁹ Carbone, Messina and Lentini 2011.

²⁰ Catalano *et al.* 2013: 18–20, 66–71.

²¹ Catalano *et al.* 2013: 71.

²² Catalano *et al.* 2013: 85.

²³ De Astis *et al.* 2003.

²⁴ Catalano and Di Stefano 1997.

²⁵ Neri *et al.* 2003.

²⁶ Bottari *et al.* 2008: 221.

²⁷ Spigo 2005: 18.

Pluviometria media annua (1946-1983)

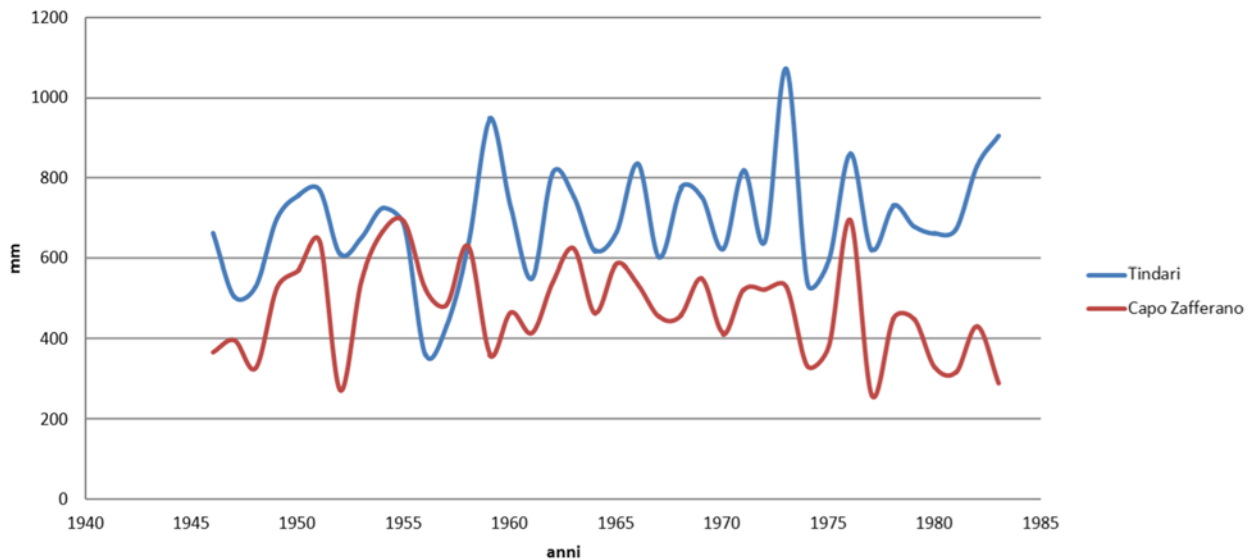


Figure 3: Mean rainfall at Solunt (Capo Zafferano) and Tindari (years 1946–1983) (by G. Polizzi).

In addition to geological data, the understanding of the ancient environment and the availability of water can be perceived through studies on climate variations. The analysis and integration of paleoclimatic data was mainly focused on its relationship to the development of societies and the fall of the great civilisations of the Bronze Age²⁸ and the Roman Empire.²⁹ This research area, however, is under development in Sicily, dependant on the enrichment of the database concerning the historical period.³⁰ As can be seen in the article by Pasta *et al.* (this volume), most of the data cover a chronological range that is too wide and too low a resolution for the period in question. Studies carried out at Selinunt³¹ show, for example, that the period between 350 BC and the 1st century AD recorded a gradual increase in temperatures and a decrease in water reserves, while between the 6th and 4th centuries BC the rainfall was greater. These data are also confirmed for the Morgantine site in central Sicily.³²

For a hypothesis of the water availability in Solunt and Tindari during Antiquity we therefore analysed the rainfall data of the 19th century, for a period of time between 1946 and 1983 (Figure 3). The weather station of Solunt was located in the promontory very close to Capo Zafferano at a height of 22 m a.s.l., and it operated between 1928 and 1999. For Tindari, the

weather station was at the site itself, at a height of 280 m a.s.l., and it functioned between 1926 and 1983.³³ Generally, Sicilian precipitation is concentrated in the cold period of the year (autumn/winter). The isohyet maps show the distribution of rainfall at the regional level over the period 1921–2005 (Figure 4). Areas with high rainfall are concentrated in the mountain ranges, where the average rainfall is between 600 mm and 1600 mm per year, in central-southern and south-western Sicily, which are the driest areas. In the rest of Sicily, the average rainfall is between 300 mm and 800 mm per year. More than 80% of this rainfall is concentrated between October and March. The dry season can last between three and six months.

In Solunto, the trend is towards a gradual decrease in rainfall from the end of the 1970s. This trend has been recorded throughout central-southern Italy and is accompanied by a gradual increase in temperatures. The average rainfall remains between 700 and 260 mm. At the annual level, the rains are concentrated mainly in the autumn/winter months (between October and February). During the spring a reduction occurs, sometimes to zero during the summer months. Over 73 years of measurements, 45 months of July were dry. In the summer months, and especially in August, intense rains can be recorded, the value of which is between 30 and 50 mm, in the form of heavy showers. The climatic conditions of Tindari are not very different, although it is possible to count on slightly more abundant rains. Here the average rainfall is 300 to 1000 mm/year.

²⁸ Cline 2014.

²⁹ Harper 2019. For the ongoing debate on the relationship between the fall of Rome and the climate see Leveau *in press*.

³⁰ Sadori *et al.* 2016.

³¹ Ortolani, Pagliuca 2007.

³² Sadori *et al.* 2013: 1981.

³³ The data used in this chapter have been collected on the website <http://www.osservatorioacque.it>, where they can be consulted free of charge.

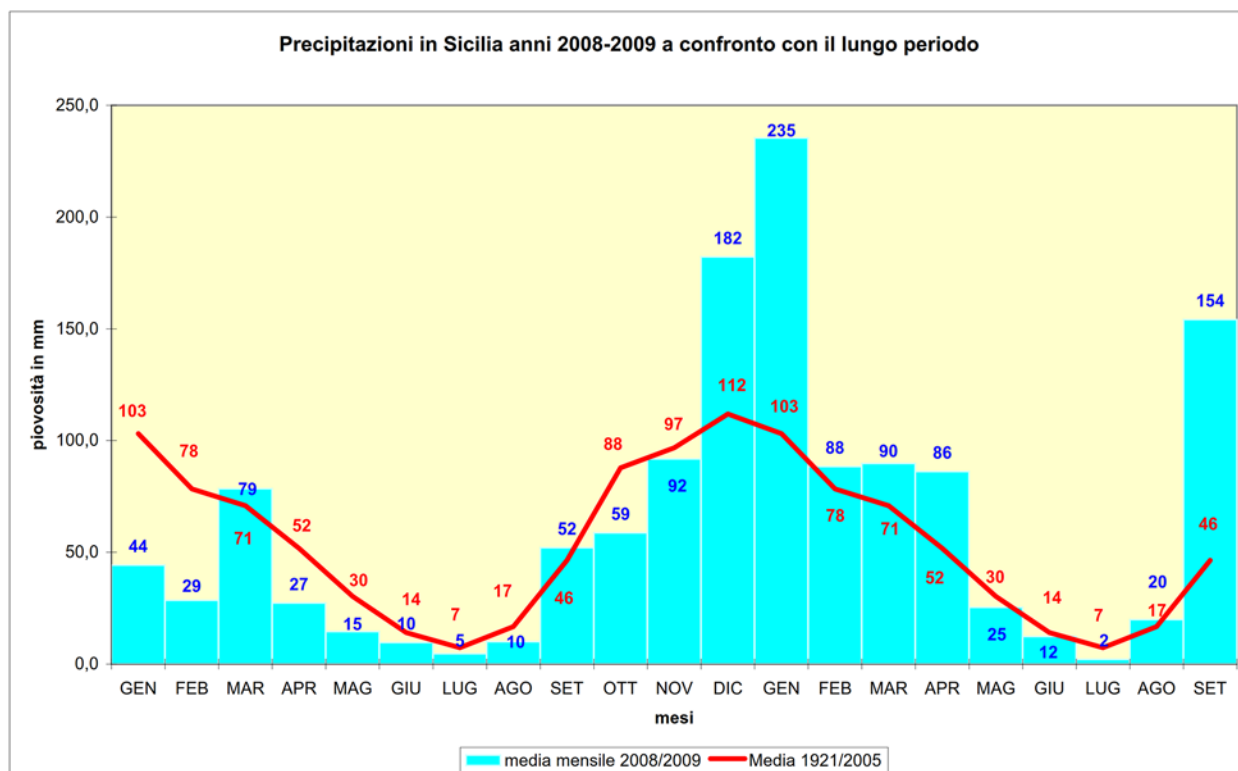


Figure 4: Average rainfall in Sicily (2008/2009/long period ratio).

For both sites, the differences in precipitation in the year are significant and the minimal curve (Figure 4) shows us the current difficulties in water supply if adequate storage is not foreseen. One might wonder, for example, how the inhabitants of the city reacted during the driest periods if they had to rely only on rainwater. If we transpose similar climatic conditions during Antiquity, especially considering the length of dry periods, the sites in question could be affected by significant water crises. In addition, in Solunt, the calculation of the rainfall flow rate, cross-referenced with an estimate of water consumption per person, shows that there was a need for a greater quantity of water than just stored rainwater.³⁴

On the basis of the rainfall data, and considering the demographic values and a need for water of 7 litres/day/person for the winter and 13 litres/day/person for the summer,³⁵ the quantity of water is sufficient, in Solunt and Tindari, for a population of 3,000 and 4,000. If, on the other hand, a value of 25 litres/person/day is considered³⁶ then it can be estimated that rainwater alone was insufficient to meet population needs, since these would increase exponentially, by estimating a

maximum number of inhabitants. So, we had to look elsewhere for other resources. This is demonstrated, for example, by the fact that the most important Hellenistic-Roman cities of Sicily had, in addition to the cisterns, additional water supplies, consisting of internal or nearby sources, such as Morgantina³⁷ and Palermo,³⁸ or aqueducts that brought in water from further away, such as Halaesa,³⁹ Kalé Akté,⁴⁰ Taormina,⁴¹ and Termini Imerese.⁴²

Our research was thus to find out how the two cities under discussion were able to supplement the meteoric resources, and we searched locally for former traces of water that have now disappeared. In this way, we propose the hypothesis that this additional water came from underground lifts, was captured in tanks, and/or used in collective buildings.

The phenomena of artesian rises of water along fault planes

The Monte Catalfano massif, where Solunt is located, has a significant specific permeability and a large capacity for storage and recharge of meteoric waters.

³⁴ Statistics on the water requirements of the inhabitants of Solunt are based on research conducted in Pompeii (Dessales 2008) and Pergamon (AvP I.4: 37–39). They will be published in a forthcoming monograph.

³⁵ Data drawn by AvP I.4.

³⁶ Derived from data FAO. Dessales 2008: 37.

³⁷ Bruno 2015.

³⁸ Agnesi 2019; Polizzi 2020a.

³⁹ Burgio in this volume.

⁴⁰ Collura 2019: 257.

⁴¹ Muscolino 2020.

⁴² Belvedere 1986.

The data collected during field missions made it possible to identify a series of main tectonic accidents generally oriented NE–SW. But more importantly, several secondary beam fracturing stalling from W to NW have calcitic laminations filling the fault planes.⁴³ These mineralisations indicate a control of fracturing on the geometry of fluid circulations and highlight the local carbo-gas potential. In Solunt, these upward fluid flows seem to have worked on a geological scale but some were active during the occupation of Monte Catalfano. Indeed, several veins and archaeological structures show laminations and concretions on the walls. The possible hydrothermal character of the waters of Solunt would be represented today, in the nearby bay, by paravolcanic phenomena⁴⁴ with deep waters rich in minerals.⁴⁵ In addition, near Pizzo Cannita and Villabate, less than 5 km from Monte Catalfano, hydrothermal activity is also reported in a text dating from the 16th century.⁴⁶ All these indicators suggest that the artesian rise of the waters worked during the occupation of Solunt.

The present urban layout of Solunt dates back to *c.* the 2nd century BC. At that time a programme of monumentalisation involved both the collective and private spaces.⁴⁷ The excavations have restored a well-integrated water network in the urban setting, where every drop of water was valued. The city, in fact, has many cisterns, individual or collective, to store rainwater and subsoil. These presented two construction techniques: either dug into the rock, and of irregular plan, or masonry and regular plan.⁴⁸ The roof received rainwater that was brought into the tanks through vertical or horizontal pipes. The cisterns dug into the rock still have an irregular shape and a niche in the south-west corner. The walls are waterproofed with a mortar based on lime and sand, often restored over the centuries, and their capacity is between 20 – 30 m³. The dating of these tanks is estimated to the 4th – 3rd centuries BC. What we found during our field missions, is that the location of these cisterns is linked to the limestone substrate and conditioned by the need to exploit the groundwater veins, through the presence/absence of the fractures of the mountain. The presence of spring water left traces through limestone concretions visible at the south-west corners of the cisterns. The plan in Figure 5 shows that several cisterns were dug at the level of the natural fractures of the mountain that we noticed on the ground (the red dotted line), and that several cisterns often exploit the same natural fracture.

We observe the same phenomenon in the construction of community structures, as at the South Baths (Figure 6), located in the south-east sector of the city, near the old urban gate. The building occupies an area of almost 300 m², organised on two terraces.⁴⁹ A cistern to the west of the *frigidarium* Nord (Room H) received rainwater, but also captured the hydrothermal rising waters via a fracture in the mountain. The tank has a capacity of almost 20 m³, has an L-shaped plan, and is on a slope towards the north. The walls are waterproofed with a lime and sand coating. The same natural fracture probably fed a small fountain inside the room. Of the latter, there only remains an empty space for the housing of a block, with a drain hole on the west wall of the room (Figure 7).

The discovery of the practice of recovering groundwater in the installation of the cisterns allowed us to look again at some poorly understood archaeological structures, i.e. within the sacred sector of the city (Figure 8). The importance of water in the cults of the Phoenician-Punic world has recently been well highlighted.⁵⁰ It is likely that in Solunt, too, as in other Punic sites on the island (i.e. Monte Adranone),⁵¹ water played an important role in the ritual sphere. The sanctuary of Solunt, currently being studied via Elisa Chiara Portale's archaeological excavations, is organised on two terraces and equipped with three main sacred buildings (Figure 8, AB, C, DE). A fourth building further south (Figure 8, F), probably to be read as a service space for the sanctuary, has a large irregular cistern, the only one for the entire religious sector, installed on a fracture of the mount. It is likely that this tank exploited the resurgent waters, as suggested by the presence of a niche in the south-west corner and the presence of calcareous concretions (Figure 10).

Traces of concretions were also found on a sporadic architectural block from the 'Edificio sacro a due navate',⁵² just north of the service building (Figure 9). The block in question (44 x 29 x 19 cm) has a rectangular shape and a bevelled side with a hole in a circular section of 6 cm in diameter, inside which are the concretions. We cannot say anything about its exact function, but the traces of stratified concretions suggest the passage of a spring water that was in some way collected and used. The same reduced diameter suggests a water supply function, while all the pipes linked to the passage of rainwater or runoff have a maximum width of 19 cm, probably related to the need to clean the pipes, but this would not be the case for the block in question.

⁴³ Catalano *et al.* 2013: 175–176.

⁴⁴ Sulli *et al.* 2011.

⁴⁵ Grassa *et al.* 2006.

⁴⁶ Amico 1856; Di Matteo 1986.

⁴⁷ Portale 2006.

⁴⁸ Polizzi 2019; Polizzi 2020b.

⁴⁹ For a general description of the building, see Trümper 2020: 368–376.

⁵⁰ Usai 2014; Fumadó Ortega 2019.

⁵¹ Trombi 2020.

⁵² Portale 2020.

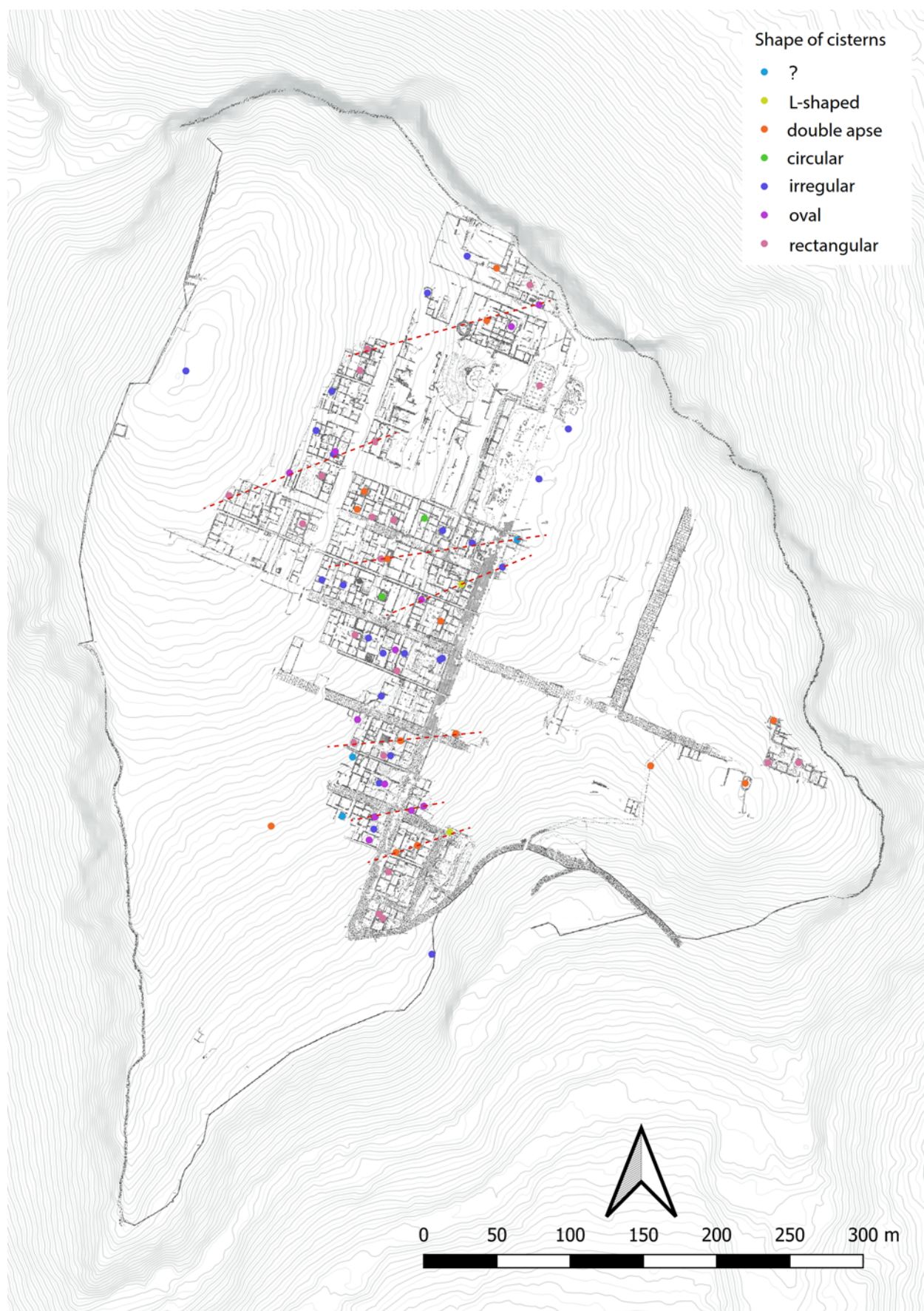


Figure 5: Plan of Solonte with indication of cisterns and natural fractures (elaboration: G.I.S., G. Polizzi).

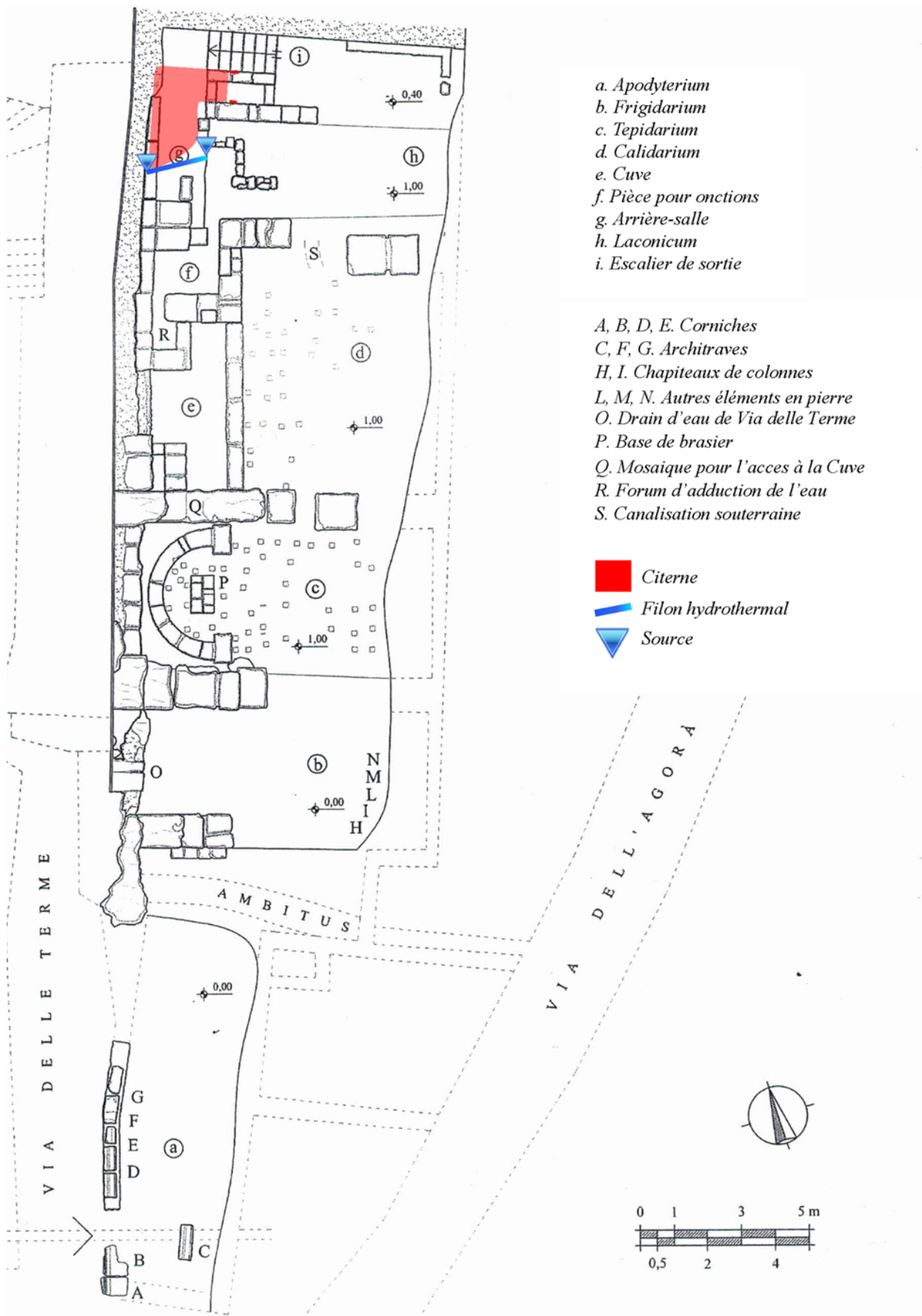


Figure 6: Solunt. Plan of South Baths (from Polizzi et al. 2017).



- 1. Source alimentant la citerne
- 2. Source et prise d'eau creusée dans la roche

Figure 7: Solunto. Orthophotography of the west wall of room 'h' of the South Baths (photo: G. Polizzi, elaboration V. Dumas).

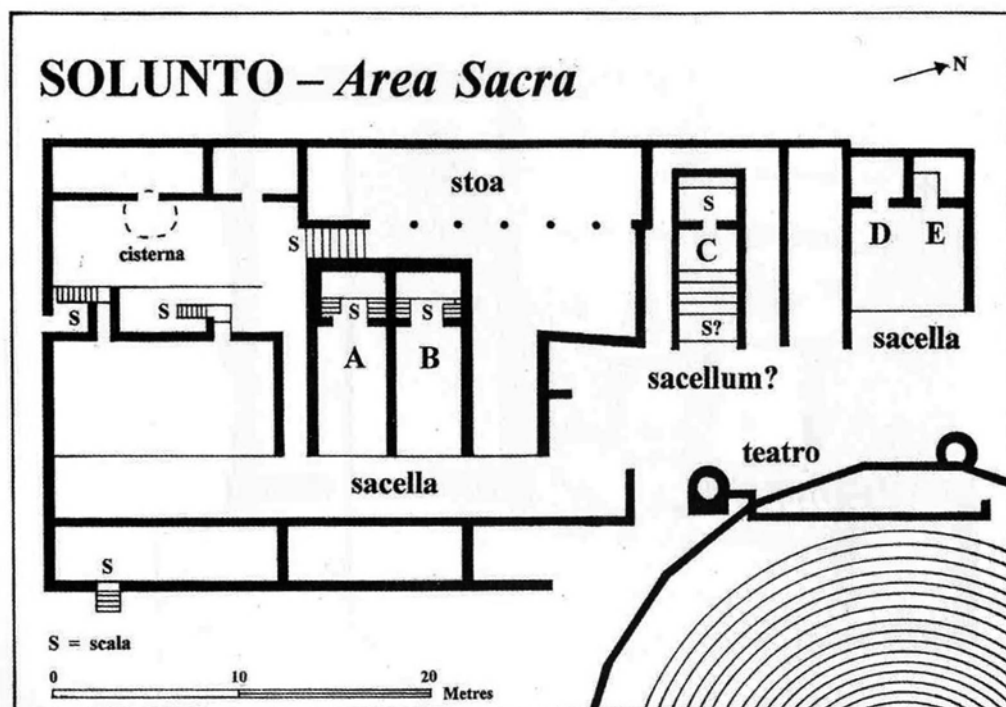


Figure 8: Solunto. Plan of the sacred terrace.

Table 1: Results of U/Th dating performed on calcitic laminations of substratum fracturations and archaeological structures in Solunt.

Labcode	Sample description	[²³⁸ U] ppm		[²³² Th] ppb		d ²³⁴ U _M (‰)		(sup ²³⁰ Th/ ²³⁸ U)		(sup ²³⁰ Th/ ²³² Th)		Age (ka)-before 2017
7251-	SOL 16-01 A	0.093	0.001	6.834	0.055	9.90	1.00	1.071	0.003	44.47	0.12	sup 500 kans
7252-	SOL 16-01 B	0.167	0.001	0.633	0.005	16.89	1.00	1.021	0.003	820.74	2.18	sup 500 kans
7253-	SOL 16-03	0.134	0.001	0.160	0.001	25.56	0.71	1.052	0.002	2694.49	4.14	sup 500 kans
7435-	Solunt-17-02	0.194	0.002	2.138	0.017	-2.64	1.31	0.991	0.001	275.56	0.39	sup 500 kans
7436-	Solunt - 4A	0.120	0.001	0.481	0.004	2.84	0.86	1.005	0.002	770.78	1.73	sup 500 kans
7437-	Solunt - 4B	0.138	0.001	1.828	0.015	5.70	0.97	1.001	0.002	123.37	0.19	sup 500 kans

Dating of calcification and concretion

In all surface-usable hydrogeological indices, absolute dating has been undertaken. In order to better characterise over the long term fluid transfers within the massif, U/Th (MC-ICPMS Neptune +) have been made⁵³ on the series of laminations lodged in the fracturations of the geological formations and then of the archaeological structures.

The development of calcitic laminations of fracturations in the Brechic limestones yielded results all greater than 500 Kans (Table 1) indicating artesian upwelling conditions in place prior to the Middle Pleistocene, probably during the regional Plio-Pleistocene tectonic activity phase. The samples taken at the small baths, although carried out on concretions affecting ancient structures, gave the same type of dating. It will be necessary to determine why such a result could have been obtained. Another architectural block, coming from the 'Edificio sacro a due navate' (Figures 9 and 11), and even more clearly affected by laminations developed during its operating period, will be analysed using the same methods to provide further clarification on this point.

Elementary analyses on laminations of substratum fracturations and archaeological structures

In parallel with the U/Th dating, geochemical analyses by X-ray fluorescence on the laminations and concretions of the site were undertaken. The spectrum of X-rays emitted by matter is characteristic of the composition of the sample, and by analysing this spectrum we can deduce the elementary composition, i.e. the mass concentrations in elements.

Samples were previously dried at 60°C for 48 hours. The elemental analysis was performed using an Olympus Vanta C series portable x-ray fluorescence unit (pXRF), using energy dispersive x-ray fluorescence (ED-XRF)



Figure 9: Solunt. Sporadic architectural block from the 'Edificio sacro a due navate' (photo: G. Polizzi).

with two-beam ground-based geochemical calibration, measuring Mg, Al, Si, Ca, S, P, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, W, Zn, Hg, As, Pb, Bi, Se, Th, U, Rb, Sr, Y, Zr, Nb, Mo, Ag, Cd, Sn, and Sb. This is particularly in order to define the distinct elementary signature of each of the elements that can characterise the deep or karst origin of the reservoirs whose resurgences are at the origin of the concretions studied. All elements with an atomic number less than 11 (H, He, Li, Be, B, C, N, O, F, Ne, Na) are not detected individually by the pXRF technology used and are classified as Light Element (LE) by the Olympus Vanta C geochemical software.

XRF analysis shows that the concretions/laminations of the substratum fractures (Figures 11–14, Table 2) are mainly composed of calcium (especially CaCO₃ calcium carbonate in its compound form). Other elements present such as Silica (Si) Aluminium (Al) or Iron (Fe) are also relatively common in carbonate geological contexts. The absence of elements Na, SO₄, Cl, Pb, Zn, Au, Ag... (alkaline, sulphate or metalliferous mineralisation) indicates that these are weakly mineralised waters of karstic origin and not hydrothermal (in the hydrogeological and geological sense). On the other

⁵³ By Edwige Pons Branchu, LSCE, UMR 8212, Paris Saclay, France.

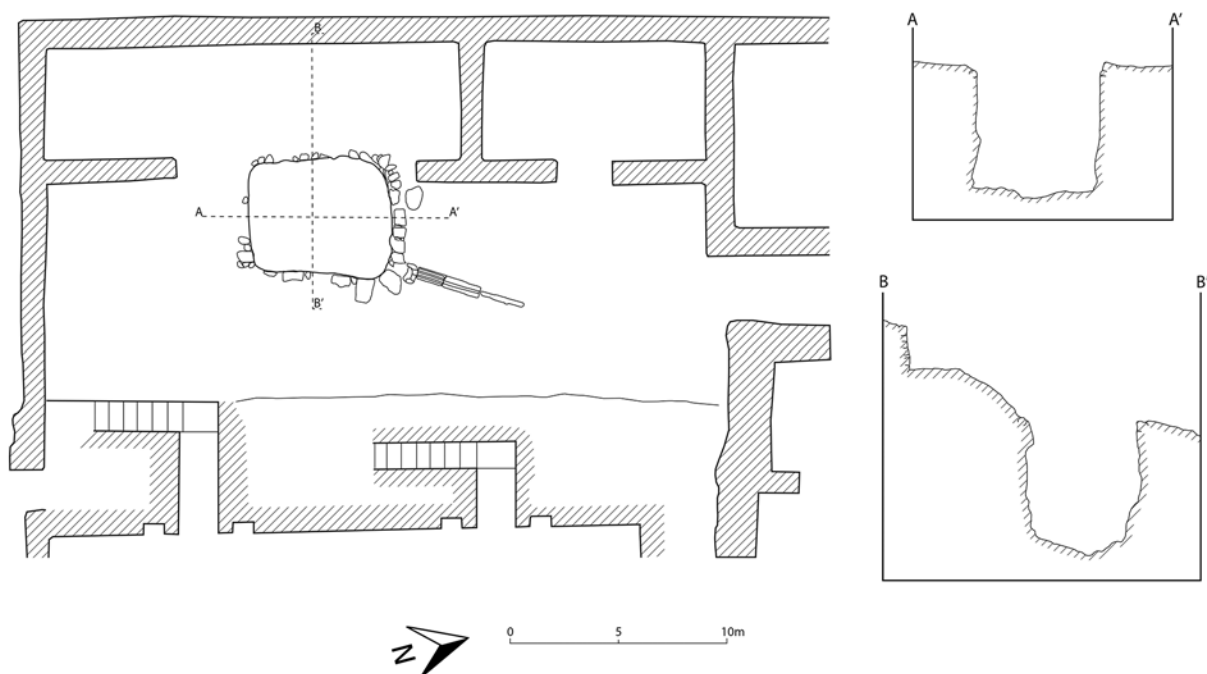


Figure 10: Solunt. Plan and sections of the South-West building of the sacred terrace (elaboration: G. Polizzi).



Figure 11: Solunt. Digital microscope details of the laminations of the SOL 18/19 sample at the architectural block of the 'Edificio sacro a due navate' (photo: V. Ollivier).

hand, the geochemical results of the concretions affecting certain architectural structures of the baths and of the sacred building with two naves (Figures 15, 16, Tables 3, 4) indicate a much richer elementary composition. Calcium (Ca) is present in much smaller amounts, as is Silica (Si) Aluminium (Al) or Iron (Fe) and there are many other elements, including Sulphur (S), Manganese (Mn), Copper (Cu), Zinc (Zn) or Lead (Pb)



Figure 12: Solunt. General view of the calcitic lamination of the SOL 18/10 sample within substratum fracturing (photo: V. Ollivier).



Figure 13: Solunt. Detailed digital microscope view of the calcitic laminations of the SOL 18/10 sample within substratum fracturing (photo: V. Ollivier).

which, although in modest quantities, underline the more youthful character of the encrusting waters. This point of hydrothermalism is a marker of the change in the origin of the waters whose engines remain to be determined. The relative improvement in water quality prompted by this change is also a parameter to be explored in relation to the human occupations of the site which have directly benefited from it.

These first data on Solunt, combining U/Th dating and elementary analyses, bring new arguments in terms of the existence, from the Pliocene/Pleistocene, then, after an indefinite period of time, up to Antiquity, of a specific hydrogeology in the Mont Catalfano massif. The morphostructural and tectonic context characteristic of this sector, where a strong porosity and tensions at the origin of intense fracturing dominate. The hydrogeological consequence was the development of

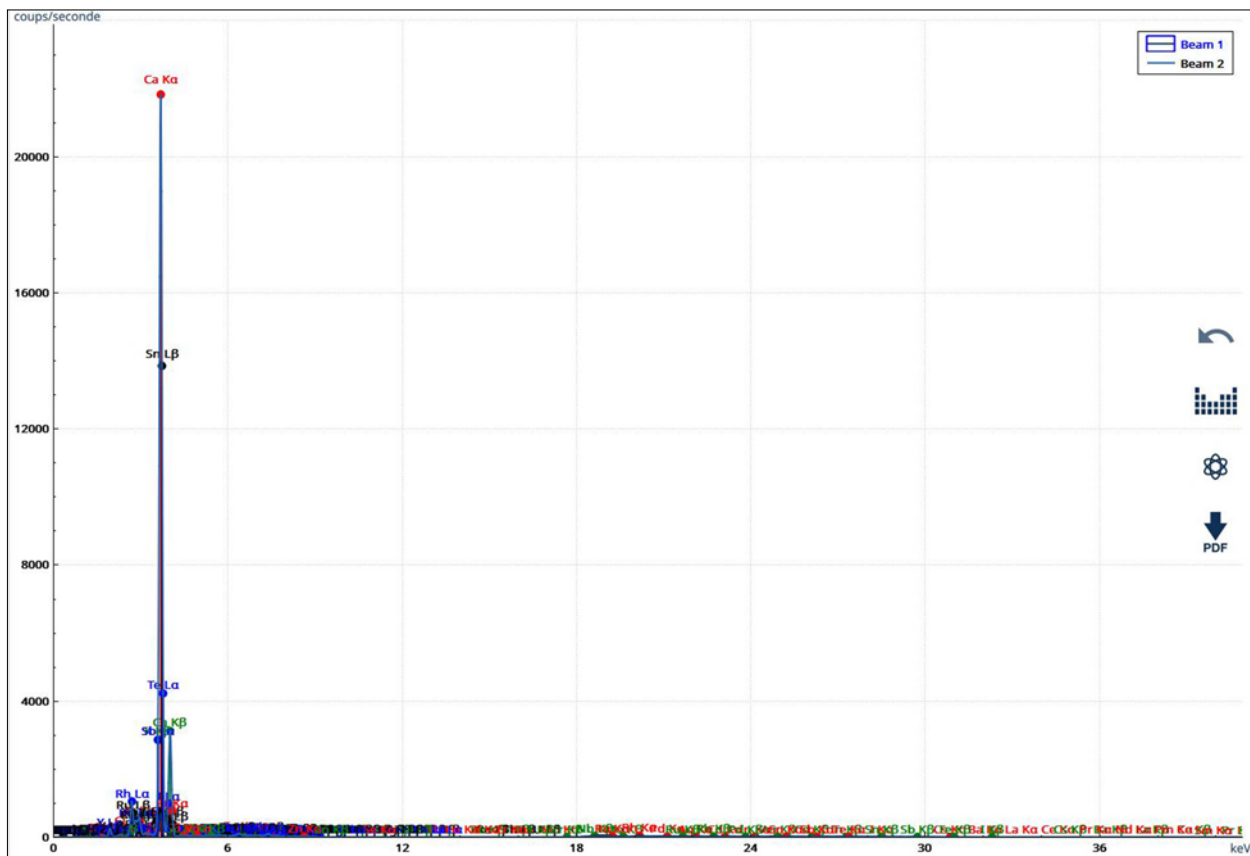


Figure 14: Spectrum of the elements composing the SOL 18/10 sample at the level of the Solonte substratum fracturations (elaboration: V. Ollivier).

Table 2: List of elements composing the SOL 18/10 sample at the level of the Solonte substratum fracturations.

El	PPM	+/- 3σ
LE	60.52%	0.83
Ca	38.03%	0.79
Si	9550	620
Al	4300	2000
Fe	600	110
Sr	32	6
Nb	7	7

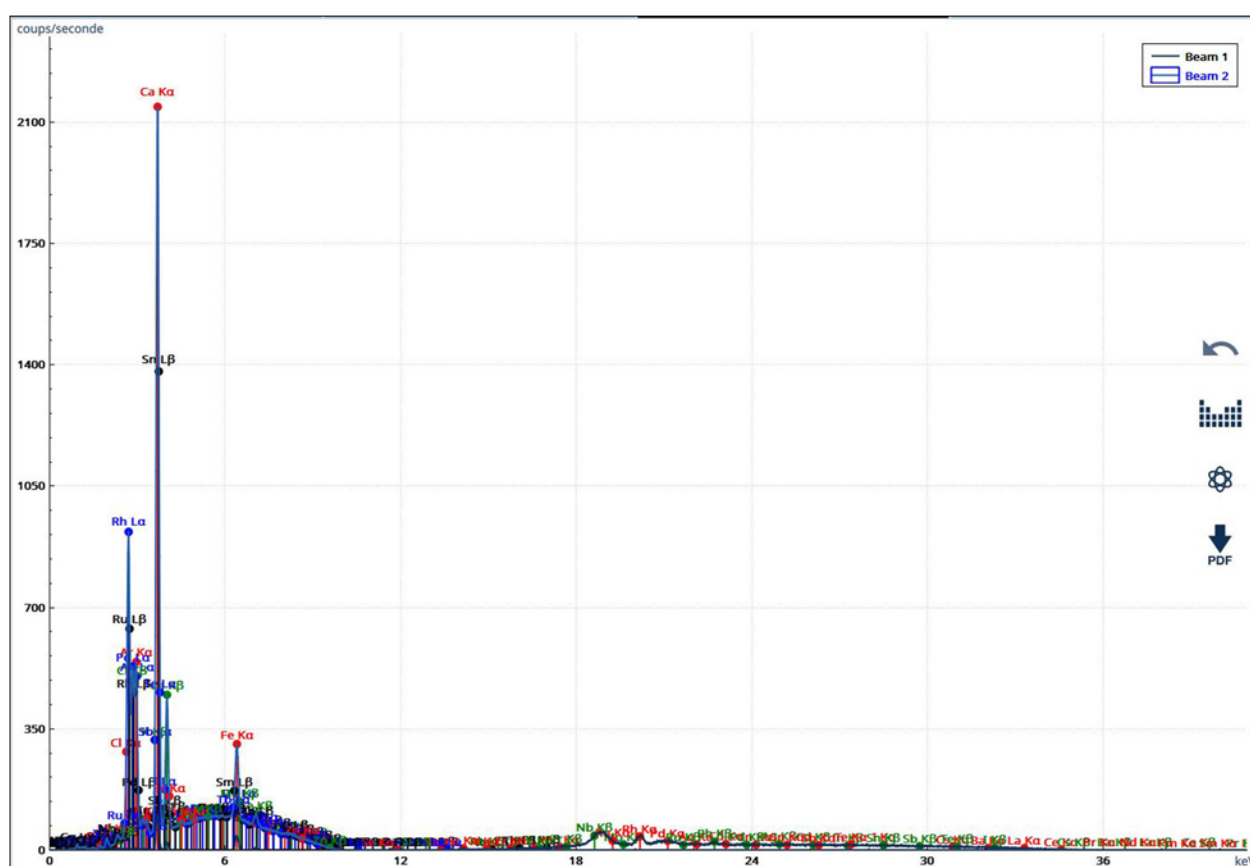


Figure 15: Spectrum of elements composing the SOL 18/08 sample at the level of the Solonte South Baths (elaboration: V. Ollivier).

emergences with hydrothermal potential that allowed an efficient water supply to the city of Solunt, this, in turn, augmenting the water stored in the tank devices harvesting meteoric waters.⁵⁴

The same hydraulic problems facing Solunt are found at Tindari (Figure 17). The city was founded in 396 BC by Denys the Elder (Diod. XIV, 78, 5–6), and the first occupation of the summit took place in the south-west sector, now occupied by the sanctuary of the Madonna del Tindaro.⁵⁵

Since the first excavations, cisterns were found dug into the rock, leading to the supposition that the city could have been supplied exclusively by rainwater.⁵⁶ This hypothesis has been maintained, even in recent years, since the discovery of tanks in new excavations;⁵⁷ the discovery of a public, large vaulted cistern has helped maintain this hypothesis.⁵⁸ This cistern, of rectangular shape and large dimensions (16 m x 14 m; depth not determined), probably had a public function

⁵⁴ Polizzi et al. 2017.

⁵⁵ Leone and Spigo 2008: 102.

⁵⁶ Lamboglia 1953: 73.

⁵⁷ Ravasi 2018: fig. 15; Leone and Spigo 2008: 44, 48, 77.

⁵⁸ Gulletta 2012: 300–301.

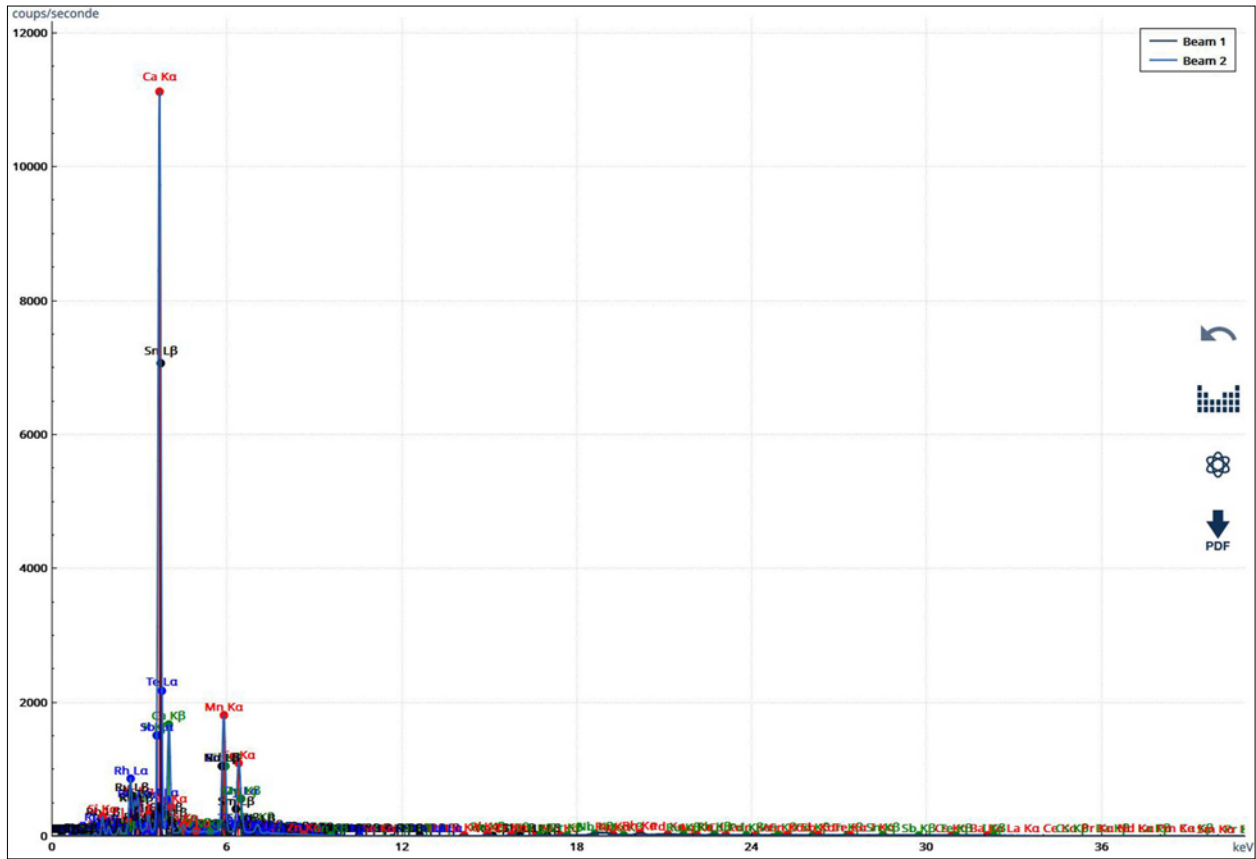


Figure 16: Solunt. Spectrum of elements composing the SOL 18/19 sample at the architectural block of the ‘Edificio sacro a due navate’ (elaboration: V. Ollivier).

Table 3: List of elements composing the SOL 18/08 sample at the small thermal baths of Solonte.

El	PPM	+/- 3σ
LE	90.43%	0.49
Ca	7.42%	0.26
Fe	6170	410
Si	5990	950
Al	4600	3800
K	2760	230
S	1030	250
Ti	680	590
Mn	130	100
Th	42	28
Sr	35	7
Cu	27	26
Zn	24	16
Mo	18	12
Pb	16	12
Rb	10	5
Zr	9	8

Table 4: List of elements composing the SOL 18/19 sample at the architectural block of the 'Edificio sacro a due navate', Solonte.

El	PPM	+/- 3σ
LE	59.53%	0.92
Ca	22.76%	0.51
Si	7.16%	0.21
Al	3.62%	0.30
Mn	3.42%	0.12
Fe	2.037%	0.075
K	5700	210
Ti	3060	690
S	3030	180
P	1250	270
Pb	286	31
V	270	95
Cr	210	150
Y	202	14
Ni	164	46
Cu	113	35
Sr	113	10
Zn	102	24
Zr	92	11
As	60	23

and collected the waters of the theatre, as in a similar example at Solunt, dated to the 2nd century BC.⁵⁹ However, its architecture, which uses bricks extensively, suggests that it was restored during the Imperial age (1st century AD).

The hypothesis of an exclusive supply by rainwater, however, has to be ruled out because of the discovery of an ancient aqueduct in the territory of the ancient city. The survey conducted by Michele Fasolo in the nearby countryside, found pipes of an aqueduct that led the waters towards the city from perennial springs located upstream of the village of Scala, 3 km south of Tindari.⁶⁰ The poor state of conservation of the aqueduct means that a precise chronology cannot be put forward, nor its complete route, however the latter would seem to cross along its route various sites of Late Republican and Imperial times. The pipes of this aqueduct, of conical shape, and with openings for inspection not always present, have dimensions inferior to the pipes of the aqueducts known elsewhere in Sicily⁶¹ (length: 42.5 cm; max mouth diameter: 9.5 cm; wall thickness: 5 cm), and find no parallels among similar ancient works (Figure 18). The presence of mortar at the ends of the conserved segments suggests that the water passing through them was under pressure.

We should therefore ask ourselves when, and in what environmental context, this aqueduct was built. The presence of an aqueduct, in fact, would require a significant commitment by the city, especially if it had internal sources within the city. One of these sources was detected during the Watertraces missions. Indeed, in addition to the aqueduct and cisterns, the ancient city could be supplied by a natural source from within the city – located along Teatro Greco Street, in an area of the city that, according to hypotheses still under study, housed the Tindari agora/forum.⁶² This ancient source, now dry, is located between the public space marked by the presence of the so-called 'Basilica' and the fortifications, more precisely between towers VI and VII⁶³ (Figure 17, n. 18).

We have proposed the existence of a natural source in this sector after explorations in 2017, during which we were able to recognise concretions characteristic of the presence of an exurgence near a tank. A more targeted exploration carried out in 2018 confirmed this hypothesis and recognised a calcareous tufa bank formed by the presence of karstic or hydrothermal water. Finally, the concretion was cleaned in April 2019, making it possible to recognise a niche with traces of tile concrete. A second niche appeared on the northwest side. Further south, the tank was cleaned. The proximity of the source to the cistern had suggested

⁵⁹ Polizzi, Torre 2018.

⁶⁰ Fasolo 2013: 97, fig. 109.

⁶¹ See the contribution by Aurelio Burgio in this volume.

⁶² Ravesi 2018.

⁶³ For the numbering of the towers, see Leone 2020: fig. 6.

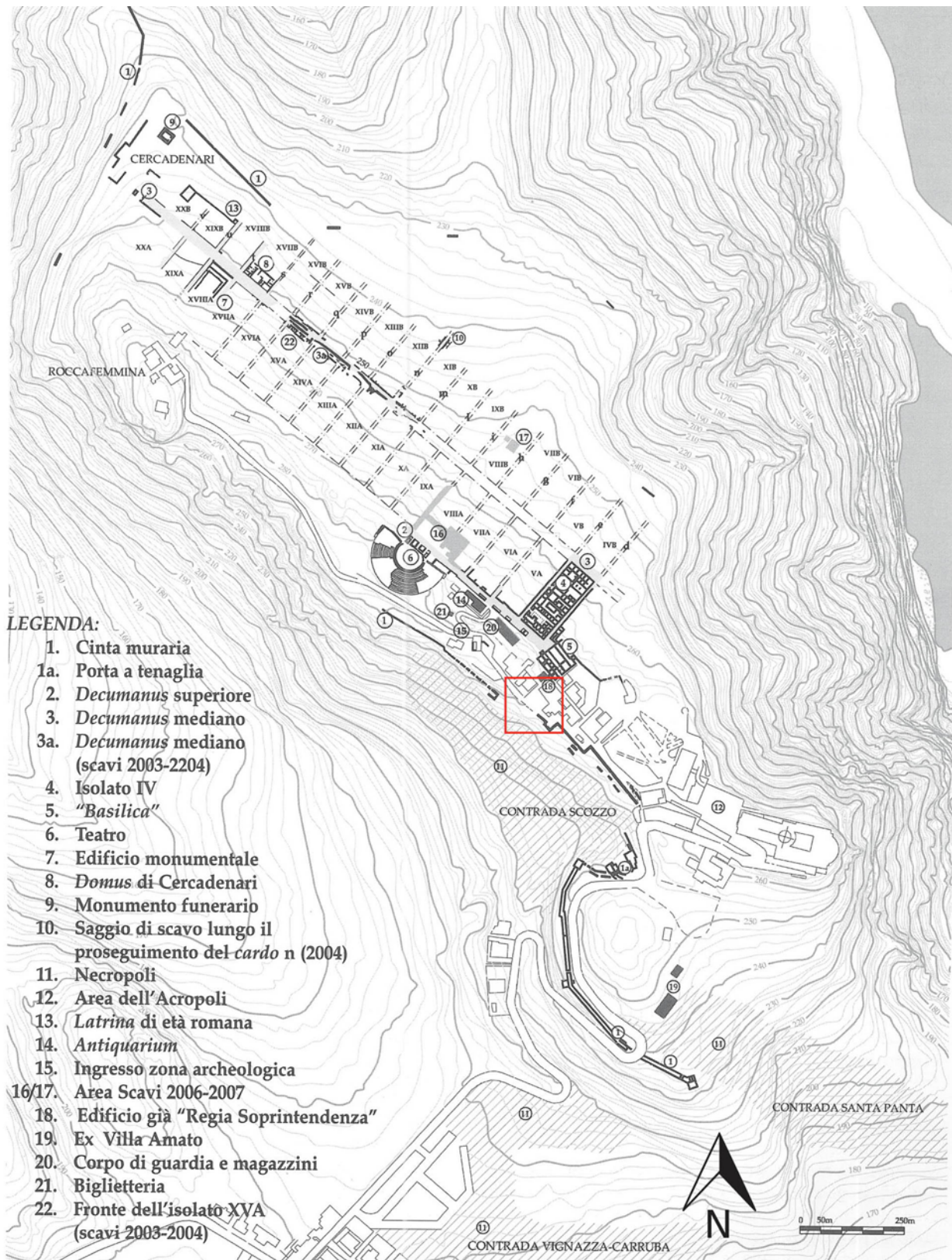


Figure 17: Map of Tindari. In red, the area of the spring (from Spigo 2005).



Figure 18: Tindari. Aqueduct pipe (photo: G. Polizzi).

a possible functional connection between the two, with an interpretation of the latter as the source water reservoir.

It is important to note that the area of the ramparts near the source appears to be characterised by access to the city, as suggested by a map of 1814⁶⁴ (Figure 19). Due to modern works, it is no longer possible to verify the exact position of this access, however the strategic position of the source should be noted – close both to the public space and an access to the city through the ramparts.

A new mission in February 2021, under the Watertraces project, has allowed further examination of the remains of the source. After cleaning the limestone tuff and the cistern, we were able to better understand the architecture and functioning of the hydraulic system (Figure 20), organised in three sectors from north to south: in the north it is possible to see a normal fault, which should correspond to the rising point of the water; further south (2 m), a limestone tuff formation arranged with three opposite niches is partially hidden to the east by a modern reinforced concrete platform that prevents a complete reading of the monument; finally, further south, and at a level c. 60 cm lower, a tank/tank was installed.

The limestone tuff is arranged with three niches, artificially dug. The main niche (niche 1) has a width

of 0.89 m and a preserved height of 0.71 m. It has walls covered by irregular stones glued by concreting effect. To the north of this niche is another one of oval shape, 1.35 m wide and 1 m deep, preserved to a height of 0.68 m. The internal walls of the niche have been artificially regularised. Further north, a modern concrete staircase covers the space between the fault and the tuff. To the south of the central niche is the local metamorphic rock, partially covered by limestone tuff arranged in the shape of a niche, now almost completely destroyed. Only the bottom part is preserved, to a width of 50 cm. Here the geological substrate was cut vertically, sheltering stone blocks of regular shape (Figure 21).

To the south of the calcareous tuffa is the cistern/reservoir. It is partially covered by the modern platform, which does not allow its development to be perceived towards the north. In addition, parallel to the southern wall a modern sewer was installed at the bottom of the tank, which caused damage to its east and west walls as well as to its bottom. The southern part of the tank has a regular shape, with a straight wall, 3.90 m long, oriented east–west. The hollow walls in the rock are coated with waterproofing concrete in three layers, the first with a lime and sand base, the second with coarse tile concrete, and the third with finer tile concrete. The bottom of the tank is made of coarse tile concrete, laid on a layer of lime-based and medium-sized pebbles (0.05/0.10 m). The height is preserved, near the eastern angle, to 0.80 m. On the south wall, 30 cm from the bottom, is a horizontal layer of concretions, 1 cm thick:

⁶⁴ Ferrara 1814.

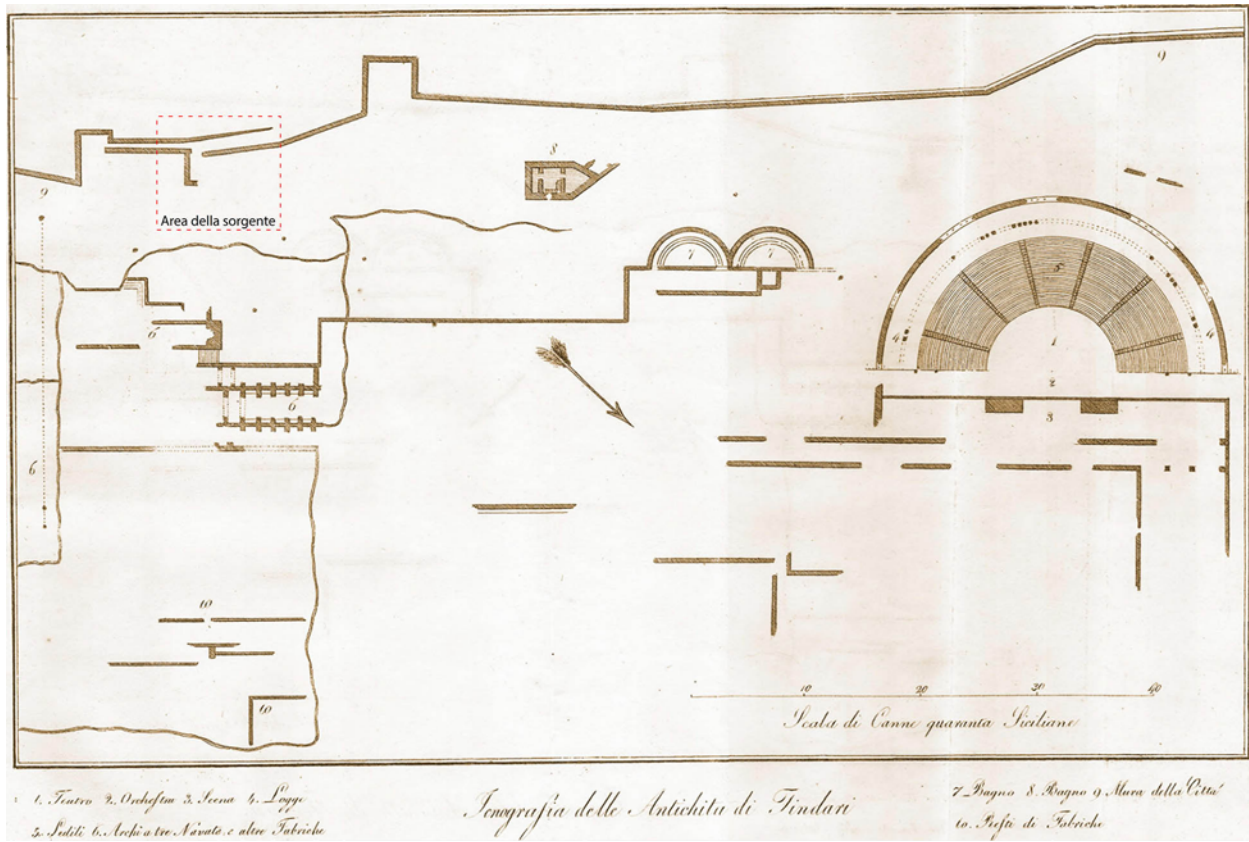


Figure 19: Old plan of Tindari (from Ferrara 1814).

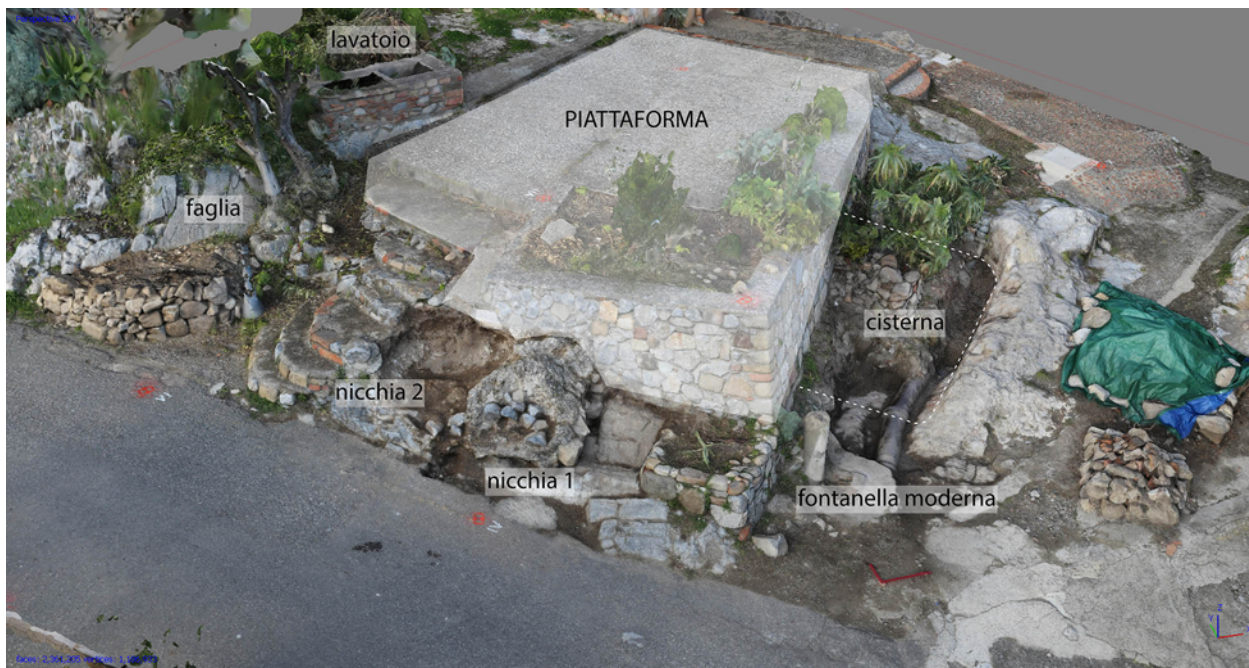


Figure 20: Tindari. General view of the source. South-west view (elaboration: G. Polizzi).



Figure 21: Tindari. Detail of the artificially cut geological substrate (photo: G. Polizzi).



Figure 22: Tindari. Detail of the horizontal layer of concretions (G. Polizzi).

this stratum is the result of the prolonged deposition of spring waters (Figure 22). This form of carbonatation indicates the presence of spring water inside the tank. Through analyses focused on laminations of this type, it is also possible to define the carbonation rhythms in terms of their intensity and chronology; these will have

to wait for a future field mission, but it is now possible to define the very nature and origin of the waters responsible for these carbonation phenomena.

Calcareous concretions (travertine, tufa, caving, calcareous crusts) generally provide valuable

information on: the origin and quality of the waters (karstic, hydrothermal, hypothermal, meteoric), the hydrodynamics of the environment (depending on the concretion morphotype), the state of the vegetation cover (participating in the dissolution of limestones and the remobilisation of carbonates), the climatic context over time (stimulated expression or constraint of carbonation), anthropogenic activities (sensitivity of carbonatogenesis processes to detritism and pollutants). As at Solunt, one of the approaches adapted to the study and characterisation of these different components is elemental X-ray fluorescence analysis.

Elementary analyses on the encrustations and laminations of the archaeological structures of Tindari

Considering the facies, crystallisation modes, and morphologies observed, the carbonate formation of the tufa type of the via Teatro Greco in Tindari is directly related to the supply of water from karstic or thermo-mineral sources. Biochemical construction phenomena related to the activity of algae and bacteria also played a fundamental role in the genesis of these encrustations. The type of inlays encountered is comparable to the tufa and travertines of river, source, or cascade that can be encountered in natural contexts. However, it was necessary to ensure that it was not a hydrothermal/hypothermal component in order that we could better understand the hydrogeological functioning of the massif and determine the origin of the waters, a parameter directly influencing the modalities of their exploitation during the occupation phases of the site of Tindari.

The X-ray fluorescence analyses carried out on the travertine formation (Figure 23, Table 5) confirm the origin and part of the composition of the waters responsible for the concretions. The dominant element is Calcium (Ca = 27.14%), which underlines, if necessary, the supersaturation in carbonates of the waters. The second element present in greater proportion in the measured elemental cortege is Silica (Si= 6.54%), a common element in this type of substratum. The other elements remain as traces and indicate only a very discreet influence of processes of circulation of fluids from deep contexts. The low mineralisation of concretions refers to contexts related rather to karstic or pseudo-karstic domains.

In the morphostructural context of the Tindari headland, the hydrogeological mechanisms of emergent systems can be complex. The first results of the isotopic analyses of Strontium in the current waters (an element also present in the concretions), collected at the source of Casa della Vita, a few hundred metres from the formations studied, allow us to estimate the

location of the reservoirs by delivering a $87\text{Sr}/86\text{Sr}$ ratio of 0.707970 characteristic of the lower Oligocene/Miocene lithologies to which the local Capo Orlando Flysch Formation belongs.

The waters of the via Teatro Greco concretions appear to have karstic or pseudo-karstic origins, as indicated by the X-ray fluorescence data, and therefore do not fall under hydrothermal mechanisms. In detail, these rocks probably underwent, during the Neogene (Lower Miocene?), one or more phases of alteration at the origin of the development of alterations. The transition from bedrock to other forms is usually done through a karstified horizon, characterised by the presence of karst-like conduits, in which sometimes the other form still remains in place. This horizon often develops between a saprolitisation front (in contact with the other form) and an alteration front (in contact with the healthy mother rock). To this must be added the presence of karst-type drains, taking advantage of the vacuum generated by the presence of faults and fracturing. Karstification or pseudo karstification of flyschs develops in the core fault (breach) and decreases in the damaged area. The 'karstic' conduits connected in the unsaturated and saturated zone of the massif pass the pressure wave and form a surface resurgence.

Conclusions

From the integrated analysis of the Solunt and Tindari sites certain initial findings can be made. Data from hydrogeological observations, isotopic analysis (Sr) of waters and XRF measurements indicate to us relatively clearly that the ancient cities were well supplied with hydrothermal/hypothermal (Solunt) or karstic (Tindari) waters, in probable support of meteoric waters. New data are still being processed but all seem to support this first finding of a meteor/deep water model⁶⁵ that can be validated both in geochemistry and in terms of the resulting surface formations (concretions and travertine buildings). The question of a connection between the location of ancient cities, hydrogeology and water management is now clearer.

From the hydrogeological point of view, and with the help of the first geochemical measurements obtained, the observation of reservoirs, appearing more and more mineralised, of the Pliocene/ Pleistocene, in ancient times at the city of Solunt makes it necessary to search for the origins of such a phenomenon, as well as its validation. Such research involves new reflections on the link between the evolution of the origins of these water sources, their quality, their availability, and the modalities of human occupations, including the management of such resources over the long term.

⁶⁵ Polizzi *et al.* 2017.

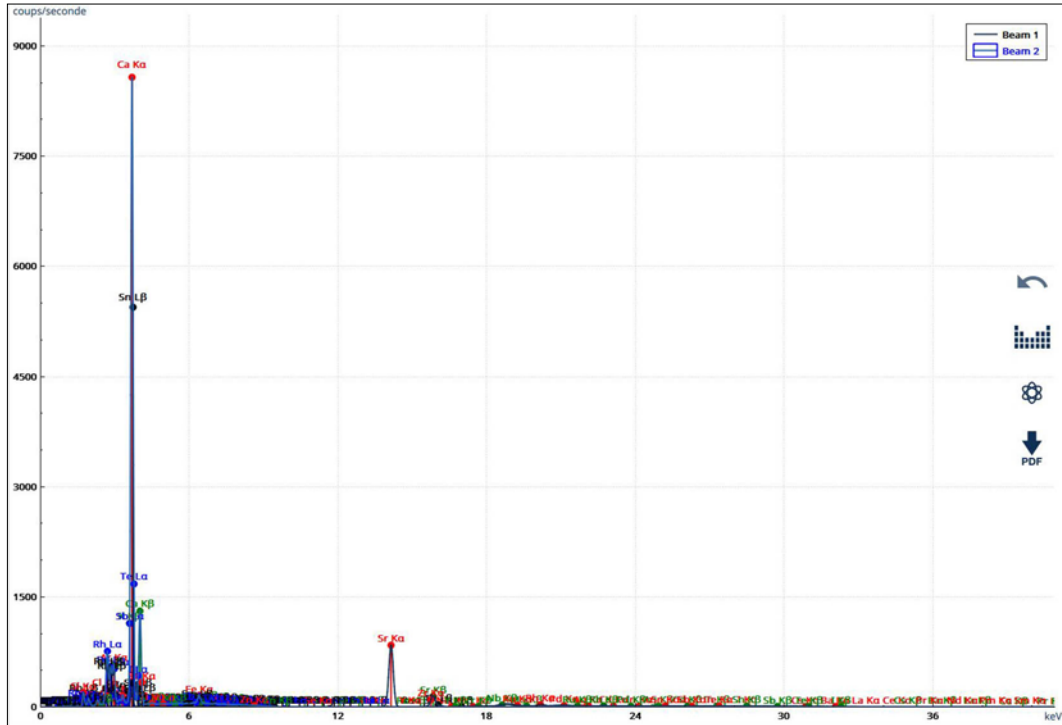


Figure 23: Tindari. Spectrum of elements composing the sample TIN 18/01 at the calcareous tuff of via Teatro Greco (elaboration: V. Ollivier).

Table 5: List of elements composing sample TIN 18/01 at the calcareous tuff of via Teatro Greco in Tindari.

El	PPM	+/- 3σ
LE	63.4%	1.1
Ca	27.14%	0.80
Si	6.54%	0.24
Sr	9350	290
Al	7900	2800
K	3440	220
Fe	3090	300
S	2830	240
P	1160	350
Ti	820	640
Mn	260	140
Zr	119	36
Th	88	58
Cu	35	29
Zn	29	19
Mo	16	16

At Solunt, the urban organisation, as well as the location of the sacred spaces, seem determined by the points of spill of the deep waters; a sacred building, and several houses, have cisterns for collecting them, in addition to the rainwater. The flow of these waters was then guaranteed by a system of pipes and various tanks that directed excess water out of the city. The ‘South Baths’ were built over a spring, which, in addition to its strategic position at the entrance of the

city, must have determined the siting of the building in this area.

Tindari’s water source suggests specific attention to the urban organisation of the city, given its proximity to the public sector of the ‘Basilica’ and the ramparts. It is likely that the opportunities offered by the source could also have encouraged the creation of a gateway in this sector.

Even if the dating currently available does not provide a coherent chronology to the phases of ancient occupation of the sites, the link between sources/water spill and archaeological structures remains clear: in Solunt and Tindari there is a very close relationship between the environment, water infrastructure and urban organisation, which confirms the importance of a study integrating hydrogeology and archaeology in this case.

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