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SHALLOW REFLECTION SURVEY IN THE SELINUNTE NATIONAL ARCHAEOLOGICAL PARK (SICILY, ITALY)

Abstract. A seismic reflection survey with seven short profiles was carried out in the Selinunte National Achaeological Park (Sicily). From the results, it was possible to obtain information on the geological structures supporting the Greek Temples. Some operational and methodological aspects are also discussed.

INTRODUCTION AND BRIEF GEOLOGICAL OUTLINE

The work was carried out as part of a coordinated project having as objective the application of geophysical techniques to archaeology.

In parallel to our shallow reflection prospecting, other groups were investigating the same area with other geophysical methods, such as gravity, magnetic, electrical and electromagnetic and ground penetrating radar. The results of these surveys are being published contemporaneously. The Selinunte National Archaeological Park, which is one of the most important archaeological sites in Italy, was chosen for these experiments.

Some of the above methods (e.g. ground penetrating radar) were particularly aimed at locating possible archaeological features, while others, such as gravity, electrical and the present seismic work, were devoted to the reconstruction of the shallow geological structures in the area.

From archaeological considerations, it was particularly important to single out the conditions of the calcarenitic layer supporting the Greek Temples and of the underlying horizons with a good degree of detail.

With regard to seismics, due to the presence of this calcarenite with velocity higher than that of the underlying layers, the refraction method was rejected a priori and we decided to carry out a reflection survey, at least as a first experiment.

For the operational and methodological aspects, we wondered whether the survey would be successful with recording equipment not specifically designed for reflection surveying but which met the prerequisites of practicality and facility of operation. We were also hoping to obtain practical information on field procedure; and, finally, we wanted to know whether we could carry out a processing that whould be acceptable even without the help of special hardware or software.

There are, in fact, numerous papers on the latter aspects, particularly on prospecting procedures, sources of energy and problems relating to specific cases of the application of shallow and high resolution reflection seismics: Knapp and Steeples (1986), Miller et al. (1986, 1989), Miller and Steeples (1991), Henson and Sexton (1991) and references within, being among

Manuscript received February 20, 1992; accepted March 25, 1992.

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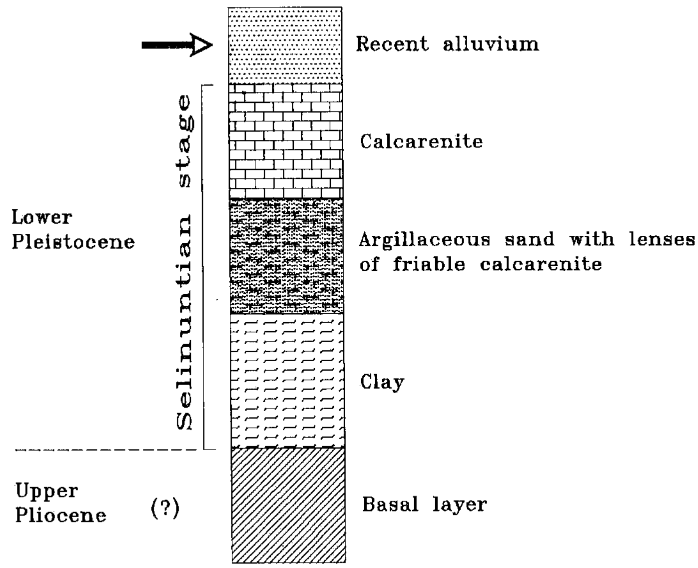


Fig. 1 — Typical stratigraphic sequence of the area of Selinunte. The arrow indicates the approximate position of the plane on which the seismic profiles were carried out.

the most recent and significant.

From the geological point of view, according to the overview given by Amadori et al. (this issue), the Selinunte area is characterized by the so-called Selinuntian Stage, in the Lower Pleistocene bordering with the Upper Pliocene. Fig. 1 shows details of the typical stratigraphy of the survey area. The arrow shows the approximate position of the field plane of the seismic profiles.

RELFECTION SURVEY

The survey consisted of seven seismic profiles with positions as shown in Fig. 2. Profiles 1, 2, 3 and profile 4 were respectively located in the two test sites, the so-called Greek Area (90×90) and the Roman Area (40×40), where the other research groups also applied geophysical methods. Profiles 5, 6, and 7 were sited to obtain a broken line, starting from the area of the temples in a SW direction as far as the topographically low area corresponding to the position of the old port of Selinunte, now entirely buried.

Table 1 shows the field parameters. Since profiles 1-5 were particularly aimed at very shallow targets and profiles 6 and 7 at deeper structures, the geophone spacing was 2 m for the former and 5 m for the latter.

An Abem Terraloc MK II, 24 channel recording system was used; the record length was 0.2 s with a 0.0002 s sampling interval in fixed gain for each channel; the analog filters were out. Our greatest misgivings about the usability of this apparatus concerned the low dynamic range (only 48 dB) and the fact that the analogic filters were insufficient.

Single geophones with relatively high natural frequency (100 Hz for profiles 1-5 and 50 Hz for profiles 6-7) were used in order to attenuate ground roll in acquisition. On this subject it should be noted that on reducing the bandwidth, the use of high frequency geophones certainly reduces axial resolution. As known, the bandwidth needed to identify closely spaced beds depends on the polarity of the reflection coefficients at the boundaries and on the character of the downgoing pulse. For positive reflection coefficients and a zero phase wavelet, the required spectrum width W is approximately equal to 1/T, where T is the TWT between the boundaries that are to be resolved (Espey, 1983). As a numerical example, if the available bandwidth W is in the order

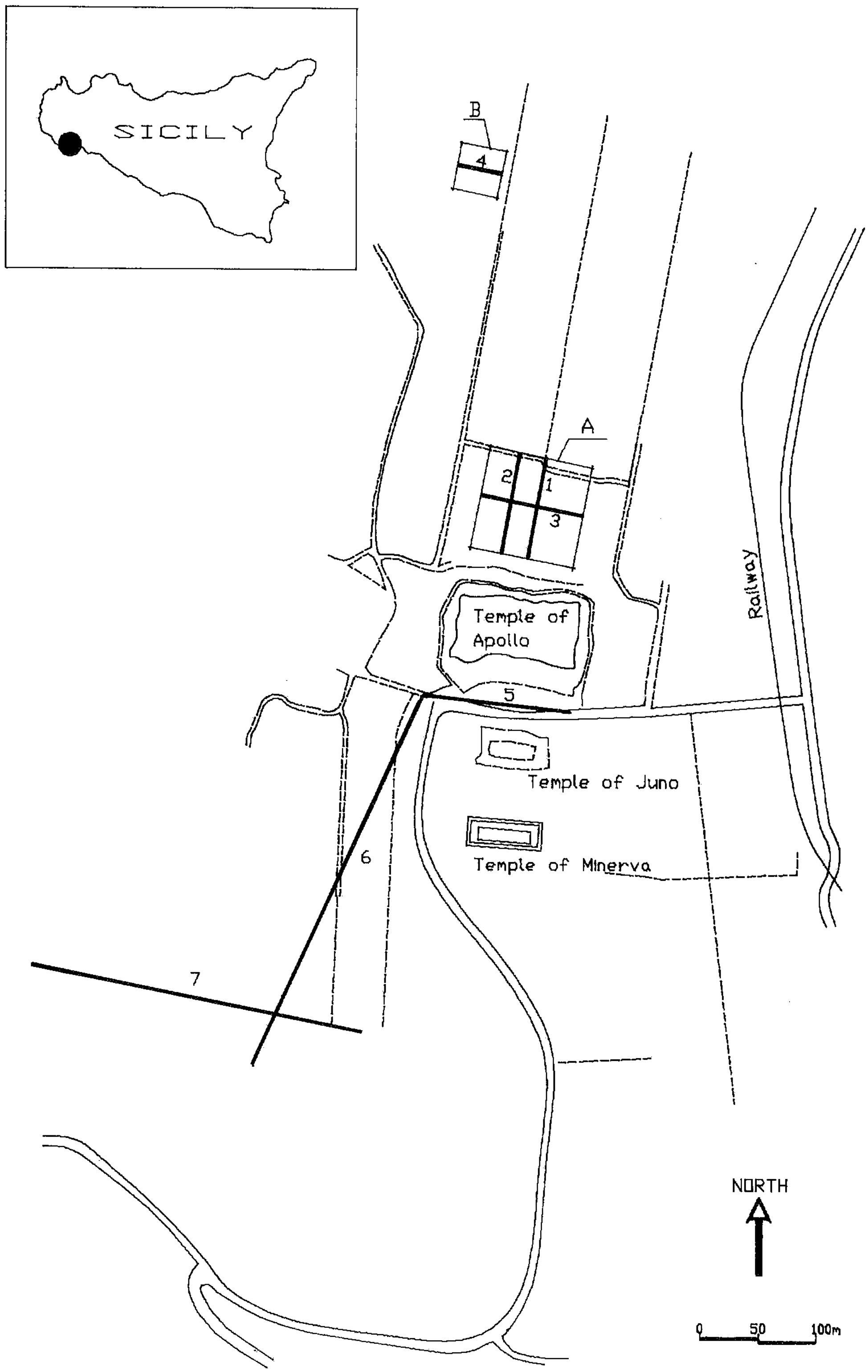


Fig. 2 — Position map of seismic profiles 1 to 7. A and B indicate respectively the two test sites called Greek Area an Roman Area.

Table 1

Profile n.	N. of records	Shot int. (m)	Channel int. (m)	MO (m)	CL (m)	CDP Fold (%)
1	35	2	2	4	46	1200
2	32	2	2	4	46	1200
3	17	4	2	4	46	600
4	24	1	1	2	23	1200
5	37	2	2	4	46	1200
6	36	5	5	10	115	1200
7	25	5	5	10	115	1200

Channels: single geophone 100 Hz natural frequency for profiles 1-5; 50 Hz for profiles 6 and 7.
Energy source: hammer for profiles 1-4; gun for profiles 5-7.

of 400 Hz (say in the range 10-400 Hz), the maximum nominal time resolution is 2.5 ms. If single 100 Hz natural frequency detectors are used, and if we consider them as ideal low-cut filters, the bandwidth is reduced to 300 Hz and, consequently, the maximum time resolution becomes 3.3 ms, which means that the deterioration is in the order of 30%. One further aspect to be taken into account is that concerning lateral resolution and therefore spatial sampling. In fact, if maximum spatial bandwidth is needed over the whole time frequency band, that is up to the maximum frequency value F without aliasing, then the following should be assumed:

$$Dx \leq \frac{V}{2 \times F} \tag{1}$$

where Dx is the interval between single geophones and V the minimum value of apparent velocity to be expected (e.g. see Berkhout, 1984).

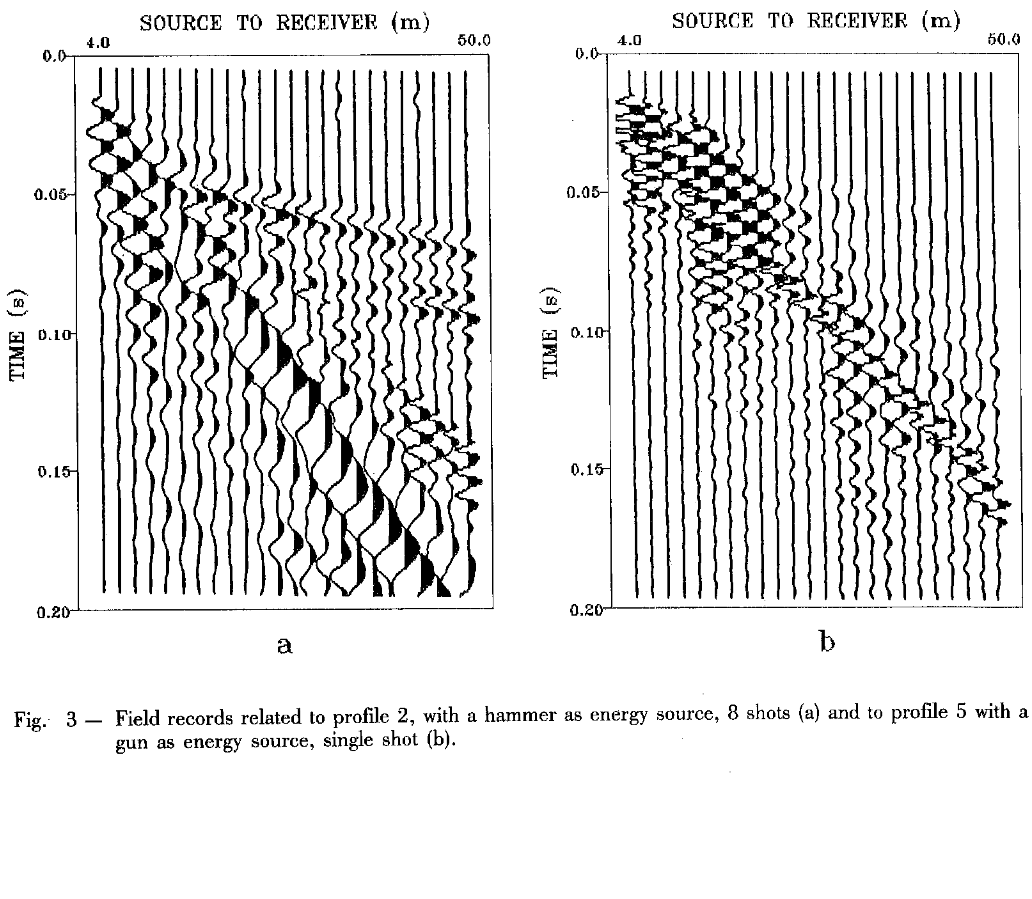


Fig. 3 — Field records related to profile 2, with a hammer as energy source, 8 shots (a) and to profile 5 with a gun as energy source, single shot (b).

As a first approximation, in our experiments we estimated V and F to be in the order of 1500 m/s and 350 Hz, respectively. Consequently, on substituting these value into equation (1), a geophone spacing of less than or equal to 2.14 m was deduced. Actually, in our shortest profiles a spacing of 2.0 m was adopted.

Another typical tool for ground roll attenuation is a properly designed pattern of geophones, which acts as a filter in the wavenumber domain. Since the spatial bandwidth of ground roll and that of shallow reflections can overlap significantly, the risk of attenuating shallow reflections when attenuating ground roll by using patterns should be taken into account.

Moreover, specifically regarding resolution, it is demonstrated (e.g. see Berkhout, 1984) that "lengthy field patterns should be avoided at all times, as they generate a dramatic spatial band-limitation", and that in "high resolution surveys lengthy field patterns should not be used".

Patterns of closely spaced geophones could then be used in order to collect a stronger signal and attenuate the short wavelength noise components, but this would not be the best solution for ground roll attenuation.

Thus, at least for these first experiments and taking into account the practical difficulties related to the availability and use in the field of a relatively large number of detectors, we preferred to use single high frequency geophones.

A few simple measures were also adopted in an attempt to attenuate the noise due to the air-coupled wave. These included placing the geophones very accurately in order to give a certain degree of protection from this noise and to obtain an optimal coupling with the ground. However, it should be mentioned that in some circumstances, depending on the geometry of the cable and the energy source employed, these measures proved poorly effective. More particularly, they gave good results in profiles 1, 2, 3 and 4 with small source-receiver separation values and a hammer as energy source with vertical stacking (an average of 8-10 shots), while they were totally ineffective in profile 5, which was taken with the same geometry as for profiles 1-3 but with a gun as energy source without vertical stacking.

Consequently, the quality of the data was generally acceptable for the first four profiles and, though considerably less, for profiles 6 and 7, where the same gun was used but with source-receiver separation values more than 3 times higher than in profile 5.

A clear proof of the above is supplied by Fig. 3, where two significant records respectively from to profiles 2 and 5 are shown. While in Fig. 3a the noise is on the whole acceptable and the shallow reflections can be seen, in Fig. 3b the air-coupled wave is very prevalent and signals are extremely weak.

DATA PROCESSING AND STACK SECTIONS

Data processing was carried out with a system based on a Compaq SLT 386s/20 computer, using a Vesna software package by Spectratec which allows the following processing sequence: record conversion, edit, spectral analysis and filter design, filtering, statics, CDP sorting, velocity analysis, NMO correction, CDP stacking, time section, depth section. Routines for automated statics, muting, velocity filtering, deconvolution and migration are not available at present.

Concerning static corrections, the only reliable data were those for lateral velocity variations in the surface layer, which were controlled with small ad hoc profiles. Consequently, since the topographic relief was flat or at least monotonic for all the profiles, statics were limited to the weathering layer, with a reference level at shallow depth parallel to the surface. However, only very small time shifts were introduced, so that the consequent improvement was very low.

Automatic velocity analysis with the semblance method gave poorly stable results, even in cases where the data were apparently acceptable. For this reason, the velocity functions reported in Table 2 were obtained from a large number of constant velocity sections, which proved to be one of the most demanding tasks of the entire processing.

Effective wavelet processing routines being unavailable, the only way to improve the quality of the sections was to submit the data to drastic filtering. Since in the records for profiles 1-5

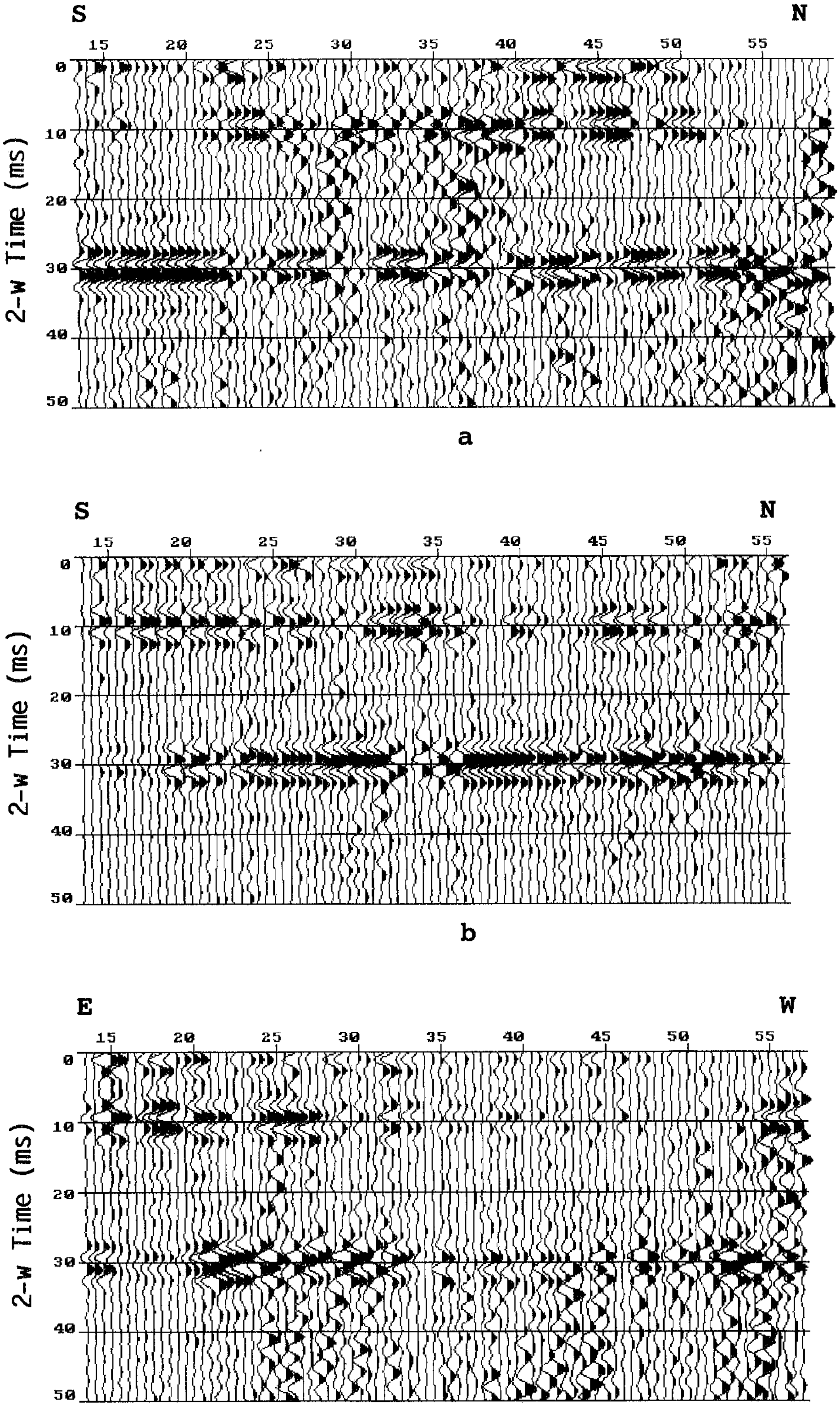


Fig. 4 — Stack sections of profiles 1 (a), 2 (b) and 3 (c). Interval between CDP traces 1 m. CDP fold 1200% for profiles 1 and 2, 600% for profile 3.

Table 2

Profile n.	Two Way Time (s)	Velocity (m/s)
1/2/3/4/5	0.01	700
	0.03	1300
	0.05	2000
6	0.01	700
	0.06	1200
	0.10	2000
7	0.01	600
	0.05	1200
	0.10	2000

the dominant reflection frequency was in the order of 300 Hz, the corresponding data were filtered with a 200-400 Hz band-pass, 36 dB ripple and 20 Hz transition band filter. The 60-200 Hz band-pass, however which was applied to sections 6 and 7 gave the best results. Actually this step, rather than the use of high frequency geophones, represented the most significant bandwidth reduction.

Figs. 4-6 show the seismic sections obtained. The quality of sections 1 and 2 (Figs. 4a and 4b) is discrete. These sections are parallel and 30 m apart. There are two clearly visible reflectors with generally good continuity. Section 3 (Fig. 4c) is perpendicular to the first two sections. Here the reflectors are much less clear, which is certainly due to the smaller CDP coverage (600%) compared to the previous sections (1200%).

In section 4 (Fig. 5a), the shallower reflector disappears completely, while the deeper one is at about the same time as in the preceding sections.

Section 5 (Fig. 5b) is undoubtedly of very bad quality, the reasons being twofold: first of all, the strong noise level generated by the energy source (gun), as already pointed out in the comment to the field records reported in Fig. 3. Secondly, the presence of a more complex geological situation in the shallower parts, where the strong lateral variations produced by digging and demolition at uncertain periods, of which clear traces are evident, have created equally strong static shifts, absorption of high frequency energy, and therefore loss of continuity and resolution.

Sections 6 and 7 (Figs. 6a and 6b) were acquired and processed with the same parameters. Quality and resolution are definitely inferior compared to sections 1-4, but at least in section 7, thanks to the higher source-receiver separation, there was no negative effect due to the source generated noise as in section 5. In these sections, however, some reflectors can be identified, even though not always very clearly.

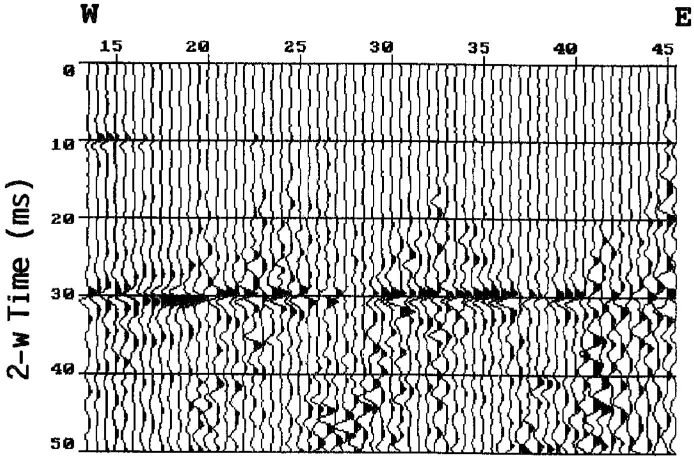
GEOLOGICAL INTERPRETATION

Time sections were depth converted using the velocity functions reported in Table 2, and the computed depths were referenced to the datum adopted for statics which, as stated in the previous section, follows the topographic relief. The geological interpretation was superimposed on the depth converted sections.

Fig. 7a shows the geological interpretation of section 1, which is also representative of sections 2-3, as well as of section 4 except for the lack of the shallower reflector.

As can be seen, the first reflector is associated with the contact between argillaceous sands with lenses of friable calcarenite and clay, while the second reflector very likely represents the passage to a basal layer (Pliocene?).

While section 5 is practically uninterpretable, in section 6 (Fig. 7b) we can still interpret the same transitions as in the previous sections, even though with a little more difficulty.



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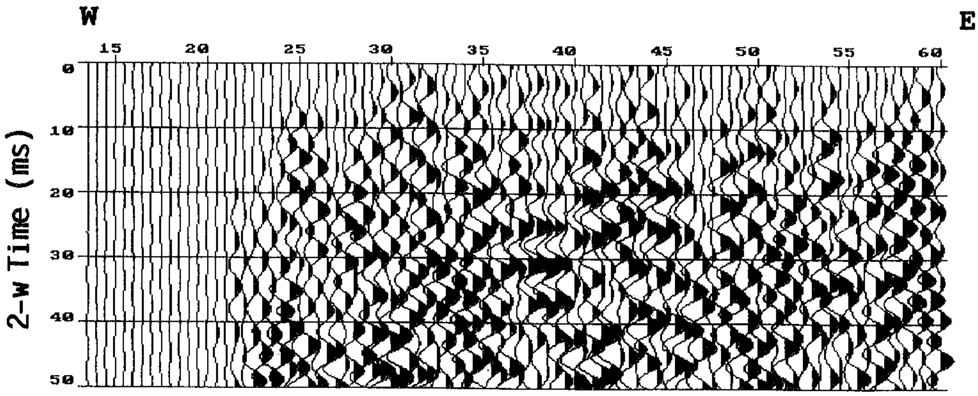


b

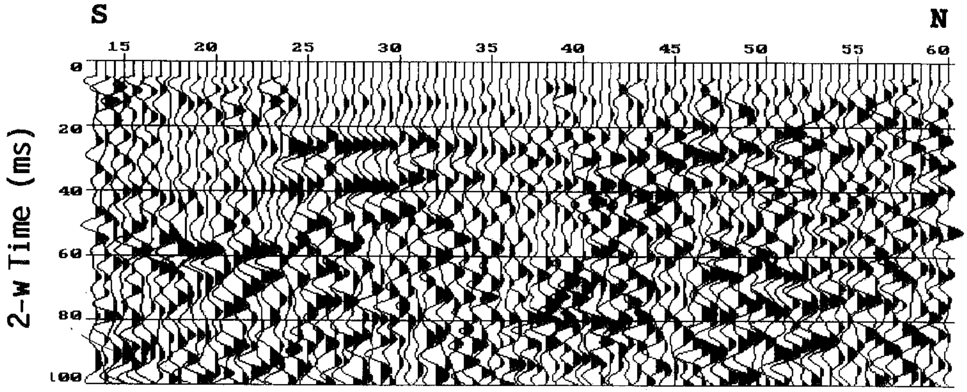
Fig. 5 — Stack sections of profiles 4 (a) and 5 (b). Interval between CDP traces 0.5 m for profile 4 and 1 m for profile 5. CDP fold 1200%.

In section 7 (Fig. 7c) the sand-clay and the clay-basal layer passages can be interpreted.

Generally, while in the Greek and Roman Areas (sections 1-4) the situation is quite regular, with significant variations essentially in the shallow (e.g. disappearance of the sand-clay contact and consequently, probably, both of the sands and of the overlying calcarenites in the Roman Area), on moving S and W the geological and structural picture appears more complex, with a general lowering of the structures, important discontinuities and significant thicknesses of more or less recent alluvial deposits (sections 6-7).

DISCUSSION

One of the main targets of our prospecting, that is the definition of the calcarenitic layer on which the Greek Temples of Selinunte were constructed, was not reached. This is also due



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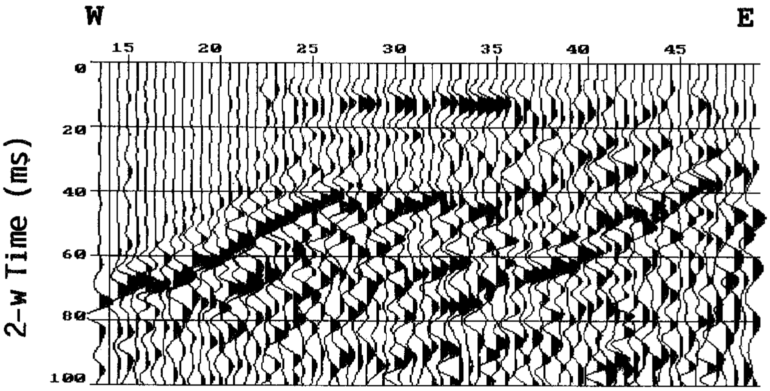

b

Fig. 6 — Stack section for profiles 6 (a) and 7 (b). Interval between CDP traces 2.5 m. CDP fold 1200%.

to the fact that our initial hypothesis was wrong: i.e. that the bottom of the calcarenitic plate and therefore the passage to the underlying sands was at a depth of at least 6-7 m.

Actually, at the sites where our profiles 1-4 were taken, the bottom of the calcarenite is at 2-3 m. Therefore, in order to locate it, both a better frequency bandwidth and a different geometry with shorter interval between the channels should have been used.
In fact, a believable, shallow model for this area consists of a surface layer 0.5 m thick with a velocity of 700 m/s (recent alluvium), superimposed over a layer 1.5 m thick with a velocity of 1800 m/s (the calcarenitic). Therefore, if our target is the reflector corresponding to the contact between the bottom of the calcarenitic plate and the underlying layer, which is located at a TWT in the order of 3.1 ms, a bandwidth in the order of at least 350 Hz should be available. Using 100 Hz geophones, the above bandwidth corresponds to a maximum frequency of at least 450-500 Hz. Under these conditions, and also taking into account that, most likely, the calcarenitic bank is not continuous or regular, but fractured and subdivided into more or less displaced blocks, in order to prevent spatial aliasing, assuming the average velocity as the minimum value of apparent belocity, it can be deduced from (1) that the maximum allowable geophone spacing is

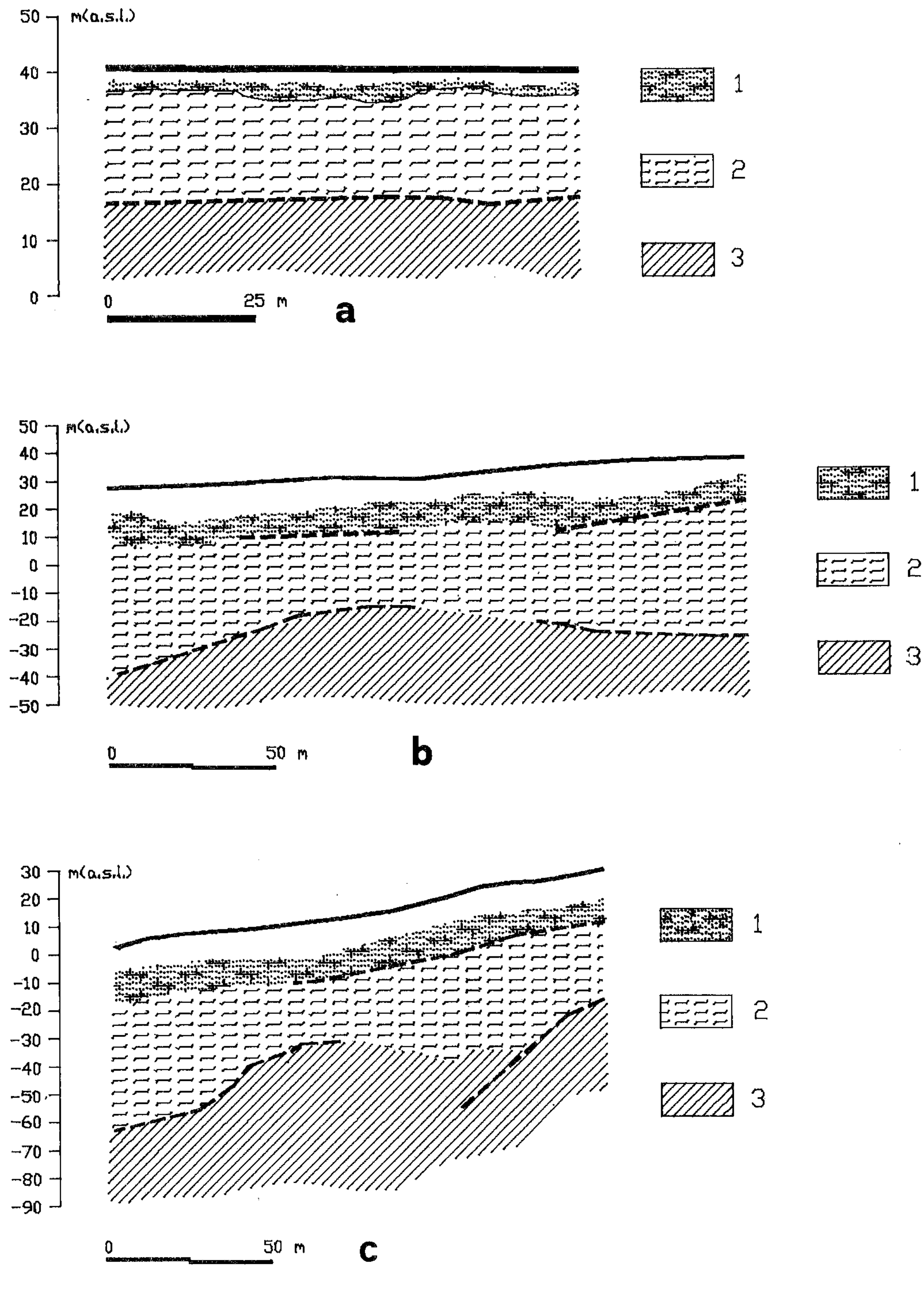

Fig. 7 — Geological interpretation of stack section 1 (a), 6 (b) and 7 (c); refer to Figs. 4 and 6. Legend: 1 argillaceous sand with lenses of friable calcarenite; 2 clay; 3 basal layer.

$$Dx \leq \frac{1290}{2 \times 500} = 1.29\ m.$$

Of course a shorter spacing, say 0.5-1.0 m, would be a better choice.

With regard to the other geological and structural objectives, considering the extent of the investigation, we believe that our results are quite significant, and that the indications they give are potentially useful even in archaeology; for example, in evaluation of the neotectonic events in the area, to which the vicissitudes of the monuments themselves in the course of their plurimillennial history could be related. At least, they could represent a good basis for further investigations.

From a methodological and operational viewpoint, the investigation provided several indications. Among which the necessity of adopting in similar situations a CDP fold of not less than 1200%, with an extremely small interval between channels, especially when no precise information on the depth of the targets is available.

Regarding the energy source, although at present no data for the same profile using different sources have been produced, a simple hammer with vertical stacking definitely seems to give better quality sections than shallow sources of energy such as guns, which on small offsets give high levels of noise.

Concerning temporal resolution, the maximum nominal value in our case should be in the order of 5 ms, due to the maximum bandwidth of 200 Hz. Actually, for sections 1-4, reflections show frequencies as high as 300 Hz, and the passband was centred on this value which was recognized as dominant for the reflections of interest. Therefore if, as an example, we consider the deeper reflector in section 2 (see Fig. 4b), which falls at a time around 28 ms, with a velocity of 1300 m/s (see Table 2) and a frequency in the order of 280 Hz, the corresponding wavelength is 4.6 m, which could be acceptable for the reconstruction of the main geological structures, but does not represent a very high resolution, at least at the scale of our survey.

Obviously, significant improvements could be achieved in acquisition by using more recent engineering equipment with a better dynamic range (in the order of 90 dB) and generally better performance, and improving the source spectrum. However, in order to attain high resolution results, this must be followed by efficient processing, which is becoming more and more possible nowadays with PC-based computing systems.

Summing up, although the present work is only a first experiment, it can be said that with the above limits, under operational conditions, it is possible to perform reflection surveying of quite good resolution with an engineering seismograph, and to process the data with relatively low power computer systems. These seem to be important aspects, especially considering the increasing demand for high resolution reflection surveys in different fields, primarily engineering.

Acknowledgements. This work was carried out with the financial support from the Consiglio Nazionale delle Ricerche.

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