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Geological survey in the archaeological area of Selinunte

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Abstract
The archaeological site of Selinunte has recently been subjected to complex geological and geophysical research to answer a series of historical queries. The first results of this study were presented in a special issue of the *Bollettino di Geofisica Teorica ed Applicata*, edited by O.G.S. of Trieste. Among the various problems not yet solved, there is that of verifing if the collapse of the monuments can be related to a seismic event which took place in the past. There is also the problem of improving the methodologies to characterize the seismic response in monumental or archaeological sites. The results of a detailed geological survey in the Selinunte area are presented. The survey was executed integrating field recognitions with electromagnetic prospecting aimed at reconstructing the lithostratigraphic and structural setting. The ancient town of Selinunte was built on sedimentary terrains from the lower Pleistocene age. The series is constituted by sands, sandy clays and clays with levels and lens of calcarenite. The evidence for lateral discontinuities in the stratigraphic series suggests that effects of ground motion amplification could have been responsible for a high level of damage during earthquakes.

Key words *geology – applied geophysics – marine geology – Selinunte*

1. Introduction

Selinunte is situated on the south western coast of Sicily (fig. 1). It stretches over three hills whose axes are perpendicular in relation to the coast line which in the area runs in an east-west direction. From East to West the hills are: Marinella or Eastern Hill, the Acropolis with its northern continuation Manuzza Hill and the Gaggera Hill.

The city on the Acropolis was founded in the seventh century B.C. by a colonist group from Megara Hyblaea (near Syracuse) and represents the most Western Greek settlement in Sicily.

The greatness of the monuments testifies the level of development which the city acquired during the sixth and the fifth century B.C. The Acropolis, borded by the two valleys of the Cottone and Modione rivers, was the site of temples and houses of nobles; it later extended as far as the low ground which is surrounded by the hills of Manuzza.

In the Eastern Hill one can find other temples. Temple G was dedicated to Zeus and represents one of the largest temples of antiquity. Near this temple there are also temples F and E. Temple E was restored in the Fifties.

Selinunte was destroyed in 409 B.C. by the Carthagenians and after diverse vicissitudes its inhabitants lived for a century and a half on the Acropolis under their rule, until the city was completely abandoned at the end of the First Punic War (third century B.C.).

Historians believe that an intense earthquake, probably during the Byzantine Age, caused the complete destruction of all the temples.

A research programme was organised to verify this hypothesis and to improve the methodologies for characterizing seismic responses in monumental areas (Boschi *et al.*, 1995; Funiciello *et al.*, 1995; Moczo *et al.*, 1995). This programme was supported by the

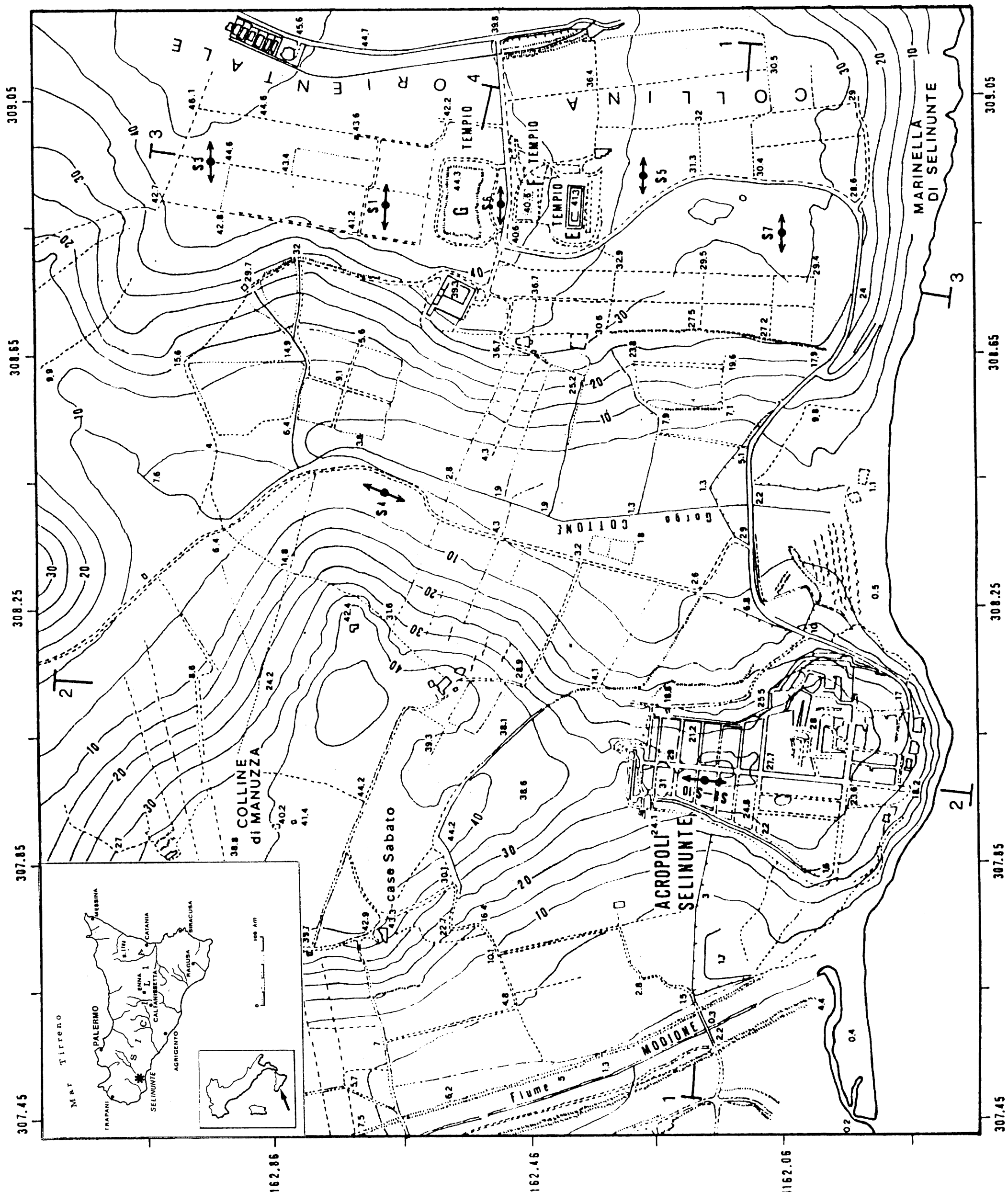

Fig. 1. Location of the studied area and the Selinunte Archaeological Park. The arrows indicate the location of the vertical electric soundings presented in fig. 5. Numbers 1 to 4 indicate the tracks of the geologic profiles depicted in fig. 7.

Strategic Project for the Science and Technology of Cultural Heritage of the Italian National Research Council.

As a first step, this paper illustrates a detailed geological survey in the Selinunte area obtained by integrating field observations with geophysical prospectings. An attempt to reconstruct the recent modifications in morphology was carried out using the results obtained during a marine geophysical survey in the sea in front of the Selinuntine coast line.

2. Geological framework of the area

Selinunte lies in the central part of the coastline between Capo Granitola and Capo San Marco in the south-western part of Sicily. The area is part of a territory which is represented by the Modione basin and partially by the Belice basin. Figure 2 presents a geological schematic map, as is depicted from sheets No. 257 and 265 of the Geological Map of Italy. This map also contains some structural features deduced from the Structural Model of Italy (CNR, 1983).

The Basin of the Modione river (old Selinus) lies in the western part of Sicily and includes the Delia basin on the West and the Belice on the East. Its surface is approximately 300 km^2 and it is approximately 25 km in length.

The Modione river originates near the town of S. Ninfa (from hills with a height of approximately 300 m), runs southwards, passing close to the towns Castelvetrano and Campobello di Mazara and flows into the sea (Sicily Channel) westwards of the Selinunte Acropolis.

As depicted in fig. 2, along its water-course the Modione river weakly cuts Pliocenic terrains (in the northern part) and the Holocenic ones represented by clay and sandy clay marine deposits with calcarenite lens, due to limited flow and reduced power.

The hills which delimit the basin area are of modest height. In the North East one finds: the «Cima Rizzo» (m 526), the «Cima Mistretta» (m 472) and the cliffs on which the city of Partanna stands. They comprise the Upper Pliocene limestones «coarse, sandy and fossiliferous, gradually passing downwards to the grey-azure clays and marly clays», (Carta Geologica d'Italia, F. 257, 1956). Going towards the South, the limit between the Modione and the Belice basin becomes increasingly uncertain due to the gentle sloping of the sides and to the intense anthropization (agriculture and urbanisation).

The eastern limit of the basin is also characterized by low hills. It is worth noting the outcrop of the Miocenic «Gessoso-Solfifera» series near Castelvetrano which, with an inarcuation, stretches in an elongating shape as far as the town of Santa Ninfa. This outcrop could represent a peninsula in the Pliocenic sea. In fact, it is surrounded by sediments of this period overlapping the Miocenic series transgressively.

From a structural point of view, as observed in the Structural Model of Italy, the main tectonic features are: the Post Tortonian thrust which in this area runs from SW to NE and passes north of Castelvetrano in the direction of S. Ninfa; the two faults west and northwest of Campobello di Mazara which follow the same direction as the above mentioned thrust; the Partanna fault which cuts the Pliocenic terrains in a prevailing NNW-SSE direction; a series of small faults which affect the Oligocene marly limestones, near the area of Piano d'Accardo (6 km SE from Partanna). The fault of Partanna is outlined by a cliff, observable from the south-eastern slope of the town as far as the Belice river. Moreover, the Structural Model of Italy indicates, also in the near-off shore of Selinunte, the presence of subsurface anomalous contacts like Post Tortonian thrust and reverse faults.

More recently, Argnani *et al.* (1986, 1987) and Catalano (1986), considering some multichannel seismic lines with well and dredge data, detected new interesting structural evidence in the Sicily Channel. Just south of the Selinunte area they found a system of transcurrent faults with N-S direction, which separates two distinct foredeeps.

From the Neotectonic Map of Italy (Ambrosetti *et al.*, 1987) it is possible to see that this area was affected by an almost continuous subsidence during the Pliocene and Lower

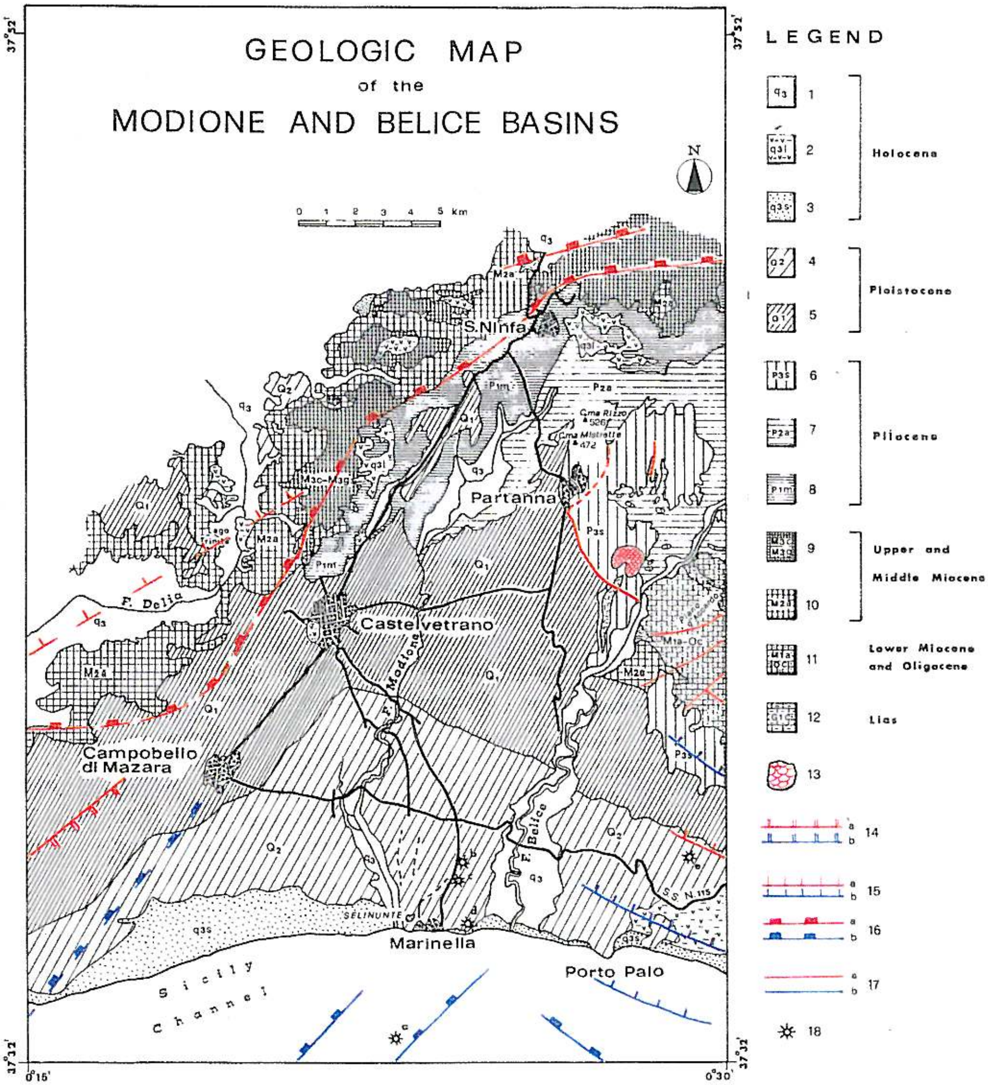

Fig. 2. Geological map of the Modione and Belice basins (from the sheets No. 257 and 265 of the «Carta Geologica d'Italia» and «The Structural Model of Italy». Legend: 1) recent alluvial deposits; 2) marshlands; 3) recent beach and moving sand dunes; 4) litoral, conglomeratic and calcareous deposits; yellowish, sandy-calcareous deposits with fauna of temperate-warm climate, with levels of grey clayey sands; 5) litoral and calcareous deposits with sandy clayey levels with fauna of temperate-cold climate; 6) sandstones, yellowish sands, clays and conglomerates; sandy and coarse limestones; 7) gray-bluish clays and clayey marls; 8) white and grey marls («Trubi»); 9) terrigenous marine deposits, evaporites, diatomites and subordinate limestone («Serie Gessoso-Solfifera»); 10) clays, marly clays, sandy clays and ochreous molasse; 11) clays, sandy limestones, marly limestone and conglomerates; 12) reddish, dense and marly limestones; 13) landslide. Tectonic Symbols: 14) Normal faults: a) surface; b) subsurface. 15) Overthrust and reverse faults: a) surface; b) subsurface. 16) Main Post Tortonian thrusts: a) surface; b) subsurface. 17) Undetermined faults: a) surface; b) subsurface. 18) Well (letters a, b, c, d and e correspond respectively to the wells: Onda 1, Marinella 1, Marinella 2, Marinella 3 and Menfi 1).

Pleistocene, but since the Lower Pleistocene it has undergone a moderate uplift. The area is also characterized by deformations caused by normal faults of the Pleistocene Age. The central part of the area under consideration seems to be in the middle of a small graben bounded by two faults stretching NE-SW and NNW-SSE. A third fault, with NW-SE trend delimits this small structure northwards (fig. 3).

To complete the framework it is useful to summarize some data on the seismicity of this part of Sicily.

According to Guidoboni (1989), Latin and Greek sources relate that many earthquakes occurred in Sicily: the earliest described was in 426 B.C. Information about other events are given: around 17 A.D., an earthquake, or perhaps more than one, was felt throughout the Mediterranean basin: Palestine, Libya, Greece and Sicily; finally a strong earthquake was recorded in 852 A.D.

According to Postpischl (1985), earthquakes within a 50 km radius of Selinunte before 1800 (with intensity higher or equal to V MCS) have also been taken into consideration. They are listed in table I (Amadori *et al.* 1992, p. 90).

In more recent times, there were two earthquakes with epicentres in the area under consideration, with intensities of VIII MCS in 1817, and VII in 1933. Figure 4 shows the epicentre distribution of Sicilian earthquakes. In the current Seismic National Classification (Servizio Sismico, 1986), Selinunte is considered to be of intermediate seismicity, but it borders on the first category (intense seismicity) of areas, such as the Belice Valley, immediately northwest of Selinunte.

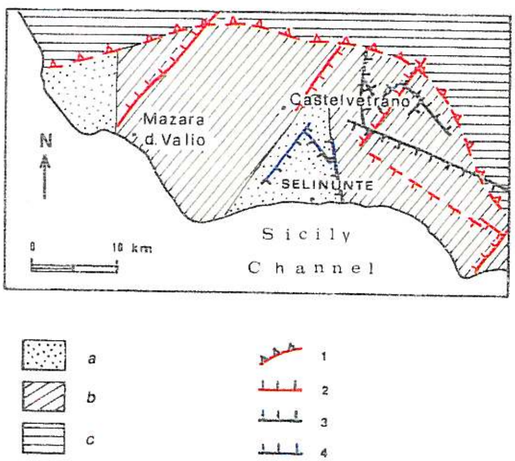

Fig. 3. Sketch from «Neotectonic Map of Italy» (Ambrosetti *et al.*, 1987), partially modified. Legend: a) continuous and intense lowering in the Pliocene and in part of the Early Pleistocene. Prevailing deformations by normal faults; b) almost continuous and moderate lowering in the Pliocene and Early Pleistocene; standstill or moderate uplift since the Middle Pleistocene. Prevailing deformations by normal faults; c) intense lowering in the Pliocene and in part of the Early Pleistocene; intense uplift since Early and/or Middle Pleistocene. Moderate deformations mainly by folds and reverse faults and, locally, by normal faults. 1) Thrust (saw-teeth on overthrown limb). Quaternary and possibly older. 2) Normal fault (hatching on down thrown side). Quaternary and possibly older. 3) Normal fault. Pliocene and Quaternary. 4) Normal fault. Pliocene (generally Middle and Late) to Early Pleistocene.

3. Geological and geophysical survey of the Selinunte area

The Selinunte area was surveyed integrating detailed geological recognition (Amadori *et al.*, 1992; Brizzolari *et al.*, 1992a) with a series of vertical electric soundings (V.E.S.), see fig. 5a-d. After this survey, the following layers were defined (from top to bottom; see also fig. 7):

a) *superficial covering*: these terrains are characterised by a sandy-clay matrix with fragments of limestone, chert pebbles and fragments of fictile materials. Several metallic objects, related to present-day farming, have also been found. Its thickness is less than 50 cm;

b) *calcarenite*: it is difficult to recognise the outcrops of this level in the area. V.E.S. determined that its thickness varies. It reaches the maximun thickness at the top of the Manuzza Hill and on the Acropolis (fig. 5a). On the Eastern Hill the maximum thickness lies under the area of the temples (figs. 5b,c). It decreases southwards and it is modest (less than 2 m) north of the G temple. Resistivity values of altered or cohesionless calcarenite range from 65

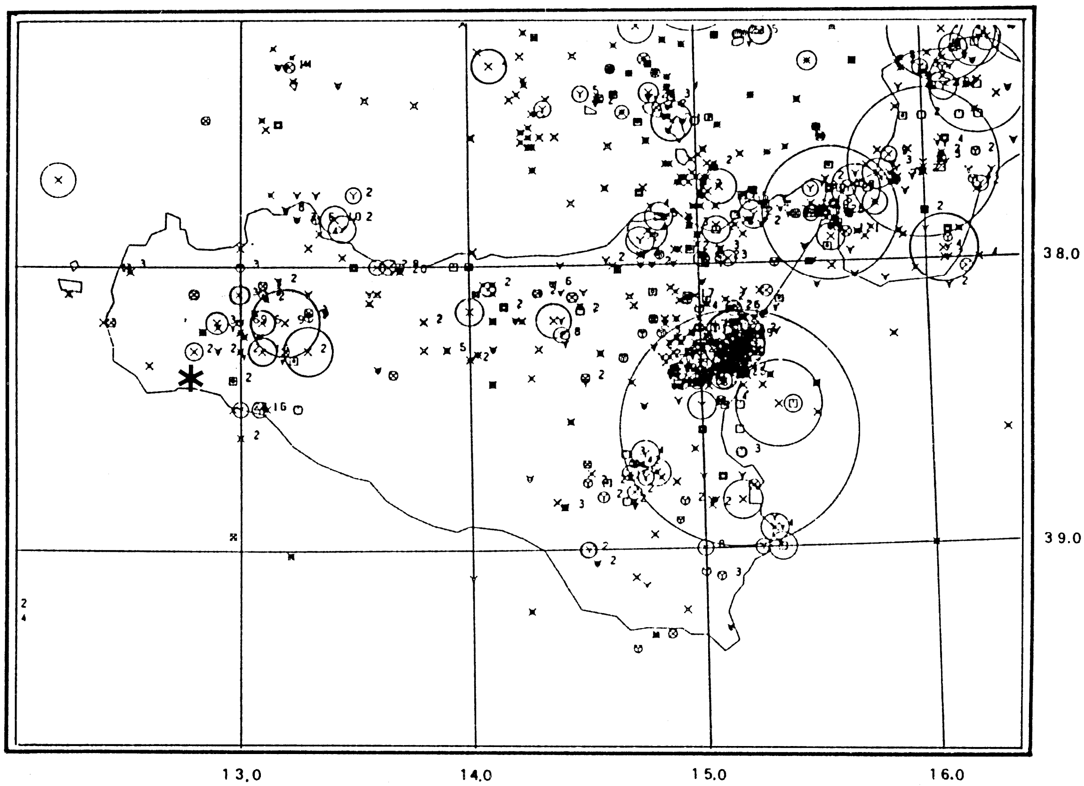

Fig. 4. Epicentre Map of Sicily (after Postpischl, 1985). Events with intensity greater than degree IV-V MKS (local magnitude > 3.5) are located. Epicentres are represented by circles, whose radii are related to earthquake intensity. The star indicates the position of the Selinunte area.

to 170 Ohm x m, while those of dense calcarenite range from 450 and 2,000 Ohm x m. A series of GPR profiles executed north of the G temple for archaeological purposes (Brizzolari *et al.*, 1992b) show that the calcarenite layer here is fractured, as explained in one of the next sections;

c) *sandy-clay formation*: its thickness is in the order of 10 m, and includes lens of scarcely cohesive and fossiliferous calcarenite which is ochre in colour. Its resistivity ranges between 20 and 35 Ohm x m. The sandy clay nature of the terrains in the central part of the Eastern Hill was confirmed by a survey carried out with the electromagnetic method at low inducting number, using an EM31 Geonics apparatus (Brizzolari *et al.*, 1992a);

d) *clay formation*: this is the last layer determined by V.E.S. (fig. 5d). Resistivity values are very low (less than 10 Ohm x m).

The survey with the Ground Penetrating Radar was carried out with a Georadar OYO YL R2 mod. 2441, equipped with two 600 MHz antennas. The profiles executed in the area north of the G Temple showed reflections at 25 ns twt (two way time). They continue for a few nanoseconds (ns). In some cases, it is possible to discriminate interruptions inside the reflecting horizon. The anomalies have slightly convex surfaces and there are hyperbolic signals at their borders (fig. 6). According to other geophysical surveys (Lapenna *et al.*, 1992), these anomalies can be referred to a layer of a fractured calcarenite which lies

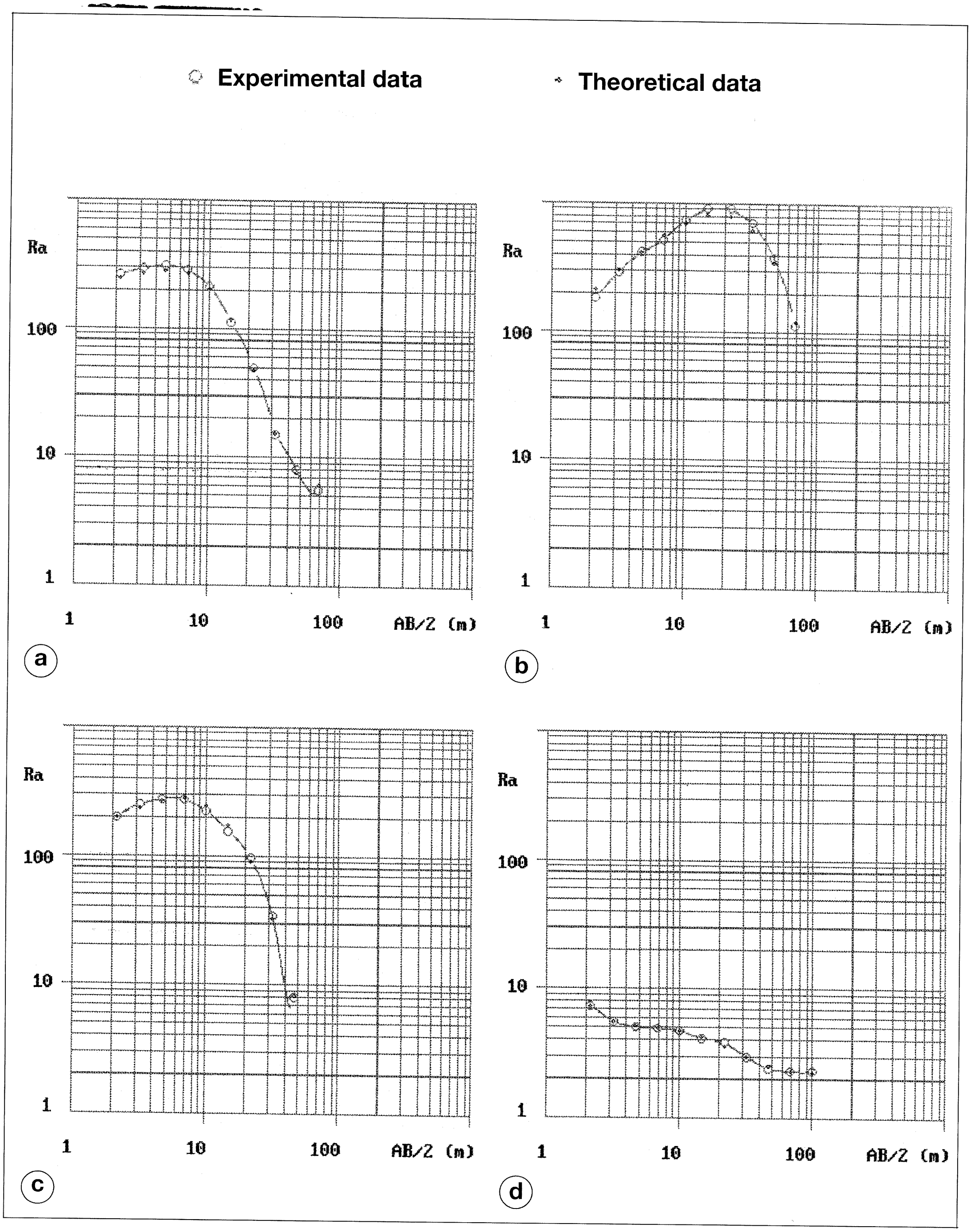

Fig. 5a-d. Vertical Electric Soundings carried out in the Selinunte Archaeological Park.

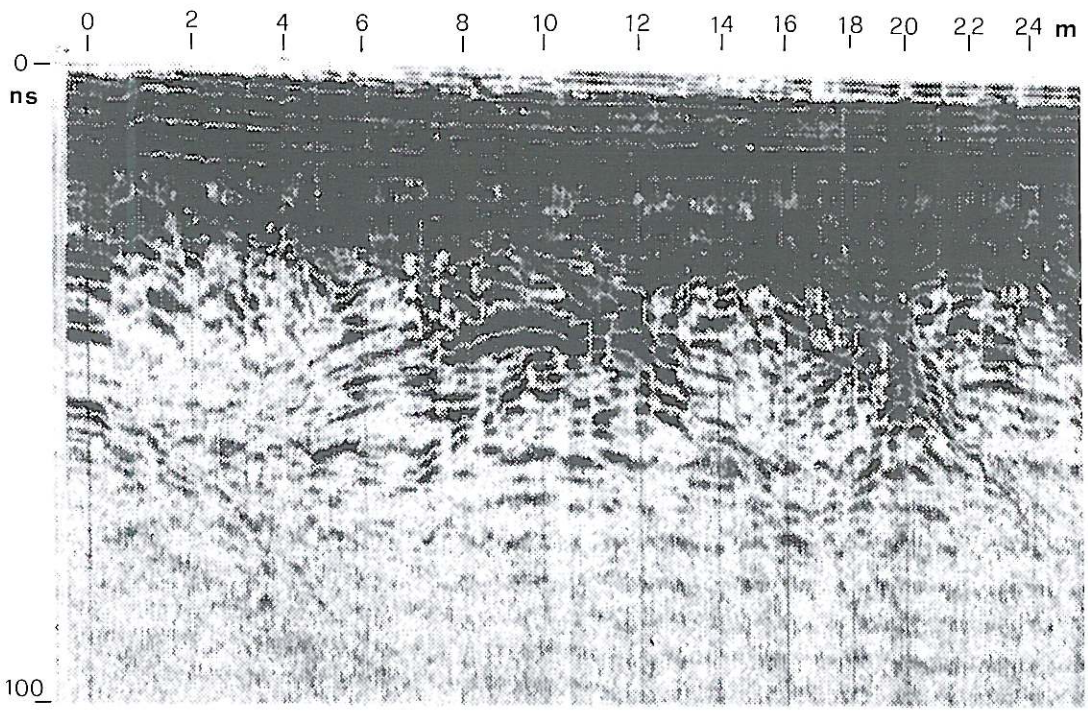

Fig. 6. Example of georadar recording obtained on the Eastern Hill, north of the G Temple. On the *x* axis the spatial intervals are in m (along the profile direction); on the *y* axis the time scale is in nanoseconds (ns). At a depth from 6 to 20 m some anomalies with slightly convex surfaces are present.

under a thin level (less then 1 m) of top soil.

Figure 7 presents some geological profiles. They are oriented as shown in fig. 1, and obtained integrating the geological survey, the V.E.S. interpretation and the results obtained in previous publications in the same area (Balia, 1992; Carrozzo *et al.*, 1992; Lapenna *et al.*, 1992).

4. Physiography of the coastal environment

It seems useful to integrate the information observed from the inland with some recent results obtained from a marine geophysical survey (Brizzolari *et al.*, 1994) executed in front of the Archaeological Park of Selinunte. Figure 8 presents a batimetric map obtained by a Sub Bottom Profiler (SBP) survey. The sea floor presents a regular slope except for the eastern part. Near the Belice mouth there is a bank which is aligned with the hills bordering the eastern site of the river.

Below the sea floor, the analysis of the seismic sections obtained by the SBP and Uniboom surveys shows many reflection events related both to strata surfaces inside homogeneous sedimentary bodies and to discording surfaces between different geological formations. With the exception of the sections near the coast line, a seismic sub-stratum is always identifiable. It is generally in discordance with the overlying sedimentary bodies. The acoustic signs of the reflections seem to be unhomogeneous both in vertical and in horizontal directions (lateral discontinuities); there is evidence of a great variety of depositional and dynamic environments. This appears to be in good

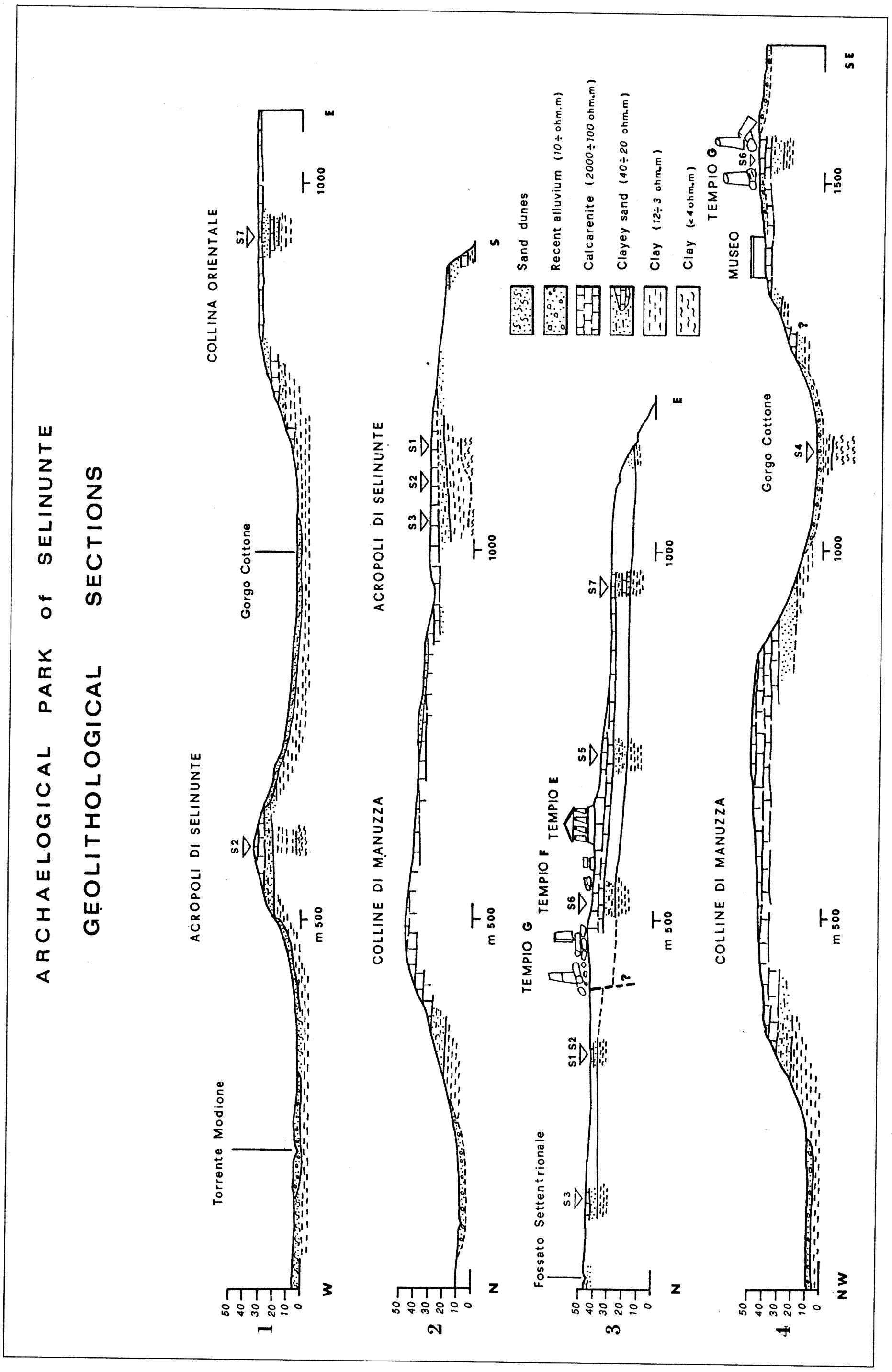

Fig. 7. Geological profiles (after Amadori *et al.*, 1992). Tracks of profiles are depicted in fig. 1.

Fig. 8. Bathymetric map.

agreement with the nature of the investigated area which is close to the shoreline and therefore subjected to high power processes due to the litoral currents and to the wave action. The area is also characterised by the presence of the mouths of the rivers Modione, Cottone and Belice; nowadays, the latter should be considered seasonally active.

Figure 9 presents the sub-stratum morphology obtained from the Uniboom and SBP and represents the deeper reflective surface which is detectable by these methods. This horizon is constituted by strata with a thickness of more than ten m, with an E-W direction and dipping to the South with a mean slope of 4°. This formation crops out on the sea floor over a large area in front of the hill which eastwards delimits the Belice mouth.

Upwards the formation is delimited by an irregular surface due to erosive processing which probably took place during an uplift phase corresponding to the last glacial period. The depressions of the surface are filled with sediments attributed to the last marine ingression, at the end of the last glacial period.

The map (fig. 9) shows the present inland morphology together with that referred to the time before the last marine ingression. It illustrates a series of interesting landscapes. On the western part of the map, near the Modione river, a subcircular depression is visible with two little cuts in proximity of the coast line. This could signify that the Modione mouth has changed its position in recent times. Between the mouths of the Modione and the Belice rivers one can see on the map a cliff dipping towards the sea with a steep slope in a WSW-ENE direction which seems to follow the present coastal sub aerial morphology where the city of Marinella lies. Close to the Belice mouth one can see that before the last ingression the old river flowed in a SW-NE direction. Probably this feature was due to the presence of an outcrop of the sub-stratum, as can be seen on the most eastern part of the area which is in good correspondence with the hills close to the Belice mouth. This outcrop corresponds with the bank visible on the bathymetric map between the levels of −14 and −24 m.

5. Stratigraphy from well data

To complete the collection of stratigraphic information, it was considered useful to include in this work some information obtained from the disposable wells drilled for oil exploration. The position of the wells is indicated in fig. 2. The «Onda 1» well was drilled southward of the Modione mouth, in the Channel of Sicily, at a distance of less than two miles from the shoreline (AGIP S.p.A., 1978). From the top to the bottom the series comprises 530 m of clay sediments of Pleistocene Age which cover 150 m of clays and marls of Pliocene Age. The series continues with Upper and Middle Miocene with a thickness of more than 1000 m. The Upper Cretaceous limestones close the series. The stratigraphy of this well together with the other disposable wells in the Selinunte inland is presented in fig. 10. The Marinella 1, 2 and 3 wells were drilled at the end of the Fifties, while the Menfi 1 well dates back to 1982. Consequently it was necessary to correlate the bottom of the terrains attributed to the Calabriano Age in the first three wells with the bottom of the terrains from the Pleistocene Age of the last well. The first two wells show a stratigraphy similar to that found in the offshore one, but with a hundred metres of Pleistocene sediments more than in the previous one. In the Marinella 3 and Menfi 1 wells the stratigraphy is as follows: under 600 m and 646 m, of Pleistocene sediments respectively, there is the Pliocene series which covers the alloctonous terrains, probably the westernmost part of the Gela Nappe (Catalano and D'Argenio, 1982). In the Menfi 1 well the alloctonous series overlaps the Lower Pliocene marls (Trubi). The well ends with the Miocene series.

6. Discussion

The results obtained from these first surveys, can help to organize the next step in the scientific programme at the Selinunte Archaeological Site. From the stratigraphic point of view, the southern part of Modione basin, which includes the Selinunte site, is character-

Fig. 9. Morphology of the acoustic sub-stratum.

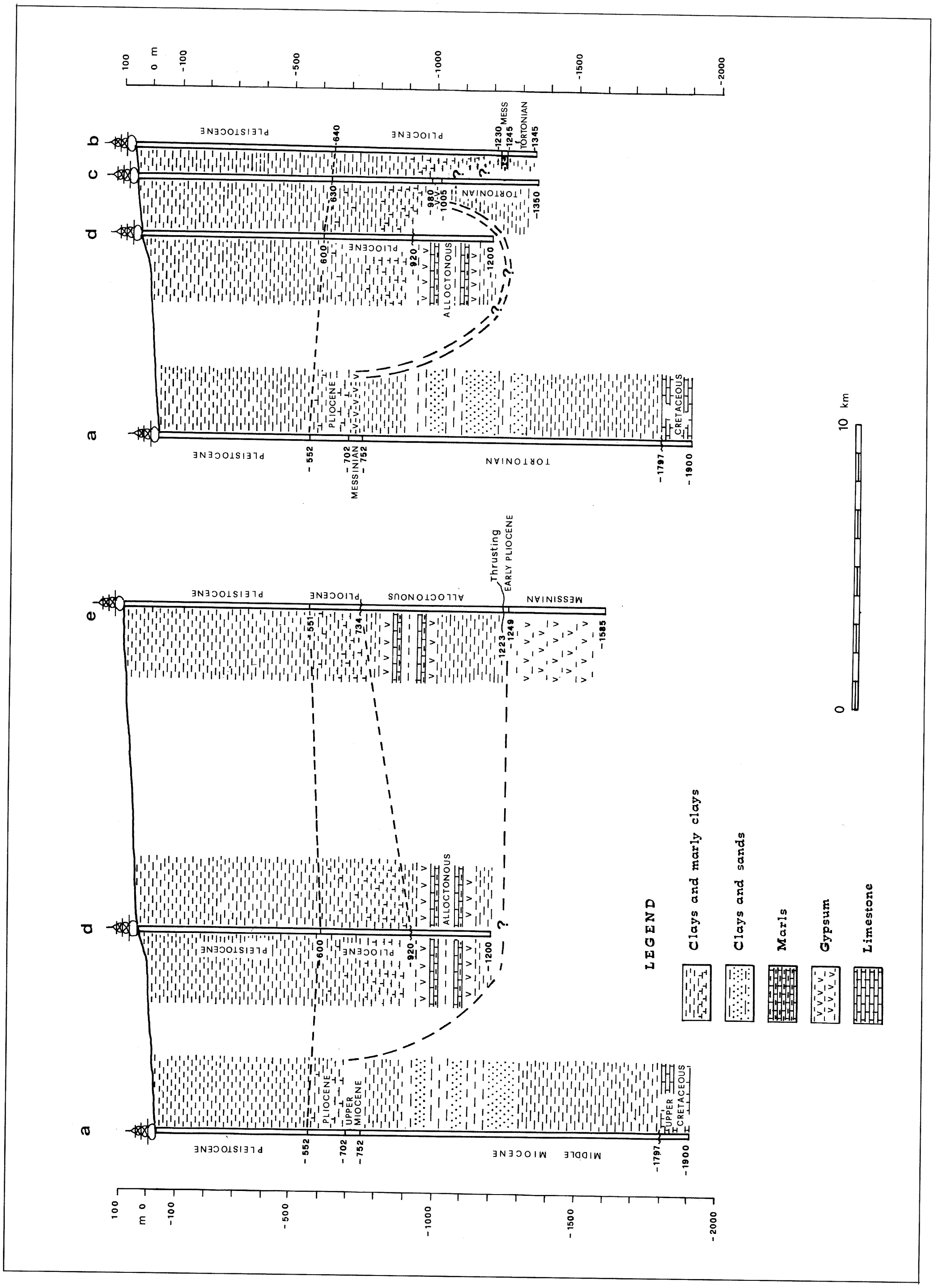

Fig. 10. Stratigrafy of the wells: Onda 1, Marinella 1, Marinella 2, Marinella 3 and Menfi 1. Their location is indicated in fig. 2.

ized by Plio-Pleistocenic marine sediments constituted by plastic levels (sandy clays and silty clays). In the last part of this series there are some calcarenitic layers and lens. These layers are partially fractured, as can be observed in GPR profiles (fig. 6). The Plio-Pleistocenic sediments have a thickness of more than 600 m as can be observed in the well data from drillings executed for mineral purposes. The results of the seismic surveys (Sub Bottom Profiler and Uniboom) near Selinunte coast have confirmed the presence of the upper part of this layer, which presents an E-W direction, with 4° dipping. This result is in accordance with Vertical Electric Soundings and with geological sections shown in fig. 7.

From a structural point of view, a few kilometres from the Selinunte area, the analysis of some onland well data detected the presence of alloctonous terrains (Gela Nappe) under the Plio-Pleistocene series. As outlined by Argnani *et al.* (1986; 1987), a wide deformation belt is present just off-shore of the Selinunte area. This deformation, which is connected by strike-slip faults with a NNE-SSW direction, occurred during the Pliocene and Early Pleistocene.

Within this framework, the next step for the characterization of seismic response of the archaeological area of Selinunte could be oriented towards the possible evidence of subsurface continuation of the main structural elements found in the near off-shore of Selinunte.

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