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Review on Land Subsidence in the Archaeological Site of Sybaris (Southern Italy)

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ABSTRACT. This paper takes into account the case history of the archaeological site of Sybaris. The research carried out until now on field and laboratory, on the basis of multidisciplinary investigations, has identified a complex phenomenon of subsidence affecting the area since ancient times. The archaeological site lies on an alluvial plain consisting of three superimposed levels of occupancy. The geological, structural, geoclimatic, geotechnical and hydrogeological circumstances responsible for the subsidence have been investigated. The geomorphological evolution of the area has been reconstructed by means of ^{14}C datings performed on peats, fossils and organic substances. This study represents a scientific advance not only for the knowledge of the environmental evolution but also for the safeguard and the management of the archaeological digs. In fact it provides a guide as to the type of action required to keep deep archaeological levels free from the groundwater invading the subsoil.

Key terms: Land subsidence, Tectonics, Sea-level change, Alluvial plain, Compression of sediments, Piezocone test.

Introduction

The ex CNR Research Center of Water Resources and Land Stability (currently CNR - IRPI) has been carrying out researches on the archaeological site of Sybaris within the CNR Committee of Cultural Heritage Special Projects. The present paper, a part of this research project, describes the complex phenomenon of land subsidence in the Sibari Plain. Land subsidence has been affecting the area since ancient times, as the archaeological digs, performed since 1879 and still continuing, have led to the identification of three superimposed levels of occupancy, indicating continuous habitation from the sixth century (the Greek town of Sybaris, 720 – 510 BC), then the third century (the Hellenistic town of Thurium, 444 – 285 BC) up to the first century with the Roman town of Copia, 193 BC, at a depth between 7 and 3.5 meters from the present ground level (FONDAZIONE LERICI, 1967) (Fig. 1).

Fig. 1- The ruins of the Roman theater in the archaeological site of Sybaris.

The historical events of the three towns were reported by numerous historians such as Herodotus, Strabo, Diodorus Siculus and Livy. The finds are concentrated in some areas, Parco del Cavallo, Casa Bianca and Stombi, being included between the previous courses of the two rivers Chratis and Sybaris (now named Coscile), which, today, have a single outlet into the Ionian Sea.

The phases of the geological evolution of the area during the last 35,000 years, and above all in the most recent times, have been identified on the basis of multidisciplinary investigations carried out both in the field and laboratory on samples taken from several boreholes. Piezocone tests have been performed for a depth of 100 meters. By means of the data collected, geotechnical classification of soils was possible. ^{14}C datings have also been performed on samples of peat levels, carbon frustules and fossil remains up to a depth of 96 meters below the presentday ground level. Topographical surveys also show ground changes at the IGM bench mark, since 1950.

The research carried out on the site of ancient Sybaris represents an advance from the point of view of the environmental evolution, and is also essential regarding the safeguard, the present and future management and visiting of the archaeological digs. Actions required to keep deep levels of archaeological interest free from groundwater have also been a part of this research, because water invading the subsoil and the archaeological remains are of special concern.

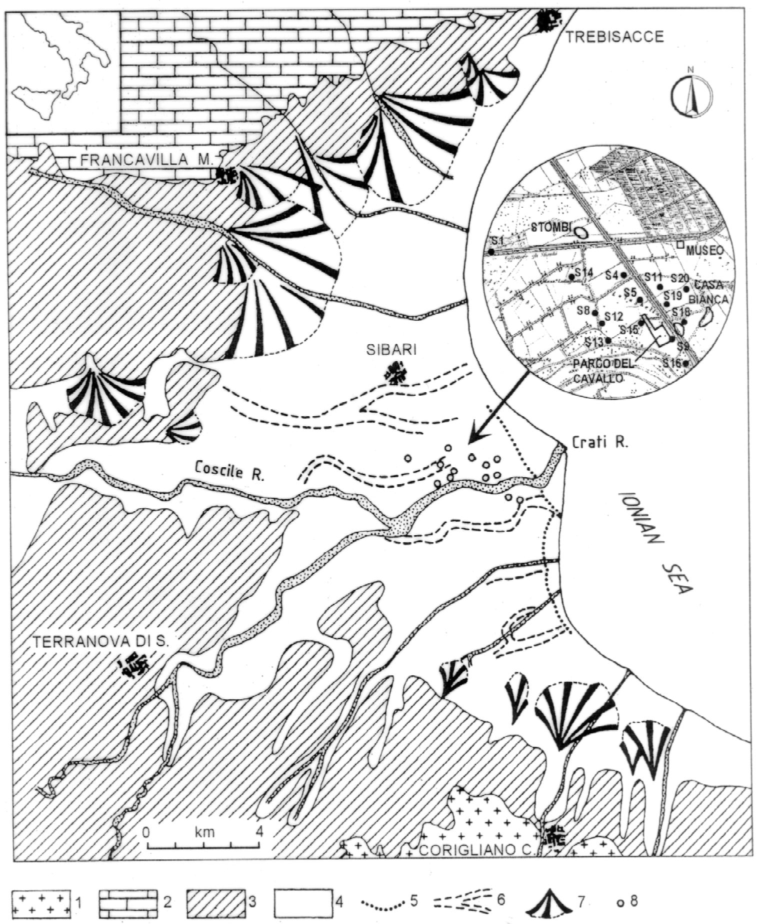

Fig. 2 – Geomorphological map with the location of the geomechanical borings drilled during the geognostic campaigns supported by CNR.

Geological and Structural Setting

The archaeological site lies in the northern part of Calabria on the alluvial plain with the same name which is crossed by the low valley of the Crati River and its tributaries. To the north and northwest, the Plain adjoins the Mesozoic limestones and dolomites of the Pollino Massif and the Apennine Miocene Flysch, while to the south and southwest it is bounded by the crystalline mountains of the Sila, (Fig. 2).This is a depression with an ENE- WSW trend. The upper part of this basin is filled up by an alluvial plain whose thickness increases from the north to the southwest, more precisely from 103 to 478 m to the south of the Crati River. A series of dune hills runs parallel to the coastline between the alluvial plain and the present beach. Close to the mouth of the Crati River there are ponds elongated in a direction perpendicular to the coast separated by thin sand bars. The marine and river terraces to be seen at the confluence of the Crati and Coscile rivers are due to the uplift phases which occurred between Pliocene and Pleistocene.

The alluvial deposits consist of sands, some of which are the finer clay-sandy variety, while others are coarser gravels that are anastomosed by frequent heterotopic facies. Interbedded levels of peat are found at various depths. The alluvial Sibari Plain consists of a graben bounded by some fault systems with various strikes, the most important being NE- SW. This regional tectonic line borders on the plain to the north, while to the south a fault belt with strikes ranging from E-W to ESE-WSW bounds the plain along the Ionian coast, separating it from the Sila massif.

Subsidence in the Sybari Plain

The research examined the causes determining morphological changes, amongst which a complex phenomenon of subsidence. Three main components have been found to be responsible for this: a) neotectonics; b) glacio-eustatic changes; c) compression of sediments. (COTECCHIA *et alii*, 1994; CHERUBINI *et alii*,1994, 2000; COTECCHIA & PAGLIARULO, 1996, 2001; PAGLIARULO *et alii,* 1995; PAGLIARULO, 2002).

Neotectonics

Pleistocene and Recent activity of the mentioned fault systems can be summarized by singling out zones which, from the Pliocene, have always or mostly been subject to uplift and zones affected by complex movements that today may be downwards and/or upwards (TORTORICI, 1983). The easternmost area of the Sibari Plain was subject to a further downward movement during the Holocene owing to tilting along an axis running roughly N-S, (Fig. 3). More precisely, within the general uplift of the southern Apennine Chain, the widespread lowering in this area is such, because the uplift has been slower than in the surrounding areas. These considerations are relevant also to the second component of the land subsidence.

Glacio-eustatic changes

The coast line in this area has undergone great changes since the end of the Pleistocene period and these have greatly influenced the sedimentation areas which are being studied as well. The end of the Tyrrhenian was characterized by Flandrian regression, which brought the sea level to approximately 100 m below the current level. The subsequent equally rapid transgression about 6000 years ago brought it more or less back to today's level, (PAGLIARULO, 2002).

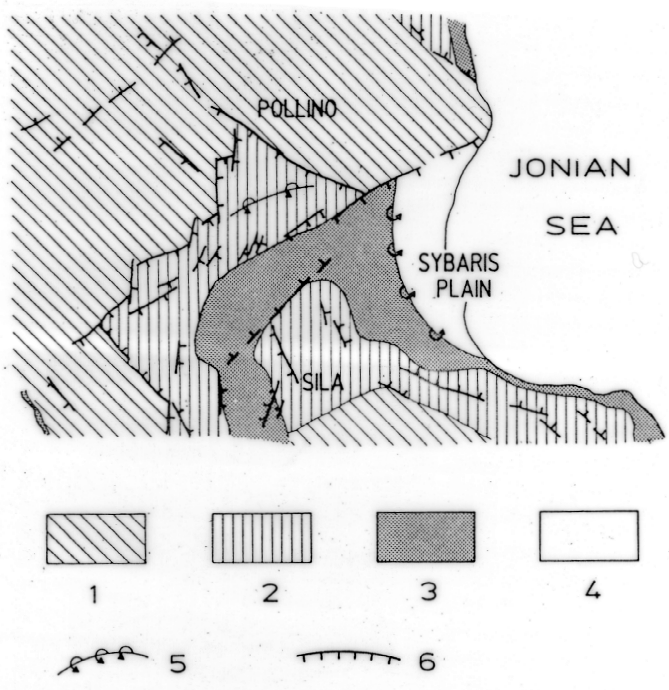

Fig. 3 – Neotectonic map: 1) areas affected mainly by uplift; 2) areas affected by subsidence followed by uplift; 3) areas affected by complex movements followed by uplift; 4) areas affected by complex movements followed by subsidence; 5) tilt axes; 6) faults. (TORTORICI, 1983; modified).

On the basis of ^{14}C datings performed on samples of peat levels found during the drilling of the boreholes, considerations could be made regarding the glacioeustatic changes. If the area was in a marshy-type transition in the period when the three levels of peat found in the S1 investigation were deposited, it can be deduced that in the range 4600– 10,000 years ago the sea level must have been lower than the current level by between 4 and 40 meters, (Fig. 4). The size of these measurements is obviously just an estimate, both due to the significance to attribute to the diagram of the glacio-eustatic variations and because the effects of these variations cannot always be easily distinguished from the tectonic component. In a previous paper (COTECCHIA *et alii,* 1994), the total subsidence rate was calculated also considering the apparent subsidence due to glacio-eustatism. On the basis of these calculations, a considerable decrease in the speed of the subsidence rate in the layers of the upper part of the ground was noticed, ranging from 6 mm/y in the lower levels to 2 mm/y in the upper ones. This trend is also confirmed by the data coming from other investigations.

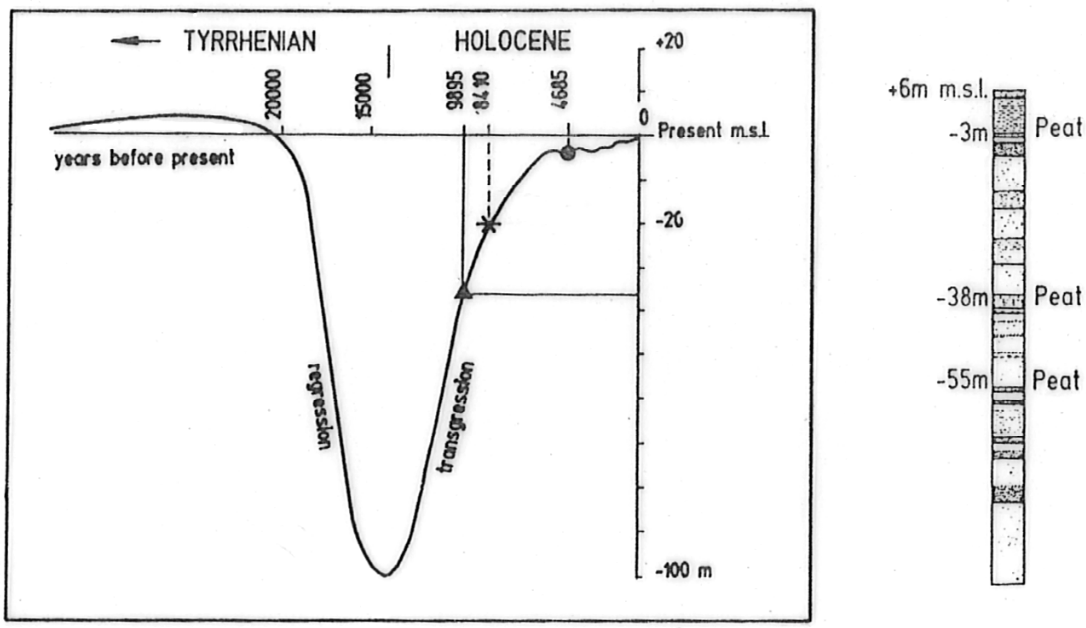

Fig. 4 – Glacio-eustatic curve for the Ionian Sea (COTECCHIA, DAI PRA & MAGRI, 1971) and three ^{14}C dated peat levels found in borehole S 1.

^{14}C Datings and the geomorphological evolution of the Sybaris Plain

During the geognostic campaigns carried out, 20 boreholes were drilled with a variable depth of 10 to 120 meters from the current ground level, (Fig. 5). During the execution of these tests numerous samples were taken both for mineralogical-petrographic analysis and for ^{14}C dating. The absolute uncalibrated age of the carbon frustules and the remains of fossils was obtained by means of analyses with the Accelerator Mass Spectrometer (AMS), considering the small quantity of organic substances. The analyses were partly carried out in the Australian National Tandem for Applied Research of Sydney and partly in the Department of Physics and Atmospheric Sciences at the University of Tucson, Arizona. The following remarks can be regarding the sediments in the boreholes.

The upper part of the stratigraphic columns show lithologic characteristics which are typical of rearranged land resulting from the presence of layers with settlements; indeed at a depth of ca -4.50 m compared to the ground level, the remains of buildings and various pieces of ceramics were found. Moreover the absolute age of 2900 ± 45 yr BP of the sample taken at -4 m in S 18 is entirely compatible with the Hellenistic age back to which the roadway of Thurium dates. Below this depth the different rock types become more frequent, changing rapidly from the clayey silts to fine quartz sands with large quantities of mica and from these to sandy silts between –35 and –45 m from the ground level. Then down to a depth of –75 m, the sediments show more uniform lithologic features and the particle size becomes extremely fine. This variability indicates a depositing environment which varies from lagoonal to coastal, more precisely the area defined as intertidal.The lithology is almost totally uniform from a depth of –71.3 m from the ground level, whose absolute age is 11,980 ± 80 yr BP, down to the bottom of the borehole and consists of fine sands with large quantities of mica and full of organic substances, giving it its dark grey color. The uniform sandy levels are interrupted by some gravelly layers with large blocks of granitic and gneissic rocks. The largest layer is located at approximately –75 m and is probably an ancient riverbed. In the S1 and S15 boreholes, located further inland, a larger particle size was found more or less at the same depth.

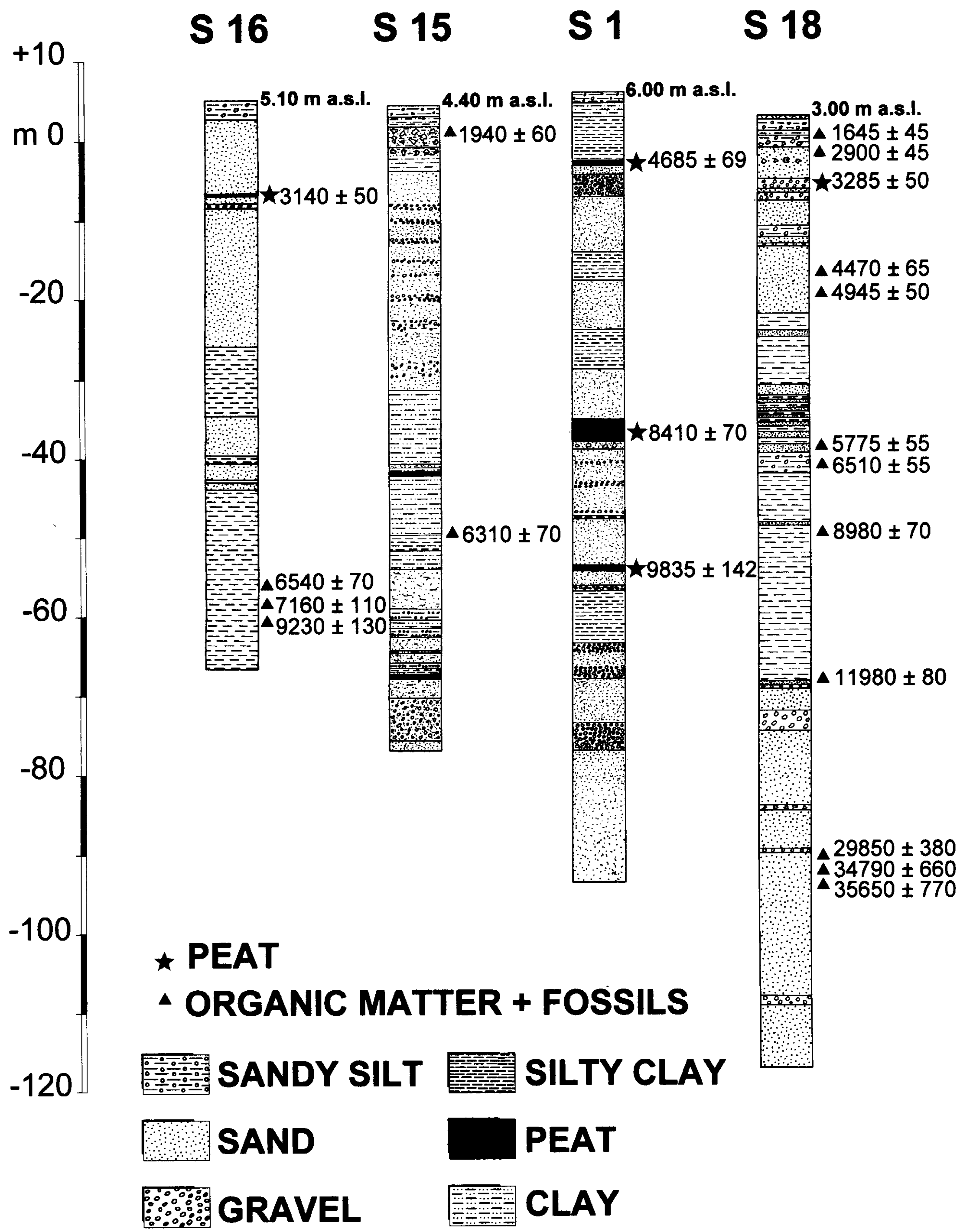

Fig. 5 – Soil profiles along the deepest boreholes indicating the conventional ^{14}C age in yr BP.

An attempt has been made to reconstruct the geological evolution of the Plain of Sybaris in the last 35,000 years on the basis of what has been set out before and by interpreting the sequence of deposits (PAGLIARULO e COTECCHIA F., 2000). Up until 35,000 yr BP Wurmian glaciation was going on and thus eventhe Mediterranean area must have been affected by a cold climate, (MOORE, 1982). The deepest sand samples examined in borehole S18 show a rather fine high quartz content sediment with specks of muscovite and greatly altered granules of feldspar. Moreover, in terms of fauna content the samples were found to be sterile, but with a great deal of carbon frustules. In that time the sea level must have been about 40 meters lower than the present level and, considering the cold and dry climatic phase, there must have been a reasonably low alluvial material load. Sedimentation must have taken place very slowly as is demonstrated in the deepest layers of borehole S18, where only three meters were deposited over an extremely long period of time, ranging from an absolute age of 29,850 ±380 yr BP at -93.3 m to 35,650 ±770 yr BP at -96 m.

Going towards the Upper Pleistocene it changed to a milder climatic phase than the previous one with a greater sedimentation speed and with rapid modifications in the sediment particle size. Around 20,000 yr BP, Flandrian regression began and there was a colder and drier climatic phase which culminated in about 11,000 yr BP with the cold period of the Younger Dryas, (OROMBELLI e RAVAZZI, 1996). In this period a stopping or a deceleration of sedimentation can be assumed. The climatic conditions changed with the Flandrian transgression, the temperature became milder and the sea level rose. As can be seen from the investigation logs, the lithological facies became more varied. The sedimentation environment varied from a typical sedimentary alluvial regime inland from the coastline, with marshy areas leading to the sedimentation of the peaty levels to a mixed coastal environment.

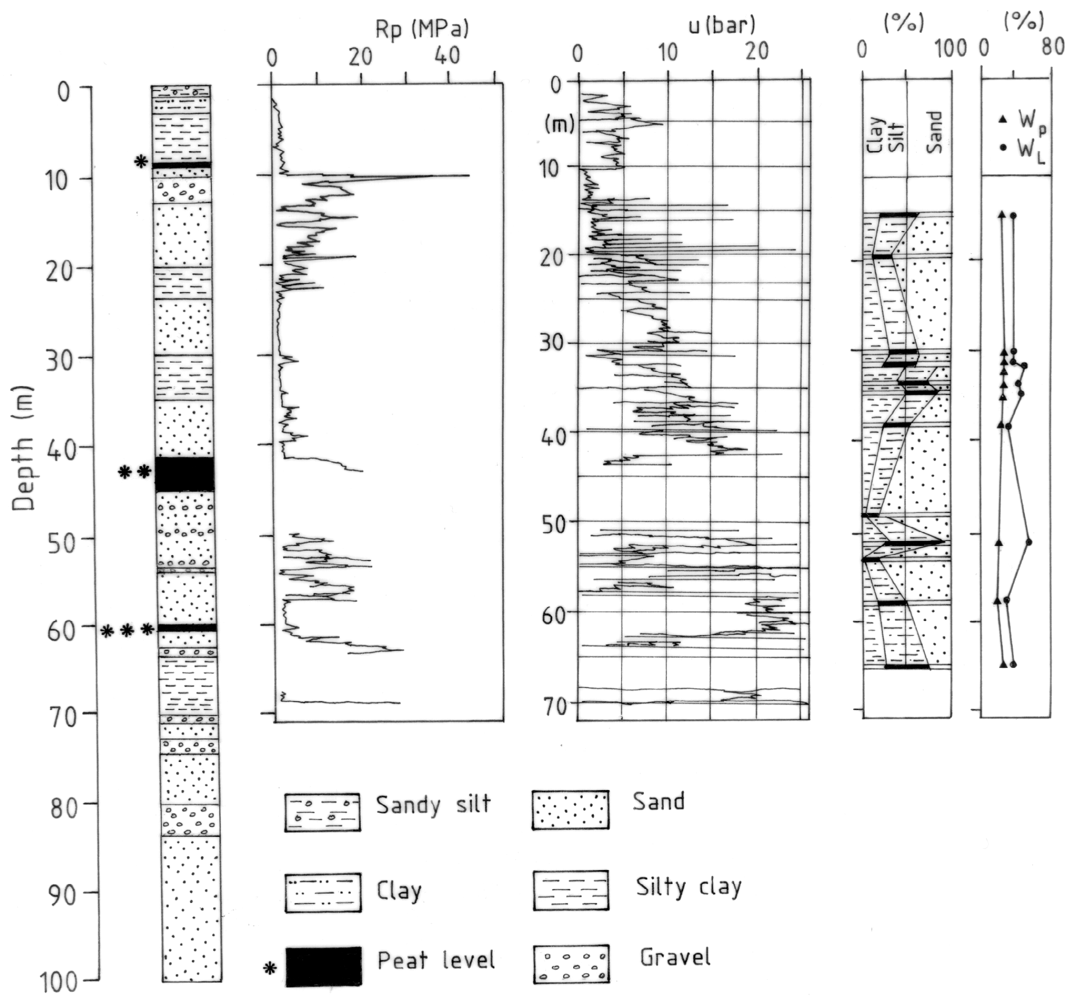

Fig. 6 - Soil profiles, size distribution, consistency limits, tip resistance and pore pressures for borehole S1.

As far as evolution during the Holocene is concerned, it can be seen that the ^{14}C age values are in line with the archaeological dating of the inhabited layers. The Roman town of Copia overlooked the sea. The tow-path now located at approximately 2.5 km from the sea, must have been located on the seashore during Roman times. As mentioned in the previous paragraph, the amount of subsidence was much slower in the layers nearest to the current ground level compared to the deepest alluvial levels. Morphological variations resulting from variations in the Crati and Coscile river courses must also be taken into account. Historical sources indicate that the ancient town of Sybaris was located between the two rivers Crathis and Sybaris (now called Coscile). Now they have one single outlet which has moved about 2.5 km towards the sea since Roman times, and they flow together a few kilometers upstream from the archaeological area of Parco del Cavallo. The stream capture of the River Coscile by the River Crati cannot have influenced the historical evolution of the ancient inhabited layers of Sybaris, Thurii and Copia, since the two rivers still had separate courses as is evidenced by some geographical maps of Rizzi Zannoni Zotti of 1714, 1759 and 1783.

Groundwater condition

The deep boreholes sunk during the campaign have provided further information about the hydrogeology of the area. The permeability coefficients, derived in situ, vary from a maximum of about 10^{-3} cm/s to a minimum of around $10^{-7} \div 10^{-8}$ cm/s. The vertical variability of hydraulic conductivity from layer to layer is thus very great. The shallow water table, which affects archaeological levels more intimately, can be found at a depth of 0.5 m bgl. This water table is dammed towards the shoreline by intruding seawater. Water for domestic use and for irrigation is pumped irrationally from the deepest water table. As a result, since 1950, some 20 cm soil subsidence ascribable to water extraction has been ascertained at the IGM bench mark located on the bridge over the Crati River. The presence of hydrogen sulfide and methane has been detected in boreholes drilled since the fifties. The local drawdown of gas-pockets is likely to speed up the subsidence of the plain, as well. This indicates the chemical reduction of organic matter by the brackish fossil water confined in the deepest layers. As this water is not thought to receive any natural recharge, its extraction is likely to result in accelerated subsidence.

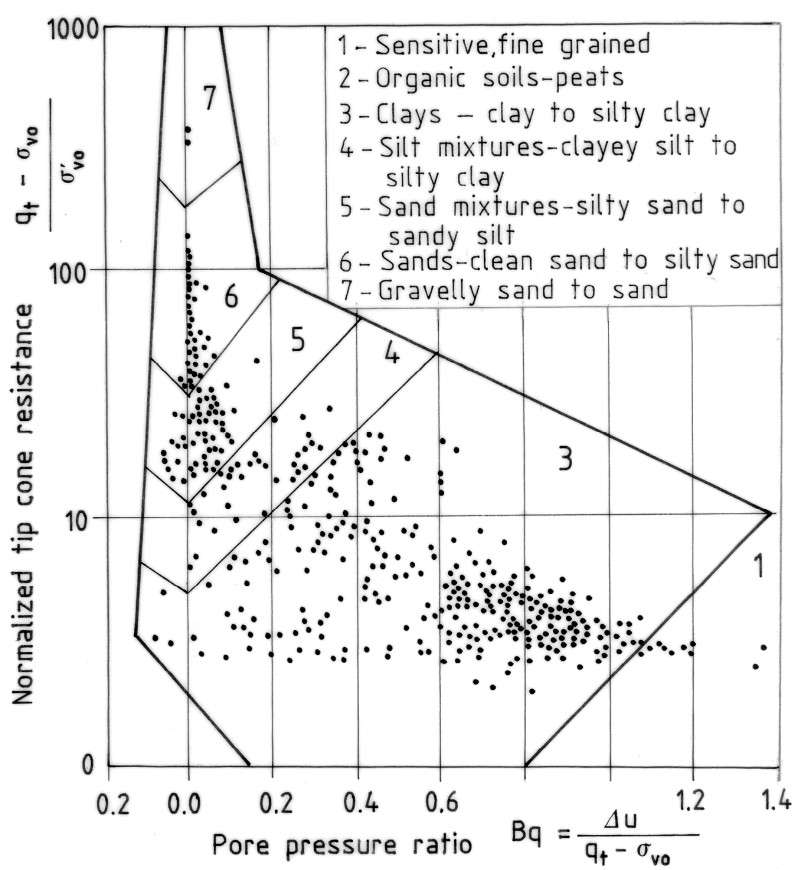

Fig. 7 – Robertson's nomogram (1990) for the results obtained using the piezocone.

Physical-mechanical properties of sediments

The S1 borehole is located next to a vertical along which a test was carried out with a piezocone (Fig. 6). As can be seen, the particle sizes and the consistence limits are rather variable. The latter in particular indicate medium or medium-high plasticity with values of activity ranging between approximately 0.3 and 1.0. The same investigation showed clay values ranging from 0 to 50%, silt from 8 to 58% whereas the largest fractions (sand and sometimes gravel) ranged from 10 to 58%. The presence of gravel and pebbles becomes prevalent at greater depths (>70 m). The unit weights remain around 16 - 17 kN/m^3. Some thin layers of peat a few decimeters thick can also be noted.

The greatest quantities of fine material are found between 23 and 42 m. Similar variations to those found in investigation S1 were also found in borehole S15, while it was ascertained that a more significant presence of clay and lime was found between 30 and 72 m. As far as other features of the deposits are concerned, the permeability coefficient values of the finest materials were found to be around 10^{-8} cm/sec with slightly lower values in some cases. After evaluation of the K_0 and comparison with the most widely accepted formulations concerning the dependence on Φ' these sediments can be considered as being normally consolidated ones. Further confirmation of their normal consolidation state was obtained from the study carried out in a previous work regarding a comparison of the state of the samples on site with the Intrinsic Compression Line (ICL) and with the Sedimentation Compression Line (SCL); the sensitivity was also found to be below average, because data acquired are located in a narrow band below SCL, even if the sediments show very different grain size distribution and plasticity indexes. It was also possible to evaluate how these sediments are generally deposited in an environment characterized by high sedimentation speed, (Skempton, 1970).

A piezocone test was performed for a depth of about 100 m at Stombi, measuring the tip resistance and the corresponding excess pore pressures. Unfortunately the lateral friction could not be read; this limits the possibilities offered by this kind of analysis to some extent. Figure 6 reports the diagrams of the as-read point resistance and excess pore pressures. It shows that coarse materials were found between about 44 and 50 m in a short stretch prior to the 70 m mark. Fine grained materials occurred mainly at depths between 22 and 43 m, with minor presence at greater depths. The materials encountered by the borehole were then classified by the procedure proposed by Robertson (1990), (Fig. 7).

It is readily apparent that there is a significant concentration of points in Zone 3, which includes clay and silty-clay ground, especially in the part where there is a B_q ratio of 0.6-0.8, thus confirming that these are normally consolidated soils. There is also a concentration in fields 4, 5 and 6; this is characteristic of soils whose particle size distribution places them between clayey silts and sands, especially in those parts where B_q is fairly close to zero. The great variability of data can certainly be attributed to the peculiar characteristics of the deposits, with a by-no-means negligible contribution from various factors influencing the test results to differing extents.

An evaluation was made of the undrained shear strength C_u in the stretch between - 22 and - 43 m on the basis of piezocone data, where a significantly stiffer bed of clayey and soft silty clayey material is encountered. The ratio C_u / σ_{vo} found for piezocone data is equal to 0.24; comparing this with different ones derived from PI or LL, values between 0.14 and 0.29 were found; according to Burghignoli & Scarpelli (1985), the C_u/σ'_{vo} values for other types of soft Italian clays range from 0.15 to 0.40.

Finally, an examination of four pressure-meter tests, performed in another borehole in the same area, enabled the C_u / σ'_{vo} ratio to be estimated in a different way as equal to 0.17.

Conclusion

The investigations carried out until now on the Plain of Sybaris have indicated the geological- structural, geoclimatic and geotechnical circumstances responsible for the great subsidence affecting the ancient town of Sybaris and thus the Hellenistic town and the Roman one above it over the past two and a half thousand years. The ground level of ancient Sybaris was found in investigations and digs carried out until today below the water table; this is approximately 2.5 meters below the current mean sea level with a relative variability of absolute distance depending on the differentiated measure assumed by the subsidence phenomena due to the lateral and vertical passage of differing sedimentary facies.

The bibliography cites the previous papers in which mention was made of the components leading to the total subsidence of the ancient site. The geomorphological evolution of the area and the influence of climatic factors on depositing sediments have been reconstructed on the basis of the numerous ^{14}C datings carried out on organic substances present at different depths in the alluvial levels. Reference has been made to the effect that the continual compression of the ground below the site over time may have had on the subsidence phenomena. The results obtained by means of in situ tests, using the piezocone in the first 100 meters of the sediments filling the plain, have shown the extreme variability of the soils with depth, the presence of significant percentages of fine grained soil, the low permeability of these fine soils and the state of normal consolidation of the sediments. Comparison of these results with the more precise laboratory findings showed a good agreement. The lithostratigraphic and geotechnical analyses both in situ and in the laboratory were found to have satisfactory agreement. The whole analysis identifies the existence of a highly compressible mainly clayey layer which is discontinuous laterally from 35-40 m in depth and is possibly responsible for the great geotechnical subsidence which has occurred in the archaeological area of Parco del Cavallo. Thus the heterogeneous subsidence which, as has been mentioned, led to the presence of deep compressible levels and occasionally significant layers of peat like in the area of investigation S1, may have caused the faults in the inhabited layers such that they are no longer flat but undulating.

The research carried out not only represents a scientific advance regarding the knowledge of the subsidence phenomenon in the area, but also regarding the present and future management and visits to the archaeological digs. Water, invading the subsoil and the archaeological remains present in it are of special concern here. All the studies carried out will provide a guide as to the type of action required to keep levels of great archaeological interest free from groundwater.

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