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Crust and Upper Mantle Models along the Active Tyrrhenian Rim

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Summary

The volcanic complexes from the Eolian islands to the Campania/Roman regions and Tuscany further north, rest on lithospheric sectors which overlie the Adriatic continental lithosphere sinking along the Apennine-Maghrebian orogenic belt. Evidence for this stems from the melting, at mantle depth, of upper crustal materials as evidenced by the widespread interaction of S-type and K-alkaline melts. The genesis of atypical magmas of the Roman Province (central-southern Italy) appears to be the result of an important block faulting and deep lithospheric rifting of the Apennine continental margin lying parallel and above relic sinking slabs. Intermediate and deep-focus earthquakes indicate that the lithospheric slab is still seismically active under the Eolian-Calabrian area and, sporadically, at the southern end of Campania. On the other end, in the Roman/Tuscan region, it seems to be almost inactive, few earthquakes having been located with hypocentral depths not exceeding 150 km. The existence of distinct lithospheric slabs along the Tyrrhenian rim is supported by surface wave dispersion and scattering measurements as well as P-waves residuals, and is confirmed by the trend of long-wavelength gravity anomalies, interpreted within the geometrical constraints imposed by aeromagnetic and seismic data. The analysis of the spectral content of seismic sources supports the existence of two distinct zones of lithospheric shortening in correspondence of Tuscany and

South Tyrrhenian sea, which are separated by a tensional region, which extends from Latium to Calabry

Introduction

Recent geochemical models for the Plio-Quaternary volcanism in peninsular Italy and the Eolian Arc have been proposed to have not only specific importance for the solution of petrogenic problems, but also to have a bearing on models of evolution of the mantle-crust system during Tertiary and Quaternary time (Civetta et al., 1989). More specifically, the contamination of the mantle by crustal material implies the presence of sinking lithosphere, which, in turn, supports the hypothesis of subduction related magma genesis for all the Plio-Quaternary volcanics of peninsular Italy (Peccerillo, 1985; Peccerillo and Manetti, 1985). Intermediate and deep-focus earthquakes indicate that the lithospheric slab is still seismically very active under the Eolian-Calabrian area and sporadically, at the southern end of Campania, while it appears to be less active and with shallower activity - few events have been located with hypocentral depths not exceeding 150 km (ING, 1990) - in the Roman/Tuscan region. Here the existence of a relic slab is mainly supported by surface wave dispersion data (Panza, et al., 1980) which point to the existence of a relatively highly rigid body at depth. This interpretation has been subsequently confirmed by applications of surface waves scattering theory (Snieder, 1988), while P-wave propagation analysis seems to be not conclusive about the existence of a high-velocity body. In fact, Spakman (1986) in his tomographic models does not show, probably as a consequence of the used reference model, a high-velocity body, while Alessandrini et al. (1990) and Amato and Alessandrini (1991) show negative residuals in the Tuscan region, which require the presence of a high-velocity body at depth. The combined analysis of different geophysical data (Panza and Suhadolc, 1990; Della Vedova et al., 1988; 1990; Royden, 1988) seems to support the presence of sinking lithosphere beneath Tuscany. The analysis of the spectral content of seismic sources, based on the analysis of space distribution of creepex (Prozorov and Hudson, 1974; Prozorov et al., 1983; Panza and Prozorov, 1991), supports the existence of two distinct zones of lithospheric shortening in correspondence of Tuscany and South Tyrrhenian sea, which are separated by a tensional region, which extends from Latium to Calabry. The definition of the lateral variations in the upper mantle properties is very important for a correct understanding of the volcanic products, therefore we discuss in this paper a comprehensive model of the area around the Tyrrhenian rim, based on the combination of all available geophysical data suitable for a study at a regional scale.

Plio-Quaternary volcanism

The tertiary magmatic activity in the area can be roughly divided into two main cycles separated by a quiescent period (e.g. Beccaluva et al., 1989). The first cycle (uppermost Eocene to Acquitanian) is dominated by calcalkaline products and shows a pronounced homogeneity of serial affinity: it requires a NNW to WNW dipping prolonged subduction of oceanic lithosphere. Subsequently, during the Serravalian and most Tortonian the magmatic activity is apparently absent in the whole Sardo-Tyrrhenian region, coinciding approximately with the last main compressional phase in the northern Apennines. The magmatism of the second cycle, presenting an exceptionally wide serial affinity and lasting from uppermost Tortonian to the present, can be defined as post-collisional magmatism. It is characterized by episodic migration of activity from an area east of Corsica-Sardinia to Tuscany in the north and through the main Tyrrhenian basins to the Campania/Roman region in the south.

Presently, geochemical and isotopic data support mantle metasomatism at the origin of magma generation. Aqueous supercritical fluids rich in CO_2, F, Cl and S bring in solution incompatible elements and react with the upper mantle. The original mineralogic constituents of the mantle, olivine and otho-pyroxene, become thus metasomatically transformed in hydrated minerals (phlogopite, k-richterite). These reactions bring to a volume increase that explains the mantle upwelling. The supply of hot fluids from the depth enhances partial melting in the metasomatized mantle, accounting for the observed potassic magmatism.

The mantle metasomatism may be driven by fluids rising from deep mantle regions, fluids representing the volatile fraction of the mantle driven upwards by rifting in the cratonic lithosphere (e.g. Bailey, 1982) or fluids liberated by dehydration of subducted oceanic crust and sediments.

The interaction of mantle-derived magma with upper continental crust does not explain the strong contamination with incompatible elements and the strong increase in the Sr isotopic ratio in consideration of the high amounts of upper crust which would be involved in the process (Civetta et al., 1989). Crustal contamination might have played some local-scale role, but the wide variation of Sr isotope ratios in most primitive rocks requires their generation in a heterogeneous source characterized by high and variable Sr isotopic composition. Even if deep mantle fluid addition cannot be ruled out, the simplest reason for it is that crustal material has been added to the upper mantle by subduction processes active in the Tertiary.

A strong geochemical similarity of the potassic series from Central Italy to potassic rocks from Aeolian Isles strongly suggests that Roman volcanics are also somehow related to old, no longer active subduction processes (Peccerillo, 1985) and not to intracontinental rifting as claimed by other authors (e.g. Cundari, 1980).

A difference has been however evidenced between the Roman/Campania region on one hand and Tuscany with the northernmost Roman province on the other. It has been found (Civetta et al., 1989) that the upper mantle composition prior to contamination has been essentially fertile peridotite in the first area, while in northernmost Roman province and South Tuscany it has been a residual peridotite that has suffered a previous melting event. The most likely contaminants have also been found (Civetta et al., 1989) to be differentiated: mainly siliceous sediments and average gneiss in the Roman/Campania region, while in the northern area the contaminants are mainly metamorphic rocks from the Tuscan basement.

The main conclusions drawn from the analysis of Plio-Quaternary magmas in the Apennines are therefore that their magma genesis is related to crustal sinking into the mantle (Scandone, 1980). Moreover, the differences in upper mantle composition and contaminants points to a variable composition of the lower crust - upper mantle under the Italian peninsula and to a different geodynamic evolution along the Apennines. In particular, a major involvment of crustal slices is required beneath Tuscany.

The petrological and geochemical data therefore suggest that the volcanic provinces of Italy have all post-collisional characteristics and reside over portions of relic lithospheric slabs. They moreover seem to distinguish different characteristics between the Tuscany and northernmost Roman province and the rest of the volcanic peri-Tyrrhenian chain (Serri and Panza, 1991; Beccaluva et al., 1991).

Geophysical data

Aeromagnetic anomalies

In 1980 the Italian oil company AGIP of Ente Nazionale Idrocarburi group has completed the aeromagnetic survey of the Italian territory and subsequently made available to the scientific community a subset of these data on a digital grid of 6 km by 6 km. The data acquired in such a way are very useful for regional studies, but cannot be used for global studies of the magnetic field of the Italian territory, the latter requiring the reduction to a common reference frame. The available information does not allow an exact reconstruction of the different reference fields, however the reduction to the same elevation can be made, with the necessary accuracy needed for general studies of the magnetic basement and deeper features which may be present in the crust.

The Italian territory is centered around a latuitude of 42°N, therefore there are significant distorsions in the patterns of the observed anomalies with respect to the actual geometries of the causative structures. This prevents a straightforward qualitative interpretation of the magnetic trends, and it is advisable to reduce the data to the Pole. In such a way one obtains a map which can be easily compared with the gravity field or its normal derivative.

The reduction to the same elevation and to the Pole has been made by Marson and Panza (1990) and their data will be used in this study. From the global representation of the magnetic anomalies field, obtained for the Italian region (Fig. 1), zones with large amplitudes and short wavelength anomalies are visible in the Tyrrhenian Sea and the Ligurian basin. Particularly important, also from a structural point of view, can be the E-W alignement extending from Bocche di Bonifacio to Naples and the N-S alignement East of Corsica (Boccaletti et al., 1990).

Della Vedova et al. (1988; 1990) have shown that the overall picture of the spatial distribution of the magnetic anomalies possesses a striking similarity with the gross features of the thickness and elastic properties of the lithospheric mantle - the 'lid' (Fig. 2). The relationship between crustal geomagnetic properties and upper-mantle elastic parameters, though very difficult to assess, is strongly influenced by the temperature distribution with depth, particularly by the depth of the Curie point. Where the lid is weak (low velocities for S-waves) and thin, magmatic intrusions are frequent, and more likely to occur, giving a magnetic signature at the surface. If the rifting processes reach extreme conditions with relevant dike intrusions and lava flows, as in the Tyrrhenian Sea, the magnetic signature at the surface is not any more comparable with that of a magnetic basement. On the other hand, the scarce magnetic signature of the Tuscan-Roman area is probably influenced by the lack of deep magnetic sources due to the presence of high temperatures, associated with very low S-wave velocities at relatively shallow depths.

More specific observations can be made considering the results of the inversion of aeromagnetic data along the profiles shown in Fig.1. Profile 1 crosses a well pronounced NS trend east of Corsica. The related magnetic anomaly has been interpreted as due to dikes of ultramaphic material, which, in turn, may witness an ancient subduction zone. The depth of the magnetic basement drops by 5-6 km at about 50 km eastwards from the coast line. The deepening of the magnetic basement is accompanied by the deepening of the Moho discontinuity. From profiles 1 and 2, the susceptibility of the magnetic basement appears to be low on about all the continental part and increases slightly at the easternmost end, as well as the wavelength of the related magnetic anomaly. This trend may be associated with the thickenning of the lithosphere.

Gravimetric anomalies

The map of the gravity anomalies for the investigated region is shown in Fig. 3. A possible representation of the crust-mantle properties in agreement with the gravity data can be obtained considering the cross-sections along the Profiles 1, 2, 3, 4 and 5. In the gravimetric modeling we have used as a priori constraints the available information about the crust from seismic data (Steinmetz et al. 1983; Recq et al., 1984; Nicolich, 1989) and about the lithosphere-asthenosphere system from surface wave dispersion data (Calcagnile and Panza, 1981). The depth of the magnetic basement has been fixed either according to the results of our inversion (see section on aeromagnetic data) or according to the models proposed by Cassano et al. (1986). Furthermore, we have imposed that the area with oceanic crust extends from the Central Fault (Raimondo Selli line) to the east of the Marsili volcano. The different density values used in the gravity modeling are shown in Fig. 4 and they comply with the criterion of minimizing their number. In particular, a possible high-density layer (thickness of about 10 km and $\Delta\rho$=0.02 g/cm^3) just below the Moho, consistent with surface-wave dispersion data and the presence of magnetized bodies in the Tyrrheanian Sea has not been included in the final models, since it is not required to explain the observed gravity anomalies. Generally, the average upper-crust density has been taken equal to 2.55 g/cm^3 with the only exception of Profile 5, where, in relation to Tuscany, we have used a density of 2.65 g/cm^3 to account for the presence of metamorphic rocks on top of the magnetic basement indicated by Cassano et al. (1986). The lower-crust density has been taken equal to 2.85 g/cm^3; in Tuscany again some deviation from the general model has been intmetric data can be easily fitted even within the constraints imposed by other independent geophysical data (seismic, seismological and aeromagnetic) along Profiles 2 and 4. A quite different situation characterizes Profiles 1, 3 and 5. More precisely, the central part of Profile 1 shows a misfit of about 40 mGal which extends over about 100 km. This cannot be simply explained assuming different densities within the ranges allowed by the V_P-ρ or V_S-ρ standard curves (e.g. Kern and Richter, 1981), which have been used, whenever possible, for the estimate of the densities from seismic velocities. The observed misfit cannot be explained with lateral variations in the crustal density, unless large deviations from standard V_P-ρ or V_S-ρ relations are allowed. On the other hand, the presence of a relatively high-velocity body in the upper mantle detected by the analysis of seismological data (Panza et al., 1980; Snieder, 1986; Alessandrini et al., 1990) explains satisfactorily the observed residual gravity anomaly, within the bouncaries of standard V_P-ρ or V_S-ρ relations (Fig. 5). The modeled density distribution therefore does not contradict the existence of a relic lithospheric slab. Profile 2 (Fig. 4), whose gravity anomaly can be completely explained by crustal structures using standard V_P-ρ relations, may be used to delimit, towards the South, the extent of this lithospheric body.

Similarly, in the eastern part of Profile 3 (Fig. 4), a quite pronounced mass deficiency is clearly visible. Unless crustal density values extremely different from standard ones are used, this mass deficiency can be balanced only admitting the presence of a relatively high-density body ($\Delta\rho$ about 0.04 g/cm^3) in the upper mantle overlain by thinned lithosphere. This is in good agreement with the presence of a sinking seismogenetic lithospheric slab recognized by several authors (e.g. Peterschmitt, 1956; Caputo et al., 1970; 1972; Scandone, 1979; Anderson and Jackson, 1987; Patacca and Scandone, 1989) which seems to be sinking more steeply in its upper part than in its lower one (Anderson and Jackson, 1987). Analogous considerations can be applied to Profile 5. The observed gravity field supports the idea of relic slabs in the Tuscan/Roman and Calabrian areas not only in the direct modeling of gravity anomalies . Such a picture finds some support also in the study of the flexural behaviour of the lithosphere by means of gravity and deflection data (Royden, 1988).

The gravity signals shown in Fig 4 and 5 are due to the superposition of gravity effects of at least three different sources related to the lateral variations of the thickness and density of the sediments, crust and lithospheric part of the mantle. In the modeling of these signals we have used the constraints, both in geometry and density, provide by other, widely accepted, geophysical means. A satisfactory fit can be reached in some cases, while in others significant misfits are evident. The problem of locating the source of these misfits, on the basis of gravity modelling, does not have an unique solution. In practice, the shallowest solutions can be rejected on the basis of lithological arguments (unrealistically high densities), but for the deepest ones there are not direct rejection criteria, and one should not make the mistake to prevent the finding of deep sources by forcing all the anomalous masses to lay, let say, within the crust. It is only through the appropriate use of all the available geophysical information that it might be possible to achieve a realistic gravity model. For this reason the gravity models of Fig 5 include also the information provided by seismological data, which have a smaller resolving power but are valid, on the average, over much larger areas than seismic data, which indicate the presence of density discontinuities within the mantle. From this point of view they represent the actual synthesis of all the available data.

The geophysical data discussed so far, in connection with the distribution of Plio-Quaternary volcanism, seem to indicate a differential sinking of the foreland lithosphere in the Northern Apennines and in the Calabrian Arc as proposed also by Laubscher (1988) with his model of "pull-arc" tectonics. The analysis of the deformation of the outer margin of the Apennines in post-Tortonian times (Patacca and Scandone, 1989) partitioning the Apennines into two major arcs is also in agreement with this hypothesis. Furthermore, the analysis of the gravity field, within the frame given by seismic and aeromagnetic data, seems to indicate the presence of a high-density lithospheric body just below the Moho under the Northern Apennines, extending soutward till the line Ortona-Roccamonfina. South of this line - till the Calabrian Arc - the gravity field does not seem to be perturbed by shallow subcrustal high-density bodies. This might mean that the intermediate and deep-focus earthquakes (h>300 km) take place in a lithospheric slab which is not directly connected with the Southwestern border of the Adriatic plate. In the Calabrian Arc the situation is gravimetrically again similar to that of the Northern Apennines and a high-density body seems to perturb the gravity field, in correspondence of the intermediate-focus earthquakes beneath the Southern Tyrrhenian Sea. These observations suggest a simple modification of the schematic model proposed by Scandone et al. (1992) which is summarized in Fig. 6 where the prospectic representation of the lithosphere, consistent withe seismicity distribution and with our gravitry modeling, is presented.

General considerations/Conclusions

All the volcanic complexes from the Eolian islands to Campania/Roman regions and Tuscany further north, rest on lithospheric sectors which overlie, or could have overlain the Adriatic continental lithosphere (Nolet et al, 1978; Panza et al., 1980; Calcagnile and Panza, 1981; Alessandrini et al., 1990) sinking along the Apennine-Maghrebian orogenic belt. The important contribution of melting of upper crustal materials, at mantle depth, required for the genesis of the potassic Tuscan rocks (minettes) as well as the widespread interaction between Tuscan S-type and Roman K-alkaline melts support this interpretation.

The genesis of atypical high-K calcalkaline, shoshonite, leucite-basanite and lucitite series magmas of the Roman Province (central-southern Italy) appears, therefore, to be the result of an important block faulting and deep lithospheric rifting of the Apennine continental margin that is parallel and above the relic sinking slabs. This process with partial melting of mantle sources progressively and heterogeneously enriched in subduction components derived from the sinking of continental-crust materials down-dragged during continent-continent collisional processes took place after the continental collision (Beccaluva et al., 1985).

The Tuscan/Roman volcanism may be explained by the presence of a lithospheric slab (Della Vedova et al., 1990), the volcanic activity to the south of Rome and up to Naples area might be due to a deep portion of the seismogenetic slab, not detectable gravimetrically, beneath the Southern Tyrrhenian Sea (Caputo et al., 1970; 1972; Anderson and Jackson, 1987). This difference between the Roman/Campania region on one hand and Tuscany with the northernmost Roman province on the other is also reflected in the petrological and geochemical differences of their respective magmas (Civetta et al., 1989; Serri and Panza, 1991). The existence of two distinct regions, one in the Nortn-Central Apennines the other in the Calabrian Arc s.s., of lithospheric shortening, separated by a zone dominated by extensional processes, is nicely confirmed by the analysis of the average spectral content of the seismic sources located in Italy in the last years.

Magnetic data indicate the presence of ultramaphic material with a N-S alignement east of Corsica; the magnetic character of the Tyrrhenian abyssal plain is remarkably outstanding denoting an intense magmatic activity. A thin sub-Moho veneer in the central-southern Tyrrhenian Sea appears to be magnetized, and there are clear evidences from seismological and gravity data of uplifting of the mantle in the Tyrrhenian abyssal plain and off Tuscany. Seismological and gravity data indicate the presence of a high-velocity, high-density body sinking in the upper mantle beneath the Tuscan area. The gravity field observed in Calabria and Southeastern Tyrrhenian Sea, where intermediate and deep-focus earthquakes do occur, present striking analogies with what observed in Tuscany. In the Southeastern Tyrrhenian Sea it is possible to observe that: calcalkaline magmatism shows a spatial correlation with the shallower and steeper portion of the sinking seismogenetic slab, while the theoleiitic one correlates with its deepest and less steep portion. On the other hand the origin of the thcleiitic magmas found in the Central Tyrrhenian Sea can be explained by the fact that the gravitational sliding of the softer asthenosphere from the top of the diapir generates a pressure drop which partially melts the new rising mantle and gives the magmas their tholeiitic character, because the metasomatised part has flown away (Locardi, 1988).

The most relevant results which can be deduced from the gravity modeling is the presence of a lateral density contrast which takes place below the Moho discontinuity under the Northern Apennines and the Calabrian Arc where the denser Adriatic and Ionian upper mantle intrudes the softer Tyrrhenian one.

Intermediate and deep-focus earthquakes indicate that the lithospheric slab is still seismically active under the Eolian-Calabrian area and, sporadically, at the southern end of Campania (Caputo et al., 1970; 1972; Panza, 1978;

Anderson and Jackson, 1987). The lithospheric root, marked by very few events with depth not exceeding 150 km, seems to be much less active in the Roman/Tuscan region. The existence of relic, passively sinking, lithospheric slabs is supported by surface wave dispersion measurements and P-waves residuals and is confirmed by the trend of long-wavelength gravity anomalies, interpreted using as geometrical constraints those arising from aeromagnetic and seismic data.

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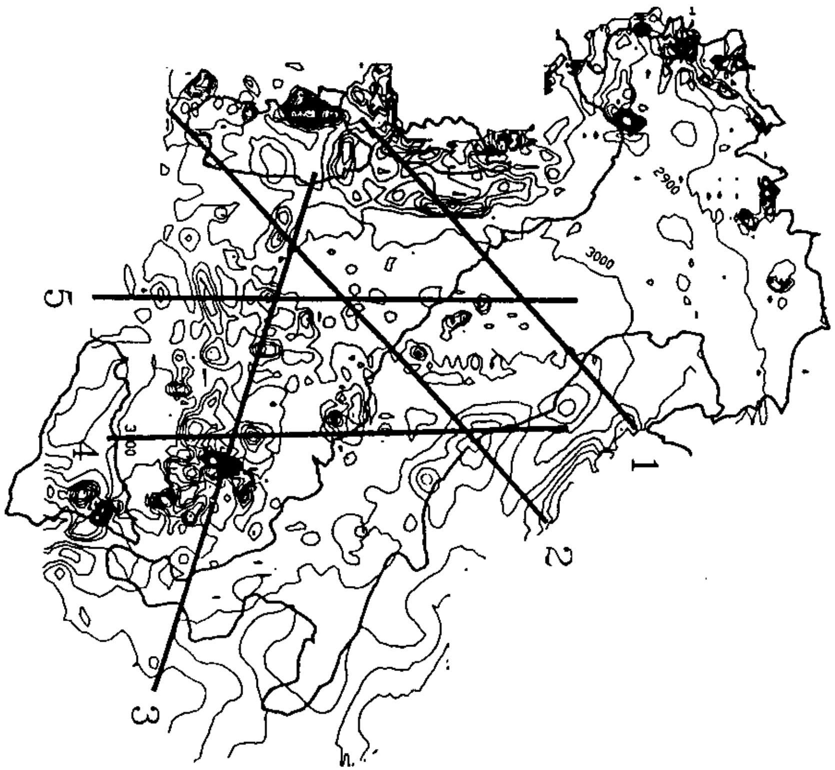
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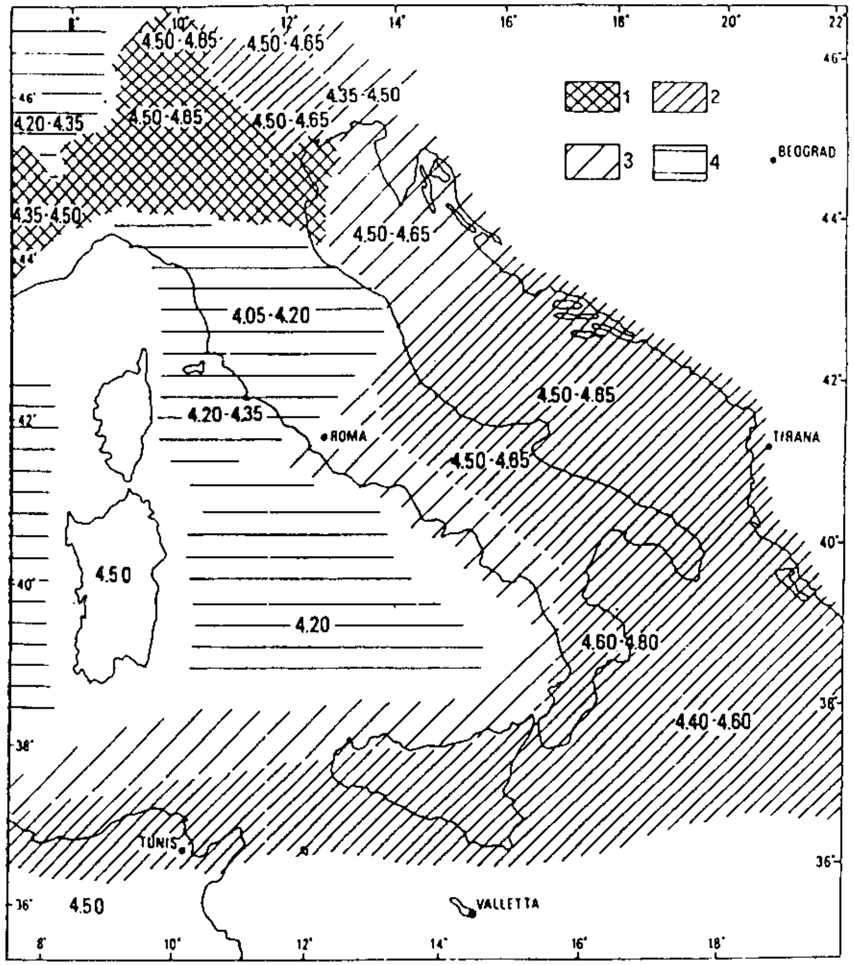
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TIRANA
TUNIS
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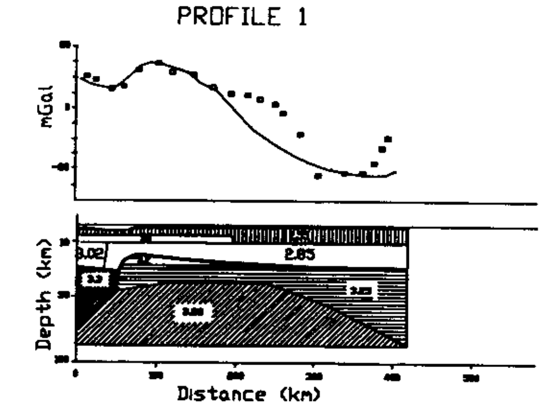
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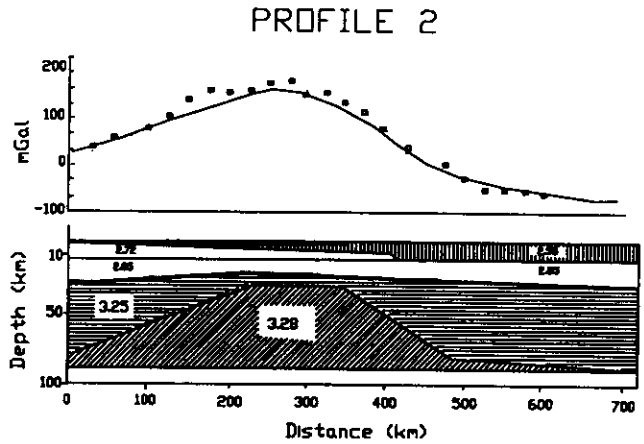
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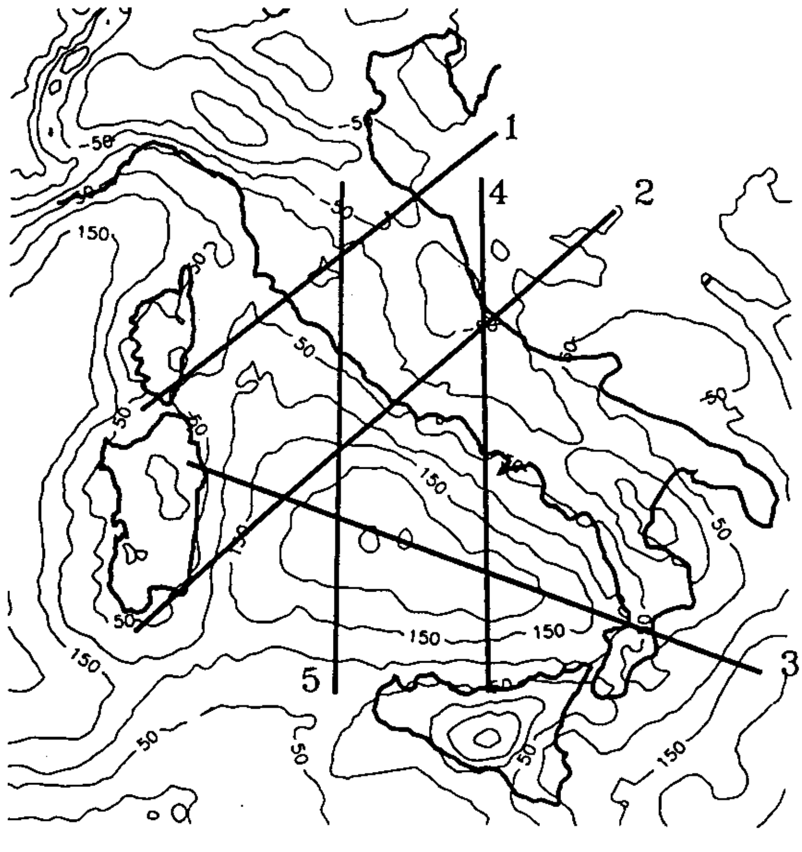
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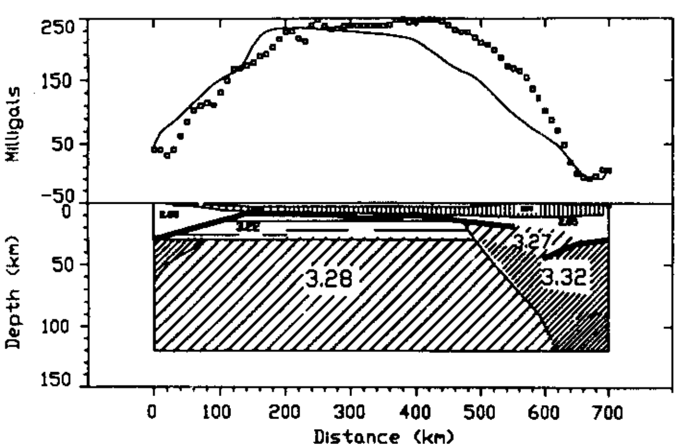

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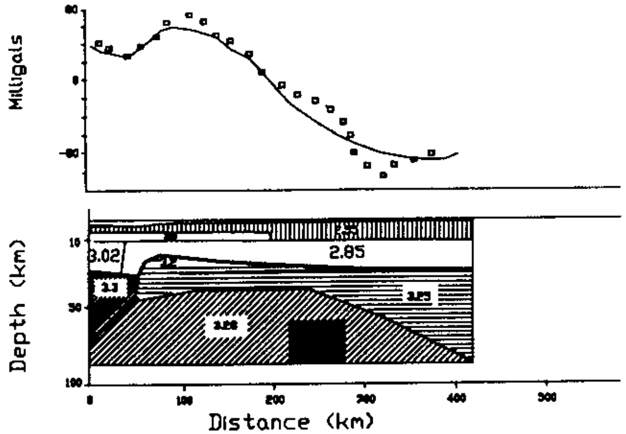

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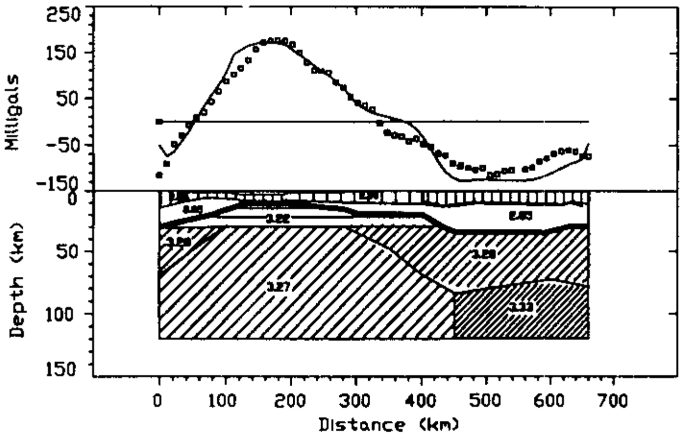

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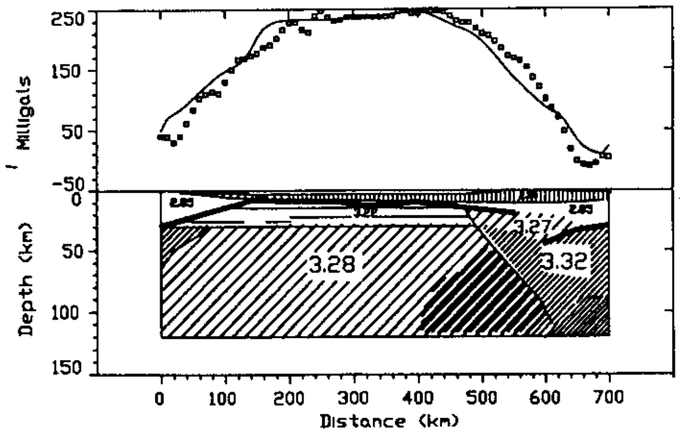

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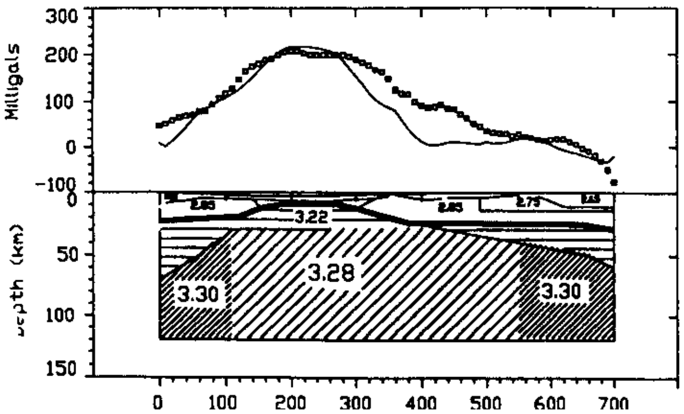

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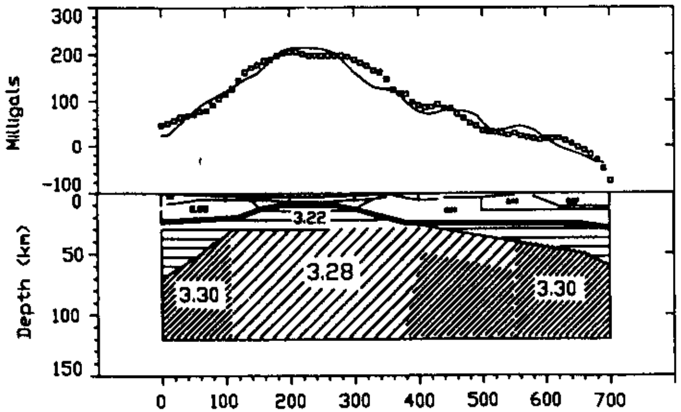

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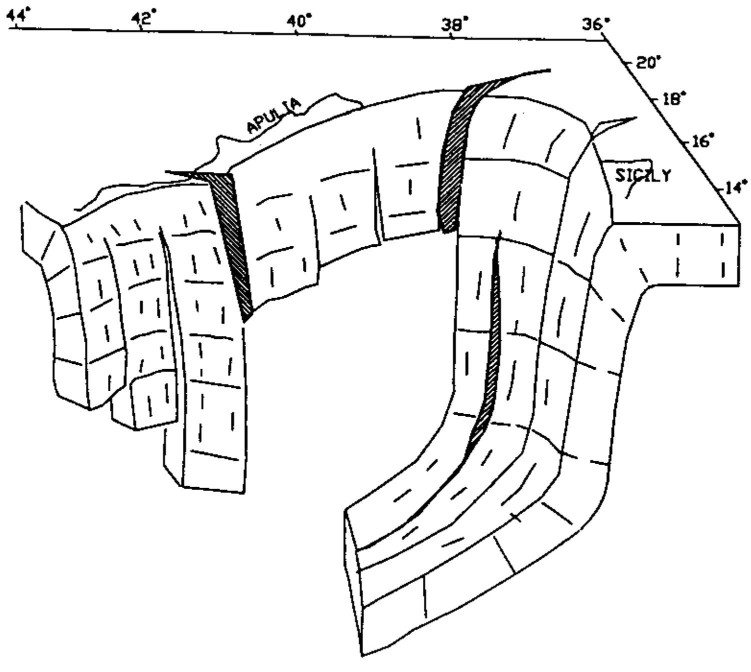
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