Geophysical study of a crustal section across the Straits of Messina (*)

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Abstract

This paper presents the results of geophysical researches which are contributed to a better definition of a structural model for the Straits of Messina and which are carried out in the area of the Straits. The present paper is based on data of dipole electrical soundings which are being carried out in the area of the Straits. The crustal model proposed for a cross section of the Straits has been based, for the upper part, on data of dipole electrical soundings and for the deeper structures, on seismological observations and on their comparison with data of active seismic. The obtained section emphasizes, with some detail in the upper part, the Graben structure of the Straits recently proposed by Cattaneo. The structural model is compared with some detail in the upper part, with the Caltanissetta model of the eastern area of the Straits recently proposed by Cattaneo. The present model confirms, with some detail in the upper part, the Graben structure recently proposed by Cattaneo. The structural model is compared with the Caltanissetta model of the eastern area of the Straits recently proposed by Cattaneo.

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Block structurally in a higher position than the Sicilian one. Such structural difference has been put in evidence by refraction seismic sections to a depth of about 18 Km. The correlation between the structures of the area surrounding the Straits and the hypocentral distribution for the heaviest earthquakes is pointed out.

**INTRODUCTION**

Seismic microzonation generally means the study of the influence of the local site conditions on the seismic motion produced by earthquakes. Some observed effects, however, cannot be satisfactorily explained unless other data are considered, which concern geologic and topographic features of the wider area of interest.

This is particularly true for geologically complex areas such as the ones of the Straits of Messina.

So far as seismic microzonation researches in this area are concerned, the first and main important problem to work on...
has been an attempt to improve knowledge of deeper structures and rock units.

For this purpose, we have performed, in the study of the upper part of the chosen profile, geophysical investigations, in order to improve knowledge of the geology of the area.

For the characterization of the crustal extent of the structures obtained through geophysical and geological investigations, we have used seismological methodologies comparing the results with active seismic data.

In an area of such great seismogenetic interest, which is not yet sufficiently known, the above suggested approach can be useful from many points of view.

GEOLOGICAL AND STRUCTURAL FEATURES

The Straits of Messina are the most important tectonic discontinuity cutting across the southern part of the Calabro-Peloritan Arc (fig. 1). This Arc, which was formed during the Apenninic orogenesis, stretches from Capo d'Orlando in Sicily, through the Peloritan mountains, the Aspromonte, the Serre, and the Sila, to the plain of Sibari in Calabria, bending towards the Tyrrhenian Sea. The Arc is mainly constituted by a complex consisting of plutonic rocks, of ercinic metamorphites and of the Mesozoic and Tertiary sedimentary rocks.

The complex known as "Calabride" consists of different units, SE vergent, which were emplaced between the Mesozoic and the Miocene. Many hypotheses have been suggested about the evolution of the complex of Mesozoic rocks and Cenozoic sediments (Brancaccio, 1971; Ghisetti and Vezzani, 1978, Barbano et al., 1979) support the assumption of a graben structure. After the orogenic phase, a transgressive phase followed the Tortonian, with the deposition of conglomerates and sandstones of lacustrine environment. In this period, a first postorogenic tectonic phase took place with the formation of some small fault
Fig. 1 - 1) Middle Pliocene - Recent Formations: quaternary volcanites, recent and terraced clastic deposits of the Upper Pleistocene, glaciological, and later sediments, sands, clays and conglomerates, calcarenites, with foraminifera («Tripoli»), evaporites, and diatomites («Tripoli»); clays, sandstones and conglomerates, transgressive on allochthonous units. 2) Tortonian - Infrapliocene Sediments: clays and whitish marls with foraminifera («Tripoli»), evaporites, diatomites («Tripoli»); clays, sandstones and conglomerates, transgressive on allochthonous units. 3) Allochthonous Units: ercine metamorphites and their mesozoic and teriary sedimentary covers. 4) Main Regional Faults. 5) Traces of deep seismic surveys profiles. 6) Seismic stations of the local network. 7) Points of the crustal profiles for which sections are represented in fig 2. 8) (1), (2) and (3) represent the shot points of the 1977 seismic survey; (4) is the focal zone of the seismic crisis in the Gulf of Patti (1978).
(Caltanisetta, the Mesima river, Cutrofiano and Sibari). In these basins the sedimentation evolved to evaporitic deposits.

Between the Lower and Middle Pliocene a compressive tectonic phase took place causing the persistent southeastward shifting of the Arc. Then the folding of the sedimentary series of the above mentioned basins occurred with the consequent formation of the synclines of Messina, Pace del Mela and Melito di F. The beginning of the breaking of the Arc into blocks can be attributed to this period, together with transcurrent movements along the Trinacria-Messina line.

The following tensional tectonic phase, between the Upper Pliocene and the Preglacial Pleistocene, more directly concerns the internal part of the Arc. The internal part of the Arc was affected by vertical movements, with the formation of mono-clinal, longitudinal grabens and horsts. Consequently gravitationally slides took place outside. The graben of the Straits of Messina, produced by the main tension WNW-ESE, is bounded by the faults of Portella Arena and Gallico. The block of the Piani di Matiniti, which is uplifted on the Calabrian side, is bounded by the graben of the Straits. The breaking of the Arc into transversal and longitudinal blocks, which occurred in this period, was furtherly emphasized during the subsequent tectonic phase. The longitudinal faulting gave an antiform structure with graben in the bend.

Between the blocks of Sibari and Catanzaro, the Sila one, in the northern part of the Arc, is divided in two longitudinal NNW-SSE blocks by the graben of Crati. The graben of Catanzaro act as a bend of the mountain range where the trend its main axis show a significative variation. Southern Calabria, bounded by the graben of Messina to the south, is longitudinally divided by the graben of the Mesima trending NE.

A further transversal breaking (the graben of Siderno), separating the Serre from the Aspromonte, becomes more evident in the subsequent tectonic phase.

This last phase developed from the Upper Pliocene on, and consisted of tensional movements, which brought about normal faults and great uplifts, with the formation of various series of
terraces. The Calabrian side of the Straits underwent a greater uplift. As far as the oldest terrace (Glacial Pleistocene) is concerned, a difference of about 318 m can be observed between the sides of the Straits (Selli, 1978).

According to Selli (1978), the complete clearing of the sides of the Straits was due to this phase, with the opening of the graben constituting the northern access, the Straits assumed their present shape.

This phase, which produced faults and lineaments (in the saddle of the Straits), E-W, N-S, NW-SE, and reactivated preexisting faults, is probably characterized by a main tension NW-SE and a slight tension NE-SW, which determined a conjugated system E-W, N-S.

SEISMIC MODEL OF THE CRUSTAL SECTION

In the previous section were presented the geological and structural characteristics of the Straits of Messina and of their genesis at a crustal level.

No direct elements are available through which it is possible to obtain the vertical extent, in the whole thickness of the crust, of the discontinuities concerning the Straits, and a crustal model for the same area.

Besides, the analysis of the crustal sections obtained through deep refraction seismic in neighboring areas — Aeolian Islands, Mounts Nebrodi, eastern side of Etna, Lower Ionian, and Southern Calabria — point out a great complexity in the area of the Straits, in spite of its extension.

The crustal sections shown in fig. 2 refer to the points marked on the seismic profiles in fig. 1; as far as the intersection points between two profiles are concerned, the sections presented are the results of averages and the synthesis of known data.

A and C sections refer to a «thinned» continental crust (Cassinis et al., in print), showing a total thickness not exceeding 20 km and a character which can be compared with the «subcontinental» crust, as defined by Konstantinovskaya and Zonenshain.
Further evidence on the continental nature of the crust in that area have been contributed by geological data pointing out the frequent occurrence of...
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metamorphic xenoliths in the volcanic products from Aeolian Islands (Harrison & Kolb, 1969). A thicker subcontinental crust is observed in section B, showing the coexistence of low

velocity layers. The other sections reported in fig. 2 refer to a 36

40 km thick crust, to be regarded as a normal continental-type

(Demp & Sheard, 1972). Cassinis et al. (1979), Typical continental

characteristics are the occurrence of high-velocity layers and the presence of a well-developed underlying small part of the crust (15 km in section C). Cassinis et al. (in press). The P-wave velocity in the upper mantle appears to be normal -

\[ V > 8 \text{ km sec}^{-1} \].

A contribution to a better definition of a crustal model for

the area of the Straits comes from the study of the propagation

of the elastic waves. The data, collected by the local network

since November 1977, make it possible to have a first quantitative

approach to the solution of the problem (Bottari et al., 1979).

The useful data came mainly from the 300 analysable

events which developed in the gulf of Patti in the spring of 1978

(Bottari et al., 1979), and in smaller amount, though of great reliability, from the explosions in the

Ionian of the November 1977 (fig. 1), which were gathered

on behalf of the Department of Geodesy and Geophysics of

Cambridge University, U.K. (Sharpe et al., 1978).

The analysis of the observations of the seismic activity in

the gulf of Patti, together with the preliminary assumption of

a flat, parallel crustal layering, has made it possible to obtain

the velocity of longitudinal waves along some refractors.

All data refers to the range of distances 0.1 - 2.0, with a greater density nearly in the range 0.2 - 1.0. The errors in the arrival times of the phases - generally first arrivals -

are negligible, both for the instrumental characteristics of the

stations and for the nature of the onset of the events, which

are prevalently as an "impetus."

For the seismic events considered (of magnitude \( M < 3 \)) it

is known the preliminary hypocentral determination carried

out by I.N.G. (National Institute of Geophysics) using a two-

layers crustal model. In the following we will discuss this model.
by MAA: it is characterized by the following values of thickness and velocity:

\[ h_1 = 25 \text{ Km} \quad v_1 = 5.5 \text{ Kms/sec.} \]

\[ h_2 = 27 \text{ Kms} \quad v_2 = 6.8 \text{ Kms/sec.} \]

Two groups of traveltimes have been analysed so that a crustal model for the area of interest might be obtained. In MAA model the groups correspond to two classes of focal depths, of 10 + 5 Km and of 20 + 5 Km respectively.

Four phases of refracted longitudinal waves have been observed on the whole. They are characterized by the following equations:

\[ T_1 = (1.26 \pm 0.30) + (19.03 \pm 0.54) \quad [1] \]

\[ T_2 = (3.86 \pm 1.02) + (17.14 \pm 0.58) \quad [2] \]

\[ T_3 = (2.51 \pm 0.11) + (17.34 \pm 0.21) \quad [3] \]

\[ T_4 = (5.97 \pm 0.29) + (14.23 \pm 0.27) \quad [4] \]

The crustal model elaborated through a feedback process with the observed data (MSM model) is characterized by four layers (Bottari et al., 1979). The first two layers, which cannot be put in evidence through the available seismological data, are presented with values of thickness and velocity on the base of a synthesis of active seismic data (Cassinis et al., 1969; Morelli, 1970; Scarascia and Colombi, 1971). The third layer, comparatively the thicker one and the most active during the crisis in the gulf of Patti, agrees with the difference of the intercept times on the time-
distance curves of equations [1] and [2]. For values of thickness and velocity of 16 Km and 5.8 Km/sec respectively. In the same way it is confirmed for equations [3] and [4] the correspondence to the Stromboli area for a thickness of 19.5 Km and

The results of the seismological work are presented in the section of the Straits in Fig. 2. The velocity in the lower crust appears comparatively low, also in respect to refraction seismic interpretations in the area of the Nebrodi and the Peloritan mountains (sections B, C and D in Fig. 1). This may also show the presence of low velocity layers.

The accuracy of the suggested crustal model has been verified in the light of the travel times of the three explosions in the Ionian (Fig. 1). If we consider the difference in the travel time of the seismic waves and consequently the different characteristics of the crustal layers by the different media interested by the seismic energy, the observations presented can be of some interest. For the Ionian side of the Straits, the few data available show a crust considerably different from MSM model, particularly in the intermediate layers. The correspondence is satisfactory, however, as far as the value of velocity of P' and the thickness of the crust are concerned.

**Dipole Electrical Soundings**

In the area under consideration, two vertical electrical soundings have been performed, by dipole technique. These soundings, together with the stratigraphic boreholes of Cannitello and Ganzirri (Fig. 8), allowed a geological section to be suggested. Such technique has been chosen because of its remarkable advantages, from the practical point of view, in respect to the classical Schlumberger or Wenner arrays, particularly for the possibility of obtaining high depths of investigation.
The measuring technique consists in:

a) energizing the ground by repeated square current waveforms with a period of 10 seconds and for a time between 10 and 30 minutes;

b) sampling the voltage signal at intervals of two seconds;

c) extracting the useful signal, masked by the telluric noise, through spectral analysis (Loddo and Patella, 1977).

The above-mentioned technique has made it possible to obtain the diagrams of apparent dipole resistivity versus spacing shown in fig. 4 and fig. 5.

For the quantitative interpretation of the dipole diagrams, they have been transformed into Schlumberger diagrams (Patella, 1974), so that it has been possible to adopt all the interpretation techniques already developed for Schlumberger soundings and, moreover, to smoothen the curves, thus suppressing the local anomalies generally present in dipole soundings and underlining all the contrasts of resistivity with structural character.

Fig. 6 shows the transformed diagram for the sounding DES 3. Remarkable lateral effects can be observed, which make it different from the typical behavior of horizontal layer situations. Also in this case an interpretation can be obtained on the base of the hypothesis of horizontal layers, and then taking into consideration the lateral discontinuities (Patella, 1977; Patella et al., 1979).
The horizontal layers model suggested (full line curve on the graph) is characterized as follows:

| Layer | Resistivity (Ωm) | Thickness (m) |
|-------|------------------|--------------|
| 1     | 40               | 140          |
| 2     | 650              | 200          |
| 3     | 3100             |              |

For the geological correlation of the three electrostrata, the first low resistivity layer can be associated to saturated sands.
Fig. 5 - Dipole apparent resistivity diagram for DES 2.

The lateral effects can be interpreted, from the qualitative point of view, through a comparison with the set of master curves published by Al'pin (1966).

The diagram shows three peaks that can be ascribed to the transit of the moving current dipole across vertical contacts.
On the basis of the spacing to which such contacts can be referred and of geological-structural data, the first lateral effect may be caused by the presence of a shallower lens of sedimentary formations with a resistivity higher than the "Formazione di Messina", as for example the Middle Pliocene sediments outcropping slightly to the west of the center of the sounding. The other two lateral effects, which can be observed at a greater spacing, may be referred to a lowering, in correspondence to the two faults crossing the profile (Fig. 8), of the high resistivity metamorphic basement.
Further information can be obtained about the basement assuming the presence of a further layer below it with extreme values of resistivity $\rho = 0$, $\rho = \infty$ (Alfano, 1974). The interpretation of the two field situations makes it possible to ascribe to the basement a minimum thickness of 2 km.

Fig. 7 shows the transformed diagram of the sounding DES 2. Though it shows a more regular behaviour than the previous one, it appears to be equally influenced by a lateral effect. The experimental points are fitted with a three layers curve corresponding to the following values of the parameters:

| Layer | Resistivity $\rho$ | Thickness |
|-------|-------------------|-----------|
| I     | $10^5$ Qm         | 60 m      |
| II    | $550$ Qm          | 180 m     |
| III   | $2800$ Qm         |           |

The geological interpretation of the electrostratigraphy is based not only on surface geology and on the stratigraphy of boreholes, but also on the results obtained in the electrical section along the line of development of the sounding DES 2. The first layer is superficial coarse alluvia and in the Middle Miocene formation locally raised by a fault. The second low resistivity layer can be related to an altered metamorphic basement.

The lateral effect can be attributed to a rising of the basement along the line of development of the sounding, which can be observed about 1500 m far from the source. Considering that the sounding has been performed along the right shore of the Fiumara of Catona, the rising of the basement appears in the area of the Piani di Matiniti, but not outcropping.

For the thickness of the basement, a minimum value of 1.5 km is obtained by the method described above.

A comparison between the two electrical soundings shows a difference in the values of resistivity obtained for the altered granite. This is confirmed by the geological data on the outcrop.
In the sounding DES 2 the comparatively low resistivity attributed to altered granite might be caused by fluids permeating a shallow fault system. So far as is known based on available information, there is a different alteration for the metamorphic rocks on both sides, which is well known from the geological point of view.

Fig. 8 presents a model of the structures along the profile, resulting from the correlation between the interpretations of the electrical data and the stratigraphic boreholes together with surface geological data.
obtained through a match of the results of the electrical soundings of Contrada Ortara (Sicily) and of San Nicola (DES 1), with those coming from the stratigraphic boreholes performed by Agip (Selli, 1978).

- Lower-Middle Pliocene: clayey marls ("Trubi") of the Lower Pliocene. This formation, transgressive on metamorphic units, is present in outcrops prevalently on the Sicilian-side. In the area under consideration it is present in small north-western outcrops.

- Middle-Upper Pliocene: sands and gravels of the "Formazione di Messina" (Marine Pleistocene). The maximum thickness is about 300 m. Near the base there are intercalations of sands and calcarenites; heteropic and/or fine-grained silty sands, locally clayey, sometimes with inorganic cementation during the middle-upper Miocene, it is often highly cataclastic or arenitized (a).

- Lower-Middle Pleistocene: sands and gravels of the Messinian and Tortonian, overlying coarse sands of the Tortonian (3°); sands with calcareous cement, alluvial cones. Highly permeable with observable thickness increase. High permeability with observable thickness increase. Some coarse sands are present on the Sicilian side. In the area under consideration it is present in small north-western outcrops.

- Continental Pleistocene: calcarenitic sandy-arenaceous intercalations and conglomerates and arenites. The thickness is loosely consolidated with high permeability. The maximum thickness is about 100 m at the lower levels and about 20 m in the upper levels.

- Recent littoral deposits, sandy and pebbly, with thick beds of conglomerates with intercalations of sands and calcarenites and conglomerates and arenites. Highly permeable with observable thickness increase. High permeability with observable thickness increase. Some coarse sands are present on the Sicilian side. In the area under consideration it is present in small north-western outcrops.
CONCLUDING REMARKS

The analysis of the model (presented on the base of geological data and of geophysical observations) confirms the graben structure of the Straits and, in particular, underlines the greater uplift of the Calabrian side, an outstanding element which can be clearly observed in spite of the local structures.

On the other hand the suggested synthesis of the data of deep seismic soundings and of seismological observations, though it offers a crustal model for the area of the Straits which agrees with the behaviour of Bouger's isoanomalies (Cassano et al., 1978), does not allow to see whether and down to what crustal level the above mentioned crustal discontinuity extends. For this purpose the two crustal sections refer to

![Crustal sections models corresponding to points D and E of fig. 1, in the southern shores of the Straits.](image-url)
the shores of the Straits are examined (fig. 9). So far as the velocities of the longitudinal waves along the refractors are concerned, such models enable, again, though the zone of the Sicilian side presents it to appear part a greater complexity, particularly interesting in the result of the analysis of the thicknesses of the layers in the two sections. It shows that the relative uplift of the Calabrian side can be observed down to about 20 Km.

It is a fact of particular interest that the foci of the heaviest earthquakes in the Straits, for which the focal depth has been determined analytically and/or macroseismically (Bottari and Lo Giudice, 1975) are located between 12 and 20 Km. Such correlation suggests, in our opinion, the first and the most important result in the context of the acquisition of all those informations on which a seismic microzonation study must be based.

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